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# Using open-source software GRASS GIS for analysis of the environmental patterns in Lake Chad, Central Africa

## Verwendung der Open-Source-Software GRASS GIS zur Analyse der Umweltmuster im Tschadsee, Zentralafrika

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### Summary

Lake Chad, situated in the semi-arid region of African Sahel, plays a vital role in hydrogeological balance of regional ecosystems. It presents an essential water source and provides a habitat for rare wildlife species including migrating waterbirds. However, the lake has shrunk significantly since the 1960s and has continued to reduce in size and extent during recent decades. Trends in drying and shrinking of Lake Chad are caused by environmental factors and changed climate. The desiccation of the lake is threatening environmental sustainability. This study focused on identification of changes in the Chad Lake area, wetland extent, and associated land cover types. The methods include the Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS) for remote sensing data classification. The maximum likelihood discriminant analysis classifier was applied for analysis of multispectral Landsat 8-9 OLI/TIRS images in 2013, 2017, and 2022. Detected changes in land cover types reflect variations in water balance and wetland area and extent around Lake Chad over recent decades. Cartographic scripting tools of GRASS GIS provide an efficient method of digital image processing for monitoring endorheic lakes of Central Africa. GRASS GIS methods provide an opportunity to automatically classify Earth observation data with cartographic scripts for environmental monitoring.

**Keywords:** Sahel, remote sensing, geoinformation, cartography, scripting language

### Zusammenfassung

Der Tschadsee liegt in der halbtrockenen Region der afrikanischen Sahelzone und spielt eine entscheidende Rolle für das hydrogeologische Gleichgewicht regionaler Ökosysteme. Es stellt eine wichtige Wasserquelle dar und bietet Lebensraum für seltene Wildtierarten, darunter auch wandernde Wasservögel. Allerdings ist der See seit den 1960er-Jahren erheblich geschrumpft und hat in den letzten Jahrzehnten immer weiter an Größe und Ausdehnung abgenommen. Tendenzen zur Austrocknung und Schrumpfung des Tschadsees werden durch Umweltfaktoren und verändertes Klima verursacht. Die Austrocknung des Sees gefährdet die ökologische Nachhaltigkeit. Diese Studie konzentrierte sich auf die Identifizierung von Veränderungen im Gebiet des Tschadsees, der Feuchtgebietsausdehnung und den damit verbundenen Landbedeckungstypen. Zu den Methoden gehört das GRASS GIS zur Klassifizierung von Fernerkundungsdaten. Der Maximum-Likelihood-Diskriminanzanalyse-Klassifikator wurde für die Analyse multispektraler Landsat 8-9 OLI/TIRS-Bilder in den Jahren 2013, 2017 und 2022 angewendet. Die festgestellten Veränderungen in den Landbedeckungstypen spiegeln Schwankungen im Wasserhaushalt, in der Feuchtgebietsfläche und in der Ausdehnung rund um den Tschadsee in den letzten Jahrzehnten wider. Kartografische Skriptwerkzeuge des GRASS GIS bieten eine effiziente Methode der digitalen Bildverarbeitung zur Überwachung endorheischer Seen in Zentralafrika. Die GRASS GIS-Methoden bieten die Möglichkeit, die Erdbeobachtungsdaten automatisch nutzend kartografischen Skripten für die Umweltüberwachung zu klassifizieren.

**Schlagwörter:** Sahelzone, Fernerkundung, Geoinformation, Kartografie, Programmiersprache

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# 1. Introduction

## 1.1. Background

Many environmental phenomena which occur in landscapes and agricultural and ecological structures present heterogeneous properties changing in space and time at various scales (Peng et al., 2020; Fahrig, 2003; Wilson et al., 2017). Various approaches of modeling, visualization, and mapping are developed with an aim of describing the nature of these structures, analyzing their origin and trends in the dynamics. Using Earth observation data is one of the key approaches in geographic sciences for analysis of environmental phenomena. The principal idea of using remote sensing data for environmental monitoring consists of satellite image analysis, which uses the information on spectral reflectance of the objects and land cover types on the Earth's surface that are visible from space and identified as various digital values of the pixels on the images (Weiss et al. 2020; Xie et al., 2008; Abdi et al., 2021). Such fundamental properties of the remote sensing data enable to identify various classes of land cover types using image processing techniques. Furthermore, comparison of several images on the same area for various time periods enables to visualize and analyze the dynamics in land cover types. This is essential for evaluating landscape changes and climate–environmental monitoring. Such an approach is possible using Landsat Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images.

This paper addresses the problem of mapping land cover type changes in Chad Lake, Central Africa (Figure 1) using Landsat images and Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS). In the past, Lake Chad was among the largest lakes of Africa with the extent varying according to climate fluctuations (Daveau, 1960). However, during the last 60 years, the lake experienced dramatic drying by around 90% of its surface area, which shrunk from 25,000 km$^2$ in 1960s to about 1350 km$^2$ (Owonikoko and Momodu, 2020; Rudincová, 2017; Zhao et al., 2022). The reasons for such significant changes include both natural and anthropogenic factors. Natural triggers for lake shrinkage consist of the complex interrelations of the hydro-climatic processes, for example, increased temperature and decreased precipitation (Buma and Lee, 2016). Another important feature of Lake Chad contributing to its shrinkage consists of the geomorphology of the surrounding basin area that is not expressed. As a result, this region has a very flat relief nearby the lake itself and its overall shallow bathymetry with the maximum depths around 7 m, the average depth 3.40 m, 2.45 m in its southern segment and 4.55 m in its north segment. As discussed in previous studies (Pédro and Carmouze, 1977) also, such flat topography is very characteristic of Lake Chad and creates conditions for the distribution of wetlands on its shoreline areas.

The unprecedented hydrological drought in the mid-20$^{th}$ century in sub-Saharan Africa significantly affected the lake volume. Climate effects included irregular rainfall patterns, changes in river discharge, and rise in annual temperatures (Pattnayak et al., 2019). All these processes resulted in a series of droughts and desertification of the surroundings landscapes. This led to the depleted vegetation and almost half of vegetation cover being lost for three decades until

