

INITIAL GIS ANALYSIS OF DRIVERS OF DEGRADATION IN LAKE SOFIA AND LAKE TSENY

Rapid assessment of turbidity in Lac Sofia and Lac Tseny (Sofia Province, Madagascar) using publicly-available remote sensing data

Dr Sietse O. Los
WWT

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Funding partners




Abstract This report investigates the sources of suspended sediment in Lake Sofia and Lake Tseny. High amounts of suspended sediment are a problem, in particular in Lake Sofia, since they limit the growth of healthy populations of macrophytes, invertebrates and fish. Three sources for suspended lake sediment have been suggested: erosion by rainfall and runoff, wind erosion and disturbance of bottom sediment in the lake by fish. Analysis of SRTM DEM data, MODIS 250 m NDVI data and Sentinel-2 20 m green, red, red-edge and near-infrared data shows that: 1. vegetation cover in agricultural areas and grasslands has declined over the past 20 years; 2. erosion risk in the catchment and turbidity in the lake is both high during the wet season and low during (the second part of) the dry season; 3. the catchment with the highest average erosion risk (Sofia) also has the highest turbidity in the lake; 4. turbidity is highest in those parts of the lake that are closest to areas in the catchment from which the largest influx of sediment is expected. In view of the diffuse nature of the sediment source, which extends to large parts of the catchment, it may be necessary to adapt agricultural practices to reduce the sediment influx into the lake. Restoration of macrophyte populations should first be attempted in lakes with lower sediment loads and, if possible, during the first part of the dry season when an extended period of low turbidity can be expected.

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About the authors Sietse Los is Principal Research Officer, Conservation Evidence with WWT, based in UK.

Author contact(s) sietse.los@wwt.org.uk

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Cover image(s) Change analysis for the Lake Tseny catchment showing changes in MODIS Aqua 250m Normalized Difference Vegetation Index (NDVI) data between April 2013 to March 2023 and April 2003 to March 2013. © WWT (2024)

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i. Table of Contents

i.	Table of Contents	3
ii.	List of tables	3
iii.	List of Figures	3
iv.	Acronyms and Abbreviations	4
1	Introduction and Methods	6
1.1	Rationale.....	6
1.2	Aims.....	6
1.3	Methods	6
2	Data.....	6
2.1	MODIS Aqua NDVI 250 m data	6
2.2	Sentinel-2 data.....	8
2.3	ESA land-cover data	8
2.4	SRTM data.....	8
2.5	Meteorological data.....	8
3	Analysis	10
3.1	Trends in vegetation greenness	10
3.2	Seasonal variations in lake turbidity	14
3.3	Seasonal variations in erosion risk	16
3.4	Average erosion risk by sub-catchment.....	17
3.5	Comparison erosion risk and lake turbidity.....	23
4	Discussion	26
4.1	General observations	26
4.2	Suggestions for further work.....	26
5	References	27

ii. List of tables

Table 1.	Summary of the Fleming Kadhimi Scoring Model (FKSM) criteria.....	16
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iii. List of Figures

Figure 1.	Locations of Lake Sofia and Lake Tseny (Madagascar).....	5
Figure 2.	DEMs of the Lake Sofia catchment from ALOS data (above).....	7
Figure 3.	ESA land-cover map for the surrounding of Lake Sofia (top) and Lake Tseny (bottom).....	9
Figure 4.	Spatial representation of NDVI for the Lake Sofia catchment.....	10
Figure 5.	Spatial representation of NDVI for the Lake Tseny catchment	11
Figure 6.	Temporal representation of NDVI for the Lake Sofia catchment.....	12
Figure 7.	Temporal representation of NDVI for the for the Lake Tseny catchment	13
Figure 8.	Seasonality in NDTI derived from Sentinel-2 data (2016 to 2023), Lake Sofia	15