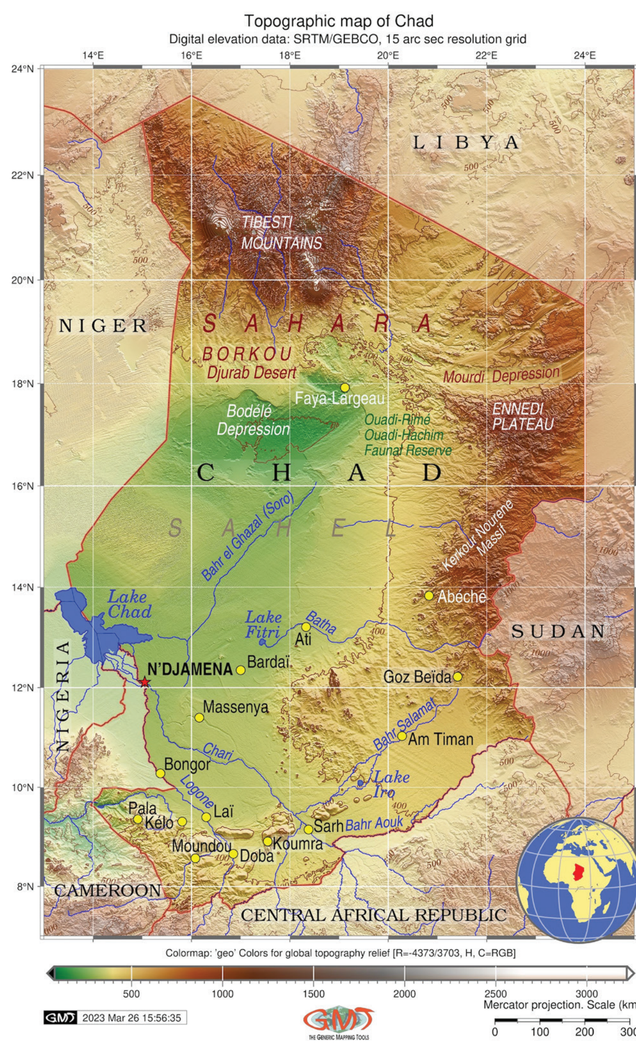


Figure 1. Topographic map of Chad. Map source: made by the author using GMT software.

Abbildung 1. Topografische Karte des Tschad. Kartenquelle: erstellt vom Autor nutzend GMT-Software.

2010s in the Lake Chad Basin (Nwilo et al., 2020). As a consequence, water level in the lake declined dramatically. Aside from natural factors, drying of Lake Chad was exacerbated by anthropogenic activities: dams construction, artificial irrigation, overuse of groundwater resources, and excessive water consumption (Yao et al., 2023; Okeke-Ogbuafor et al., 2023). The cumulative effects from all these factors resulted in the shrinkage of Lake Chad (Riebe and Dressel, 2021).

### 1.2. Problem Statement and Related Works

Accurate cartographic visualization has been a challenge in environmental sciences. It is even more essential for African studies where data are often scarce or vary significantly by sources, resolution, and spatial extent. The wide range of the geographic data poses a great challenge for mapping approaches due to their different functionality (Steiniger and Hunter, 2013).

Existing examples of mapping Lake Chad include the use of the diverse GIS software (Nzango et al. 2022; Onamuti et al. 2017; Pham-Duc et al. 2020) for environmental monitoring and mapping of Chad Lake. Other studies present cases of satellite image processing for hydrological modeling (Bennour et al. 2022), estimating shrinkage in the catchment area (Buma et al. 2018), variations in the soil characteristics in Chad watershed (Lopez et al., 2018), or fluctuations in the Sahelian climate in Chad (Wakdok and Bleischwitz, 2021).

The fieldwork-based studies in Chad region use hydrological parameters to estimate the net water balance in lake by modeling (Mahmood, and Jia, 2019). The parameters include the tributary inflow, precipitation, evaporation, infiltration, and additional data on soil moisture deficit, soil imperviousness, or infiltration rate. Such approaches address the questions of climate–environmental monitoring by simultaneously exploring multiple hydrological parameters.

However, the existing methods handle only the relatively small-scale and restricted processes limited to the target hydrological variables and probabilistic modeling (Guganesharajah and Shaw, 1984) without their extent becoming converted to the indicators of land cover changes and visualized changes in landscapes. Besides, they often require hydrological surveying, sampling, and data collection (Robinson and Robinson, 1971) aimed at converging and adjusting models. In contrast, more advanced methods of environmental monitoring include the use of remote sensing data and satellite images (Coe and Birkett, 2004). Using satellite images enables performing time series for the analysis of lake extent and associated land cover changes. In this regard, the advanced software GRASS GIS with advanced modules of satellite image analysis (Lemenkova and Debeir, 2023a) achieves attention in environmental mapping due to its powerful technical functionality.

As briefly reviewed above, the available GIS programs have limitations and may be efficient for selected operations, while they are restricted for automatic and complex image analysis. Another concern relates to the origin of data and materials, which may be captured from multiple sources and have diverse projections and resolution (Bastola and François, 2012). The combination of these tools in one research for dividing research tasks is cumbersome and not always convenient, which raises the question of the console-based programs for image analysis. This is achieved in GRASS GIS due to the programming syntax, which ensures a flexibility in mapping process.

## 2. Study Area

Lake Chad is an endorheic shallow lake of Central Africa originating from the large paleolake Chad, a relict of a giant Quaternary Megalake (Drake et al., 2022). Major sediment types include the outcrops of Quaternary (Pleistocene) and Tertiary (Neogene) formations (Figure 2). Geologically, Lake Chad presents an intracratonic sag basin with basement comprising a suite of crystalline rocks related to the Pan-African orogeny (Schuster et al., 2009).

Here, the geological units are formed during late Precambrian (pCm) and are mostly located within the Chad geological province (Figure 3). The surrounding provinces with connected watershed region include the Nubian Uplift in the north and Erdis Kufra basin in the northeast, which includes the prominent desert Mourdi Depression and is limited by the Paleozoic sandstones of the Ennedi Plateu (Figures 1 and 3). The Mourdi Depression presents a rocky valley and a grazing ground area located along a route from the Ennedi Plateau toward the northeastern region of the lake. The context of the geological setting is explained in the effects of mineral constituting soil structure and affecting its water permeability that, in turn, contributes to lake shrinkage. Besides, geologic settings are directly related to soil types, which, in turn, are connected to the vegetation types: soft soils near the lacustrine environment are dominated by aquatic plants, while rocky hard soils are typically found in the semi-desert landscapes with rare vegetation.

The palaeoecological reconstructions identified relict Saharan river deltas, landforms, and paleoshoreline of Megalake Chad (Leblanc et al. 2006). Since the last glacial maximum,

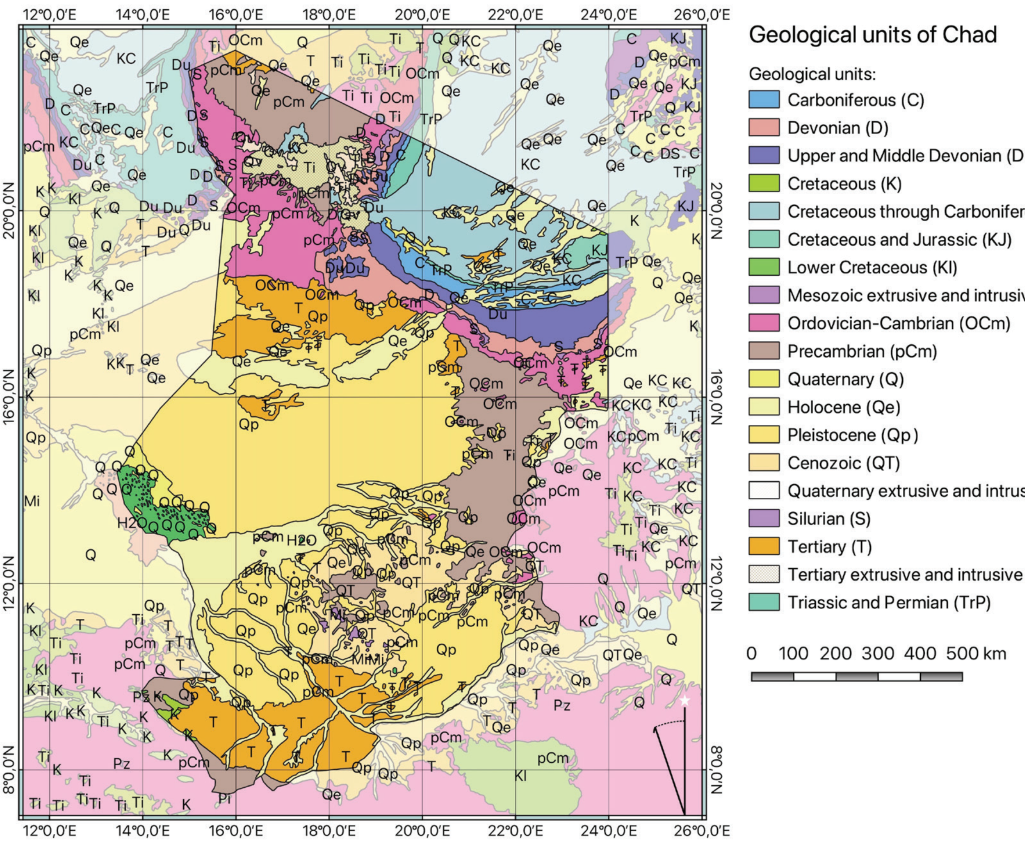


Figure 2. Geologic units of Chad. Map source: made by the author using QGIS software.
Abbildung 2. Geologische Einheiten des Tschad. Kartenquelle: erstellt vom Autor nutzend QGIS-Software.

the transgressed lacustrine deposits in the depression of the Lake Chad Basin affected the aeolian geomorphology in the catchment area through flooded accumulation of dunes in the Bodélé Depression in northern Chad and dune islands in the surroundings (Bristow and Armitage, 2016). Over the past 50,000 years, the area of Chad Lake has varied significantly in size due to a variety of factors. These include the climatic fluctuations in Sahara since the Late Miocene (Durand, 1982; Servant, M., 1983; Pouyaud and Colombani, 1989), the monsoon-driven hydrodynamics (Bouchette et al. 2010), and the geological uplifts (Burke, 1976). As identified by the littoral sedimentary records including fine-grained deposits and diatoms, Chad Megalake was one of the giant lakes in the Sahara existing in Quaternary during the humid period (Mémin et al., 2020).

A southern border of the Lake Chad region is presented by the western and eastern segments of the Congo Precambrian Belt (Figure 3). These geological units forming the Late Proterozoic orogenic chain present blocks shaped by the crustal evolution of the region. Most of Chad's granitoids originated from the end of Proterozoic (Kusnir and Moutaye, 1997). The Precambrian formations of Chad are dated by the Proterozoic Eon and include a series of sedimentary rocks originating from volcanic material with significant mineral potential. As a result of such complex geologic development, the lake has now immense catchment basins of the groundwaters, which exceeds an area of 500,000 km$^2$.

The association of geologic setting with land cover types is expressed through soil types. Thus, in the flooded plain of Lake Chad region, the main mineral type is smectite clay associated with kaolinite and illite (Jean Pierre et al. 2019), which supports groundwater hydrology and supplies water level in the lake during periods of droughts. In contrast to the rich groundwater supply, the surficial inflow of the southern segment of Lake Chad is supplied up to 90% from the Chari-Logone catchment (Black et al., 2021). The Chari and Logone rivers originate in southern highlands of Cameroon and the Central African Republic (Hutchinson et al., 1992). The northern segment depends on the minor inflows from the Komadugu Yobe River originating in Nigeria and the

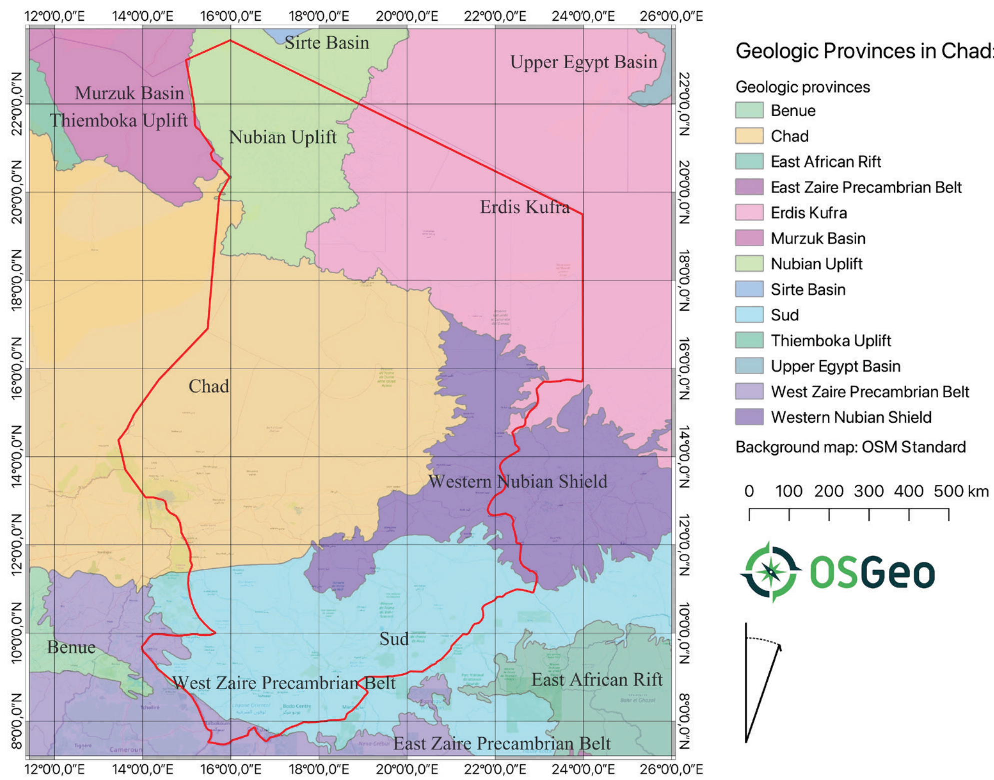


Figure 3. Geologic provinces in Chad. Map source: made by the author using QGIS software.
Abbildung 3. Geologische Provinzen im Tschad. Kartenquelle: erstellt vom Autor nutzend QGIS-Software.