Figure 9. Seasonality in NDTI derived from Sentinel-2 data (2018 to 2023), Lake Tseny.....	16
Figure 10. Spatial distribution of risk scores for the Sofia catchment.....	18
Figure 11. Seasonal variability in combined erosion risk score for Lake Sofia, by quarter.....	19
Figure 12. Spatial distribution of risk scores for the Tseny catchment.....	20
Figure 13. Seasonal variability in combined erosion risk score for Lake Tseny, by quarter	21
Figure 14. Annual risk scores averaged by sub-catchment for Lake Sofia	22
Figure 15. Annual risk scores averaged by sub-catchment for Lake Tseny.....	23
Figure 16. Seasonal risk scores for Lake Sofia catchment and turbidity values (NDTI) for the lake.....	23
Figure 17. Seasonal risk scores for Lake Tseny catchment and turbidity values (NDTI) for the lake	24
Figure 18. Hysteresis plot for catchment erosion risk and lake turbidity for the Lake Sofia catchment	24
Figure 19. Hysteresis plot for catchment erosion risk and lake turbidity for the Lake Tseny catchment.....	25

iv. Acronyms and Abbreviations

ALOS	Advanced Land Observing Satellite
DEM	digital elevation model
ESA	European Space Agency
FKSM	Fleming Kadhimi Scoring Model
GPCP	Global Precipitation Climatology Project
JAXA	Japan Aerospace Exploration Agency
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCDC	National Climate Data Center (part of NOAA)
NDCI	Normalized Difference Chlorophyll Index
NDTI	Normalized Difference Turbidity Index
NDVI	normalized difference vegetation index
NOAA	National Oceanic and Atmospheric Administration
SRTM	Shuttle Radar Topography Mission
WWT	Wildfowl & Wetlands Trust