overflows from the southern basin (Fougou and Lemoalle, 2022). Early Cretaceous clastic sediments are found in the West African Rift Subsystem of Chad (Genik, 1992), which presents the extent of the East African Rift in the southeastern region. A part of the Great Rift Valley developed during Pan African orogeny. The East African Rift System has geologic implications on the tectonic and structural aspects of mineral resource distribution and groundwater level in Chad.
The hydrology of Lake Chad plays a key role in the environmental sustainability of Africa through regulating energy and carbon cycles, participating in global climate balance, and as a key regional water source. Moreover, Lake Chad plays a key socioeconomic role in the region through support of agriculture activities and fishery and as a water source to over 30 M people in the surrounding countries: Chad, Cameroon, Niger, and Nigeria (Vaquero et al., 2021). As a transboundary water source, Lake Chad maintains the livelihoods for existence of local population, such as fishing and farming (Sarch and Birkett, 2000; Zieba et al., 2017; Baroin and Boutrais, 1997). Besides, it provides diverse ecosystem goods and services, and natural resources such as firewood or livestock rearing. This highlights the importance of measures on the environmental conservation of the lake and sustainable development of its resources. As a result, the agricultural activities of the Lake Chad region are concentrated around the lake and the two river systems which play a major role in the agricultural economics of the region.
The human-induced triggers contributing to the shrinking of Lake Chad include unsustainable agriculture with groundwaters intensively used for irrigation (Lemoalle and Magrin, 2014), increasing demand for freshwater from the lake by the population, and drilling of boreholes as hydrogeologic activities for constructing large-scale irrigation systems (Birkett, 2000). The intensive modern irrigation and farming methods in agriculture practicing include fertilizers and farm machinery for maize and millet production, which led to land degradation (Nilsson et al., 2016). Further, the analysis of the vegetation patterns and surface water levels in Lake Chad demonstrated the links of land cover types with rainfall fluctuations during wet and dry periods (Balme et al. 2006), as well as the effects from seasonally contrasted climate (Gbetkom et al., 2023).

## 3. Materials and Methods

### 3.1. Data

The data used in this study include three satellite images: Landsat 8 OLI/TIRS on November 22, 2013, November 17, 2017, and December 09, 2022 (Figure 4). The choice of years of the images is explained by the availability of the Landsat OLI/TIRS scenes, with the earliest images for the Landsat OLI sensor for 2013 due to the launch of this satellite in 2013. Moreover, the sensor spectral band pass and the high spatial resolution of 30 m across the multispectral channels (1–7) enable using the Landsat scenes for land cover analysis as reliable data sources. Finally, Landsat images provide open availability of cloud-free images (less than 10% of cloudiness). Finally, the images are taken with repeatability due to regular survey. This provides a comparable gap among the target years (2013, 2017, and 2022) when the images were collected for the analysis of changes in vegetation around Lake Chad. All images are selected in the three key control periods with gap between the data in 4–5 years, taken during cold period of late autumn/winter when there is highest water level in vegetation leaves. It is known that the level of cloudiness has a key impact on the image quality. Therefore, this study used 10% of cloudiness for all the scenes which had the lowest values in the cold period of late autumn/winter. Tested images included spectral bands in visible, short-wave infrared (SWIR)-1, SWIR-2, and Near-infrared (NIR) channels obtained from the OLI sensor.

The images covering the target region of Chad Lake were downloaded from the public United States Geological Survey (USGS) EarthExplorer repository on remote sensing data (https://earthexplorer.usgs.gov/). The images were captured from the original location in USGS EarthExplorer repository. The images were downloaded using the defined credentials with regard to cloudiness, extent, time of coverage of Lake Chad, image IDs, and access path to Landsat scenes. All elements in data collection are treated as object parameters, among which the computational region was set by the "g.region" module to match the scene of the Landsat images. The resolution of each image is moderate (30 m for multispectral bands of the Landsat OLI/TIRS sensors) with a file size of around 800–900 MB for the folder containing all necessary and auxiliary files for each scene.

Each image consisted of several tiles representing Landsat OLI/TIRS bands: multispectral visible bands, NIR, Panchromatic, Cirrus, two SWIR bands, and two TIRS bands. Although the dimensions of the bands are identical, the resolution differs with 30 m for bands 1–7 and 9 (Cirrus), 15 m for panchromatic band, and 100 m for two TIRS bands. In this study, we only used the multispectral channels of Landsat with a resolution of 30 m. Therefore, one pixel on an image corresponds to 30 m on the Earth's surface in the original Tag Image File Format (TIFF), which determines the level of details of the land cover patterns on the classification to this spatial dimension.

The images were then read into the GRASS GIS environment using the "r.import" modules. Each Landsat OLI/TIRS

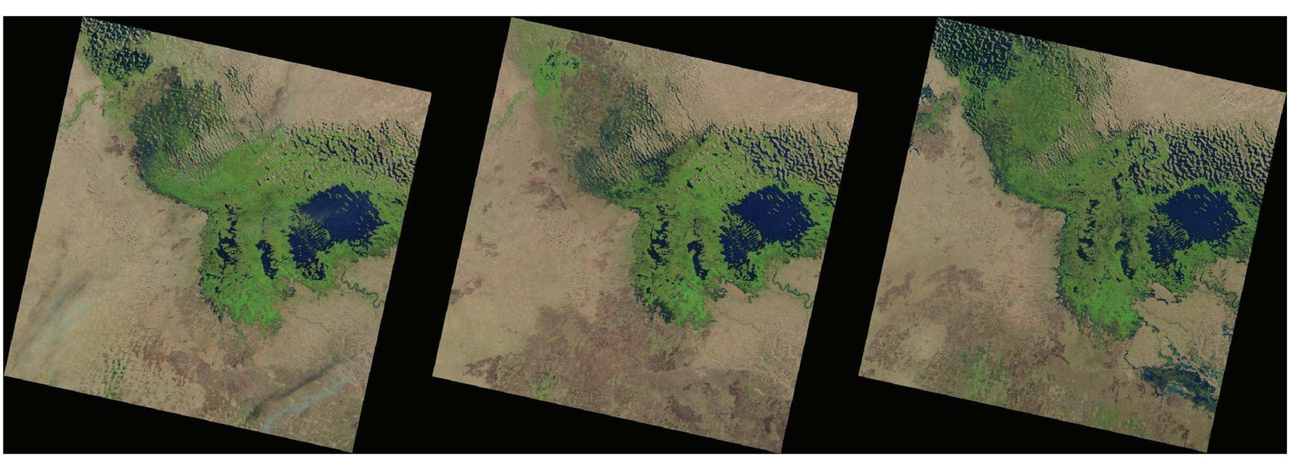

Figure 4. Landsat 8 OLI/TIRS image of Lake Chad in natural RGB colors: (left) November 22, 2013, (center) November 17, 2017, (right) December 09, 2022.

Abbildung 4. Landsat 8 OLI/TIRS-Bild des Tschadsees, in natürlichen RGB-Farben: (Links) 22. November 2013, (Mitte) 17. November 2017, (Rechts) 09. Dezember 2022.

image contained 11 bands, which were imported and processed individually using the "r.import" module. Selecting the multispectral bands from the original image was based on the "r.import" module, which collects raster data and reads them into a GRASS raster mapset environmental using the embedded Geospatial Data Abstraction Library (GDAL) library and projects the raster files into cartographic parameters defined for a mapset. Alternatively, raster files can be imported using the "r.in.gdal" library of GDAL, and the images were stored in the working folder using the location and mapset of the current project.

### 3.2. Methods

To perform image processing for Landsat 8-9 OLI/TIRS imagery, we apply GRASS GIS developed by Neteler and Mitasova (2004, 2008). The main approach includes unsupervised image classification using the maximum-likelihood discriminant analysis classifier, technically implemented by the key GRASS GIS module "i.maxlik." The embedded algorithms discriminating the pixels account for individual identities using information on their spectral reflectances. Based on this, the land cover types and objects represented on the satellite images are identified using spectral signatures relevant for each class. Programming methods and scripts present the recent trend widely used in geospatial data processing. Scripting emerged as a powerful alternative to the traditional GIS (Lighezzolo et al., 2019; Lemenkova and Debeir, 2023b; Bu et al., 2015).
Among the diverse existing methods and software that can be used for satellite image processing, a scripting-based approach of GRASS GIS stands apart due to its advantages and functionality. In contrast to many conventional software, GRASS GIS supports scripts for such optimization of data processing and minimizing the cartographic workflow. This is achieved through the repeated parts of the code which are used for data processing and enable automated detection and classification of objects on the images. Once the images were read in the GRASS GIS environment, several steps of the developed framework on image processing were implemented, as described below. Three images were evaluated covering the region of Lake Chad in the three years: 2013, 2017, and 2022. Two major approaches in processing satellite images include the unsupervised and supervised methods of classification. The main difference between these approaches resides in the way the images are processed as data and the discrimination of pixels on the image scene. While the first approach requires human-based supervision that might be prone to errors, the unsupervised classification is a machine-based method which is more objective and free of bias. In this study, we use the unsupervised classification method using the maximal likelihood classifier.
Classification was performed using the maximal likelihood approach by the "i.maxlik" GRASS GIS module, which classifies the cells on the images using their spectral reflectance. The main idea of unsupervised classification using k-means implemented by cartographic scripts of GRASS GIS is to automate and simplify the mapping workflow to increase repeatability of algorithms and precision of mapping. Such methods principally differ from the supervised classification due to machine-based objectivity as scripts rely on a straightforward concept of data partition and dividing them into several clusters automatically. Hence, every step in a mapping process is fully controlled by the machine which implements the classification automatically and uses lines of code, written according to the language syntax. In this way, hidden obstacles and bugs, often in supervised classification, are avoided, and the complete procedure of mapping is improved through objective and automatic method of image analysis. The processing workflow for each image included clustering of images on each scene extracted from the original raster file, detection of clusters with centroids using the "i.cluster" module, assignment of pixels to these clusters based on individual spectral reflectance values, and indicating their representative values by creating a signature file.
In this way, it detects land cover classes for each image for a short-term sequence of images in 2013, 2018, and 2022. The land cover classes were identified dividing the image into repetitive segments of vegetation patterns automatically using the maximum likelihood approach of GRASS GIS. The "i.maxlik" module of GRASS GIS was used for automatic generation of land cover classes based on the minimal distance search algorithm. This algorithm assigns pixels to the classes based on the distance between the pixel's value and centroid of the tested class. In this procedure, it uses the signature file generated automatically by the "i.cluster" module with the indicated number of target classes. Regular intervals of the land cover classes in the Lake Chad region are represented in Figures 5–7 showing the landscape patterns for 2013, 2018, and 2022, respectively.
The advantage of scripting in GRASS GIS is that GRASS GIS is a GIS software that is especially tuned to geospatial data processing, while the approaches of Python and R are based on general approach to data handling. Moreover, the

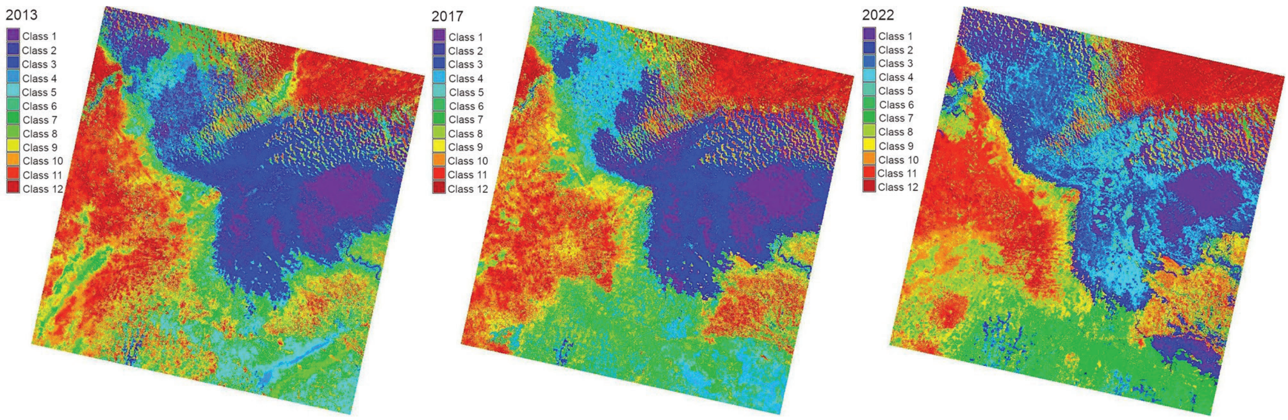


Figure 5. Landsat 8-9 OLI/TIRS image of Lake Chad classified into 12 classes of land cover types: (a) 2013 map, (b) 2017 map, (c) 2022 map.
Abbildung 5. Das Landsat 8-9 OLI/TIRS-Bild des Tschadsees, klassifiziert in 12 Klassen von Landbedeckungstypen: (a) Karte von 2013, (b) Karte von 2017, (c) Karte von 2022.

advantages of GRASS GIS scripts consist in flexible use of its diverse modules specifically adjusted for various tasks of cartographic processing: performing classification, plotting maps, adding legends, selecting colors, etc. Such modules are tuned as a collection of codes written in GRASS GIS syntax specially designed to optimize specific cartographic and geospatial tasks. The examples include computing vegetation indices, projecting the data, and other tasks.

Identification of vegetation patterns and wetlands around the flooded area of the lake was done for the target years using the detected land cover classes interpreted by the Food and Agriculture Organization (FAO) classification available for the Lake Chad region (FAO, 2008). The land cover classes indicating the increase of drought are the land cover classes 8) bare soil, 9) rocky land, 10) sandy areas, and the transitional classes, for example, land cover class 1) "gallery forest and riparian forests" changing to land cover classes 4) "savannah (Sahelian short grass savannah and herbaceous savannah)" or 5) "steppe."

Annotating the land cover classes was performed using signature file by identifying the interval breaks between the target classes using the difference in the spectral reflectance values of the pixels (cells on the image). Similar classes (e.g., three types of savannahs) were grouped based on the original resolution of the images (30 m) which enabled to identify vegetation patches with size larger that this size. In this way, the classes were grouped and located close to the patches of landscapes with similar spectral reflectance values in the original Landsat images. The algorithm performed automatic clustering and classification of each image in less than 2 s and processed raster files for the years 2013, 2018, and 2022 using the described methods.

## 4. Results

Annotating of the land cover classes around Lake Chad based on the recognized image features aimed at accurate object recognition during classification of the satellite images, which required preliminary examination of the images and analysis of major landscape types according to FAO classification. Hence, the following 12 classes were selected and identified, according to FAO: Class 1 – water bodies; Class 2 – wetlands and floodplain with aquatic plants; Class 3 – swamp forest; Class 4 – woodland; Class 5 – rocky land; Class 6 – bare soil; Class 7 – sandy areas; Class 8 – steppe; Class 9 – agriculture and irrigated areas; Class 10 – settlements and urban areas; Class 11 – savannah (Sahelian short grass savannah and herbaceous savannah); and Class 12 – gallery forest and riparian forests. Image features and associate land cover classes were recognized in the images, identified, and described as patches of land cover classes constituting the landscapes of Lake Chad. Global warming plays a key role in the meteorological setting of Chad Lake through increase of temperatures and modification of precipitation patterns. Thus, annual rainfall trends significantly decreased from 2018 to 2022 at all locations in Chad Lake. This is especially notable for northern regions located close to the Sahara Desert, which receive less precipitation in the form of rare and irregular rainfalls. Regional difference in precipitation level was reported by Pattnayak et al. (2019) as follows: rainfall (cm/month): 0.30 for Faya, 3.26 for Ati, 4.47 for Ndjamena, 9.09 for Mondou, which shows the increasing trend for cities located southward and few precipitations for the northern regions close to Sahara. Such variations in precipitation level affect the drought patterns in the northern regions of Chad and the surrounding

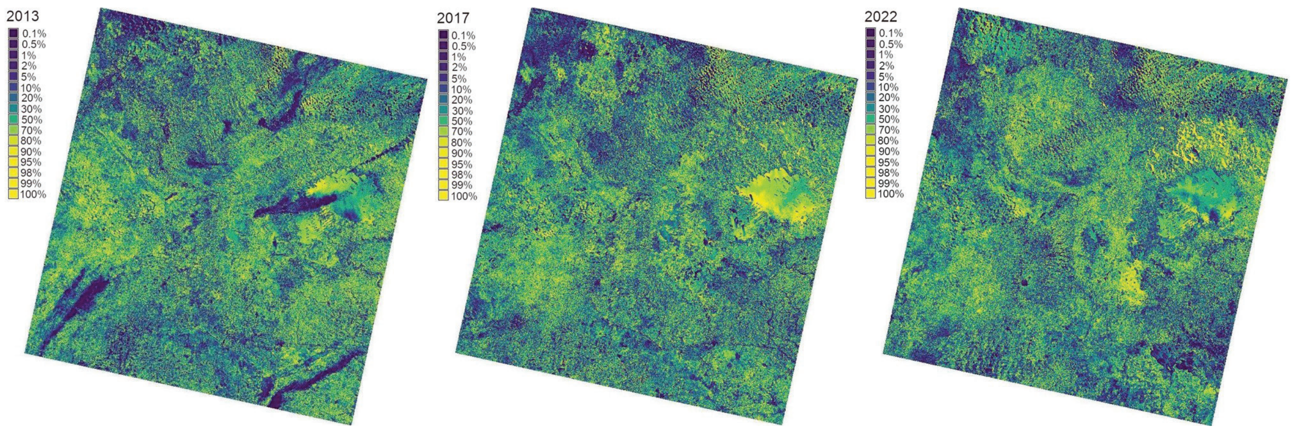


Figure 6. The rejection probability values with pixel classification confidence levels for Landsat 8-9 OLI/TIRS images of Lake Chad: (a) 2013, (b) 2017, c) 2022.
Abbildung 6. Die Ablehnungswahrscheinlichkeitswerte mit Pixelklassifizierungs-Konfidenzniveaus für Landsat 8-9 OLI/TIRS-Bilder des Tschadsees: (a) 2013, (b) 2017, c) 2022.

regions. Apart from precipitation, the temperature differs in various regions of Lake Chad according to the distance from Sahara as follows: the mean temperature ranges between 27.10 °C (Moundou) and 30 °C (Mongo), while the variability ranges between 0.5 °C (Ndjamena) and 1.03 °C (Abeche). Finally, besides climatic factors, the demographic pressure is also a serious factor in shrinkage of the lake surface and increase in droughts. Thus, the number of people living around the lake increased from 13 M to ca. 40 M from 1960 to 2022, which contributed to the changes in land cover types, especially increase in land cover classes such as 8) bare soil and 7) settlements and urban areas, which replaced the natural land cover types dominating earlier.

Pixels or objects with similar spectral characteristics on the images were allocated to the designated classes using the algorithm of the maximum-likelihood discriminant analysis classifier embedded in GRASS GIS. Using this approach, the "i.maxlik" module enabled to classify the three images and indicate specific land cover classes around Lake Chad. Annotations of the objects as land cover classes included recognition of the distribution of their extent, changes from 2013 to 2022, and detecting shrinkage in water areas and wetlands around Lake Chad and partially overlapped classes in the savannah regions. The polygon structure on the landscape mosaic on the classified maps demonstrates the interspersed patches of the landscape segments, which are identified on the Landsat images from 2013 to 2022 accordingly.

Likewise, changes in the annotated land cover classes on the images demonstrate the climate effects which resulted in variations of the land cover classes used for identification of the environmental changes around Lake Chad. The comparison of the land cover associations over years detected on the multispectral images and their changes with time on the original images and classified maps enabled evaluating the results. Although some land cover classes experienced shrinkage or changes in contours, their inner structure and topology remained identical with regard to neighboring classes, for instance, the distribution of savannah, sandy areas in the Sahara Desert and wetlands around Lake Chad. Since images were obtained with 4–5 years of time gap, such features were matched to find all possible cases of land cover changes to complete the map of the land cover classes in the region of Lake Chad.

As all the Landsat images were collected in late November–early December period, the phenological cycles of vegetation represented in the images did not affect identification of the vegetation patterns since extracting the information on land cover classes was possible in a comparative manner with regard to the period of plant growth in the Chad region (late November–early December). Using the procedure described above, the land cover classes were created with the aim of identifying the target patches of each landscape type to detect changes from 2013 to 2022. This mosaic of land cover types represents the extent of the diverse landscape types around Lake Chad to accurately detect landscape changes caused by environmental and climate effects. The changes were detected between 2013, 2018, and 2022 and used for evaluating variations in land cover types around the Lake Chad region. The repetitive vegetation patterns and objects identified as land cover classes were recognized and annotated on the three resulting maps showing the landscape changes in the land cover classes around Lake Chad.

The annotated objects for patches of land cover classes identified on the images forming the land cover classes around Lake Chad are presented as three respective maps in Figure 5, with the statistical evaluation shown in Figure 6.
Global warming plays a key role in the meteorological setting of Chad Lake through increase in temperatures and modification of precipitation patterns. Thus, annual rainfall trends significantly decreased from 2018 to 2022 at all locations in Chad Lake. This is especially notable for northern regions located close to the Sahara Desert which receive less precipitation in the form of rare and irregular rainfalls. Regional difference in precipitation level was reported by Pattnayak et al. (2019) as follows: rainfall (cm/month): 0.30 for Faya, 3.26 for Ati, 4.47 for Ndjamena, 9.09 for Mondou, which shows the increasing trend for cities located southward and few precipitations for the northern regions close to Sahara. Such variations in precipitation level affect the drought patterns in the northern regions of Chad and the surrounding regions.
Apart from precipitation, the temperature differs in various regions of Lake Chad according to the distance from Sahara as follows: the mean temperature ranges between 27.10 °C (Moundou) and 30 °C (Mongo), while the variability ranges between 0.5 °C (Ndjamena) and 1.03 °C (Abeche). Finally, besides climatic factors, the demographic pressure is also a serious factor in shrinkage of the lake surface and increase in droughts. Thus, the number of people living around the lake increased from 13 M to ca. 40 M from 1960 to 2022, which contributed to the changes in land cover types, especially increase in land cover classes such as 8) bare soil and 7) settlements and urban areas, which replaced the natural land cover types dominating earlier.
The analysis of the classified images (Figure 5) shows an overall trend in dryness and desertification of Chad Lake, which includes expansion of the desert zone southward as well as disappearance of forests replaced by the savannah shrubs and grasslands. At the same time, since Lake Chad is a part of the complex region of the sub-Saharan region, there are also reported fluctuations of the dry and wet phases in this region reconstructed for Quaternary period (Rognon, 1976). These are supported by the modeled climate changes that existed in Central Africa as proved by the sedimentological and geomorphological analysis indicating the location of alluvial flood plains, terraces, and lacustrine deltas in the past. Therefore, the additional triggers causing variations in the water level of the lake experience the effects from the long-term climatic oscillations.
The presented series of maps shows a fluctuating behavior of Chad Lake in Central Africa on the border with Sahara through the investigated periods as a result of the seasonal effects from temperature acting as triggers to land cover changes. Several segments of land cover types were compared for the lake and the surroundings. Moreover, the correlations between the extent of Chad Lake and the effects from temperature are related to the influence of climate on the environment of southern Sahara. In view of the advantage of the GRASS GIS-based approach to analyze the environmental properties of the landscapes in Chad, this paper presents a short period times series analysis of Chad Lake along with the applications of the image processing methods. The main idea of this study was to apply in a single workflow framework using open-source data Landsat OLI/TIRS and software GRASS GIS.
The study evaluated both the multi-year images and vector maps to reveal the information on Chad Lake behavior with varying data with regard to a sequence of different years. In such a way, the Landsat images were analyzed as multi-temporal time series as variation analysis. Changes in land cover types and water extent of the depressions of Chad Lake were evaluated using a series of Landsat 8-9 OLI/TIRS images processed with GRASS GIS using advanced scripting approach.

## 5. Discussion

Visualizing spatiotemporal changes in the borders of Lake Chad is essential for environmental monitoring. The basin of Lake Chad is subject to the changes caused by anthropogenic impact and variability in climate patterns. Therefore, mapping changes using satellite images on different dates enables evaluating these changes in the lacustrine landscapes. The anthropogenic effects may be diminished to the adaptive ecological monitoring measures, as well as sustainable agriculture and farming in the Chad Lake region. Advanced approach to visualization of the land cover types in Sahelian Africa is through cartographic processing of the remote sensing data (Buma, and Lee, 2020; Lemenkova and Debeir, 2022a). Using remote sensing data in mapping enables applying advanced methods for monitoring environmental changes (Bardinet, 1981; Zhu et al., 2017; Li et al., 2021; Lemenkova and Debeir, 2022b).
The comparison of several images covering Lake Chad classified for various years enabled visualizing the changes in the land cover types and increased shrinkage of land in the cold period of autumn/winter months. Thus, it highlighted the relationship between climate that contributed

to the shrinkage of lake via evaporation and raised temperatures and the hydrological response of lacustrine environment around Chad that reflected in the changes of lacustrine landscapes and depleted nearby vegetation. The difference in behavior of various land cover types and Lake Chad suggests that landscape dynamics along with seasonal variations of temperature and precipitation around Chad as quantified by the clustering and classification of the images are primarily determined by the properties of the soil in the land cover types of the landscapes surrounding Chad Lake due to the different content of minerals in soil.

The present study extended the existing research focused on variations of Lake Chad through investigation of the land cover changes in its surroundings. To evaluate land cover dynamics in the Chad Lake area, the GRASS GIS algorithms of modules were applied for image processing. Three satellite images Landsat 8-9 OLI/TIRS were classified, compared, and analyzed. The results showed the visualized changes in the land cover types of Chad Lake. For comparison of changes, the images were collected in the same period of different years. The objective approach of the machine-based classification of the images strengthens the discrimination of the images. The images are represented as triplets of the multispectral Landsat bands processed by the maximum likelihood classification. The theoretical basis of image analysis lies within the frame of remote sensing theory on image properties and variations in spectral reflectance.

The cumulative effects from several factors – geographic location, closeness to the area of Sahara desert, access to groundwater inflow to Chad Lake and local climate setting – control the water level in the lake. Moreover, during different seasons of the calendar year, depending on the global weather and integrated heat from the Sahara Desert and Sahel region, Chad Lake demonstrated fluctuations in shrinkage. Furthermore, the performed time series analysis indicates gain in urban areas and transitional land cover types from forest to savannah, as well as an increase in bare soil on the analyzed images covering autumn and winter months. Such information can support the selection of the optimized methods of agricultural lands adopted for such seasonal climate–environmental fluctuations, allowing identification of the best methods of supporting agriculture and plantation activities in the surrounding areas of Chad Lake and enabling to achieve success in land management in Central Africa.

Apart from the detected general trends in drying of Chad Lake, visible on the satellite images, there is a regional difference identified between the southern and northern segments of Chad Lake. Compared to the southern segment, the northern pool has a larger extent of variability due to higher vulnerability to droughts, as also proved in previous studies (Lemoalle et al., 2012). The reasons for such spatial heterogeneity in the desiccation of Lake Chad reflect local sensitivity to climate effects triggered by regional differences in the rainfall patterns and vegetation patterns in the landscapes. As visible on the classified images of several years (Figure 5), the remaining area of the permanent open water areas in the southern segment of the basin is surrounded by more densely vegetated swamps and small pools. This helps to maintain a lacustrine environment and prevents the southern segment from desiccation, as also reported in earlier works (Lauwaet et al., 2012).

The proposed framework benefits from the GRASS GIS functionality and coding approach and exhibits the advantages of the Landsat OLI/TIRS scenes that balance between the accuracy of visualization and complexity of the land cover types while retaining sufficient discrimination threshold for image classification. Practical results are presented as three maps based on the classified images. Finally, the workflow of image processing and plotting is effectively optimized using the alternative methods of scripts. Such methods are implemented in this work using both GMT and GRASS GIS and evaluated for mapping, annotation, and classification tasks. The GRASS GIS method is particularly efficient in terms of mapping production costs since the toolset is free and open for use. However, although the range of technical functionality of GRASS GIS is wide, the use of scripts in cartography has certain limitations. In particular, it requires a familiarity with the programming paradigm, which supports scripts through the embedded syntax.

In fact, the availability of the open-source advanced cartographic programs, such as GRASS GIS, scales with the learning approach which is required to master these methods. In addition, the import of datasets is often performed via the integration with other libraries and Python. This article presented a case of such approaches showing a GRASS GIS script-based method for satellite image processing and cartographic visualization of land cover changes in Lake Chad. Unlike previous traditional GIS-based methods of mapping which operate in the spatial domain, we performed mapping through the GRASS GIS codes, which ensured comprehensive workflow for the cartographic specification of the maps. The GIS-based methods relying on graphical user interface (GUI) tend to use the predefined designed tools and graphical methods of representation. In contrast, the proposed GRASS GIS method outputs maps made using individual adjustments in each line of the programming code using expressions and its syntax. The maps were compared pairwise for various years to analyze the underlying reasons for land cover changes with regard to the climate–environmental setting in Sahelian Africa, Chad.

## 6. Conclusion

Remote sensing data contain essential information regarding the landscapes of the Earth. Accurate classification of time series of the satellite images enables detecting changes in landscapes using this information derived from the satellite images. Such a technique supports environmental modeling of remotely located areas where direct observations are difficult to perform, such as Chad lacustrine landscapes located in Central Africa. To this end, this paper presents a case of the analysis of changes in areas of land cover types in Chad as a representative case of African regions. The dataset included the series of satellite Landsat 8-9 OLI/TIRS obtained from USGS. The detection of the land cover types was performed using the algorithms of image classification. The advanced solution of GRASS GIS for geospatial data processing is demonstrated by a programming approach that utilizes scripts for data automation. The objects that belong to the same category of segments were defined and characterized as representing land cover classes using the difference in spectral reflectance retrieved from the satellite images.

The current study contributed to the environmental monitoring of Lake Chad, which has a long tradition, going back to many years of hydrological surveying. Existing reports enabled detection of changes in the actual level of the water horizons in the lake during the continuous research conducted in recent decades (Tilho, 1928; L'Huillier, 1957; Cabot, 1970; Riou, 1972; Tubiana, 1989). Evaluation of changes in Lake Chad relied on the estimation of the climatic and hydrological data that assess the volume balance in the lake based on the field observations (Bader et al., 2011). The present study continued these works by using remote sensing data processed by a scripting approach as a novel cartographic method to environmental analysis aimed at detecting changes in Chad Lake. As demonstrated, GRASS GIS provides a logical language with a straightforward syntax for a console-based cartographic mapping using shell scripts for image processing.

The algorithm approach of scripts by GRASS GIS is largely based on using its syntax, which is very similar to the programming languages. The lines of codes perform operations controlling the appearance of the cartographic elements on the maps and form a script for presented maps plotted in JPG (or other bitmap raster formats), which can be converted to other formats. Apart from the traditional JPG, GRASS GIS recognizes a variety of miscellaneous grid formats and enables data capture via GDAL (r.in.gdal). Using GRASS GIS for satellite image processing and mapping leads to a higher quality of the produced maps, and lower time is required for workflow and scripting, compared to the cumbersome and time-consuming data processing in traditional menu-based GIS. Thus, in contrast to the existing software, GRASS GIS presents a free set of the command-line modules and options for processing geographic data in both raster and vector formats, and in particular, for satellite image processing.

The maps were plotted by the GRASS GIS scripts using the image analysis and classification of the Landsat scenes covering the region of Chad. The demonstrated methods included an automated scripting approach that ensures high print quality and accuracy of maps, prepared using the high-resolution data. Rather than using handmade cartographic workflow as in similar GIS-based studies, GRASS GIS scripting presents improved methodology that emphasizes the importance of programming as a new trend in contemporary cartography and remote sensing. A useful extension of the presented study would be to automatically generate a series of maps covering particular periods of droughts in semi-arid climate of Africa for a complete environmental risk assessment. Adding more datasets, for example, climate data, could extend the variability of factors for risk assessment.

As a machine-based method, it is a fast and effective technique compared to the conventional mapping workflow. The application of GRASS GIS showed the advantages of scripting languages as part of the new directions in modern cartographic development and remote sensing data processing. Setting the parameters of the GRASS GIS codes enables producing the highest possible quality of maps, including matching the projection and color palette tables (CPT). As demonstrated in this paper, processing earth observation data by GIS enables to better understand changes in wetland areas in the Sahelian Africa, thus supporting monitoring of the terrestrial water cycle and land cover changes in drying lakes (Jones et al., 2009). This study revealed the shrinkage of Chad Lake and visualized changes in associated land cover types caused by the cumulated effects from climate factors (droughts, increase in temperature, and decrease in precipitation) and human-related activities.

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