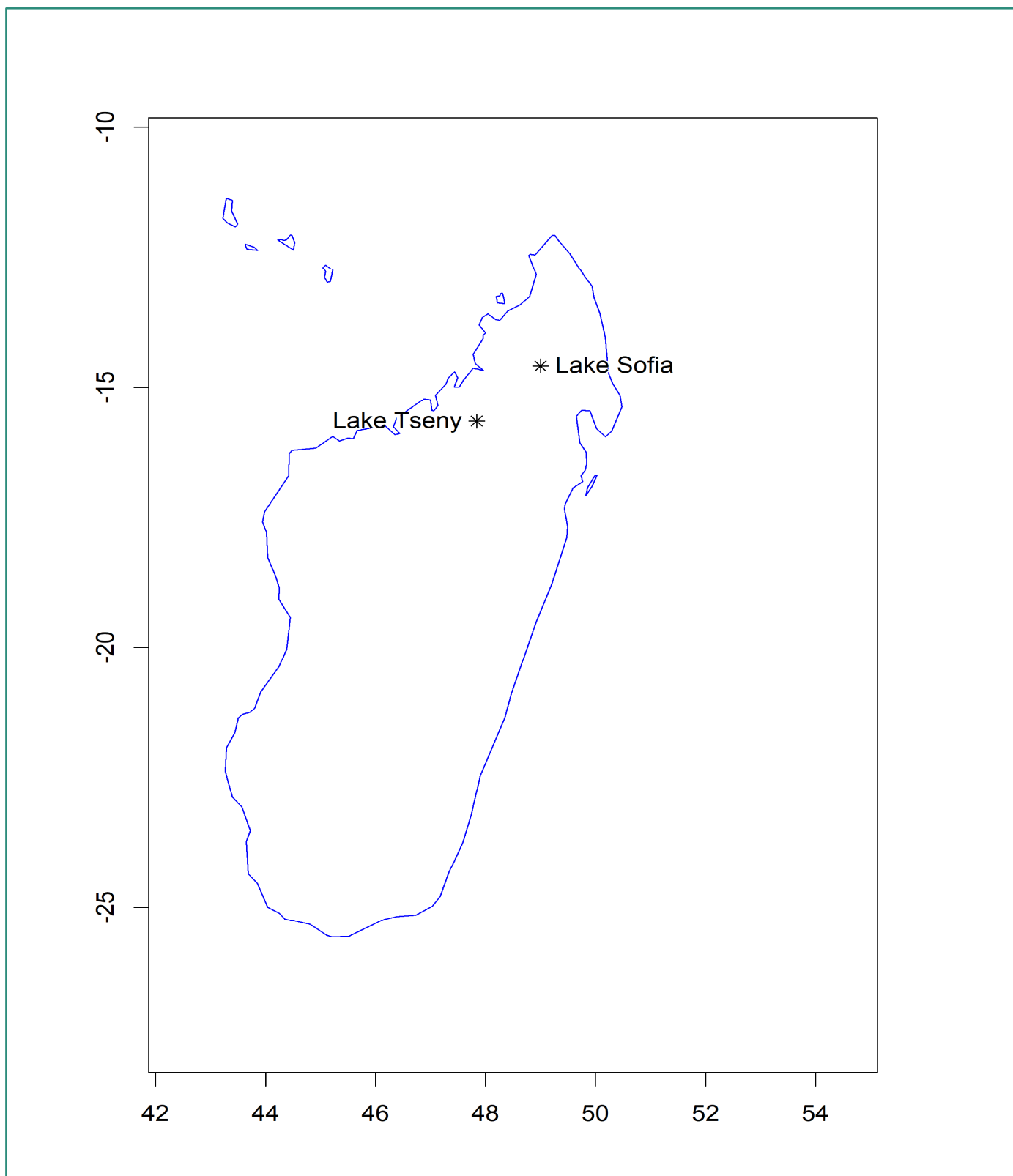


Figure 1. Locations of Lake Sofia and Lake Tseny (Madagascar)

1 Introduction and Methods

1.1 Rationale

Sedimentation is a major threat to wetlands in Madagascar, as identified in the draft National Wetland Strategy and during the planning that WWT undertook in preparation for its “Following the Water” project. High sediment loads limit light penetrating into lakes and other open water bodies, limiting the growth of plants to shallow areas and also covering lake vegetation. Sediment loads have increased significantly over the past century, and appear to be closely linked to land management (Unger 2023).

1.2 Aims

The aim of the present study is to help answer the question “What is the source of sediment suspended in Lake Sofia and Lake Tseny” (see location in

Figure 1). Lake Sofia is located in the central plateau at an altitude of about 1070 m a.s.l. and Lake Tseny is located among coastal foothills at an altitude of about 30 m (**Figure 2**).

Several years of conservation activities at each lake by WWT have identified three potential sources of sediment in the lakes:

- Erosion and transport of sediment by surface runoff into the lake
- Wind erosion is an alternative (there is evidence of high influx of Si and Ti into the lake during the dry season, which indicates its importance; see Unger 2023)
- Fish stirring up sediment from the bottom of the lake (see WWT 2023)

A secondary aim was to test whether recent, high-resolution satellite data can be used to inform environmental management in remote areas where data coverage is relatively poor, especially given the frequent temporal coverage of modern satellite missions.

1.3 Methods

We used remote sensing data to help identify which of these potential sources of lake sediments was most credible, specifically for estimating the importance of water for erosion of sediment in the catchment, and its subsequent transport into the two lakes.

Remote sensing imagery was used to obtain frequent updates of spatially detailed data – recent satellite missions such as Sentinel-2 provide data globally at 10 or 20 m resolution potentially every 5 days. The Sentinel-2 data allow monitoring of lake turbidity, lake chlorophyll and vegetation conditions in the two lake catchments. Effective temporal coverage of the land surface by Sentinel-2 data is reduced because of cloud cover but is still sufficient to obtain estimates of seasonal variability of processes of interest.

In addition to the Sentinel-2 data, data from two other remote sensing missions were used. These were a 30 m digital elevation model (DEM) from the shuttle radar topographic mission (SRTM), collected by space shuttle Endeavour, and a 20-year time series (2003–2023) of 250 m MODIS Aqua Normalized Difference Vegetation Index (NDVI) data.

2 Data

2.1 MODIS Aqua NDVI 250 m data

This is a relatively coarse resolution data set (250 m) that provides over 20 years of well calibrated data (Didan and Munoz 2019) and as such can be used to detect seasonal and interannual variations in vegetation greenness. Healthy, vigorous vegetation strongly absorbs solar radiation in the red wavelengths and reflects it in the near-infrared wavelengths and this property is exploited by the Normalized Difference Vegetation Index (NDVI) as follows:

$$\text{NDVI} = (\rho_{\text{nir}} - \rho_{\text{red}}) / (\rho_{\text{nir}} + \rho_{\text{red}})$$

with ρ_{nir} being the reflectance in the near-infrared wavelengths and ρ_{red} the reflectance in the red.

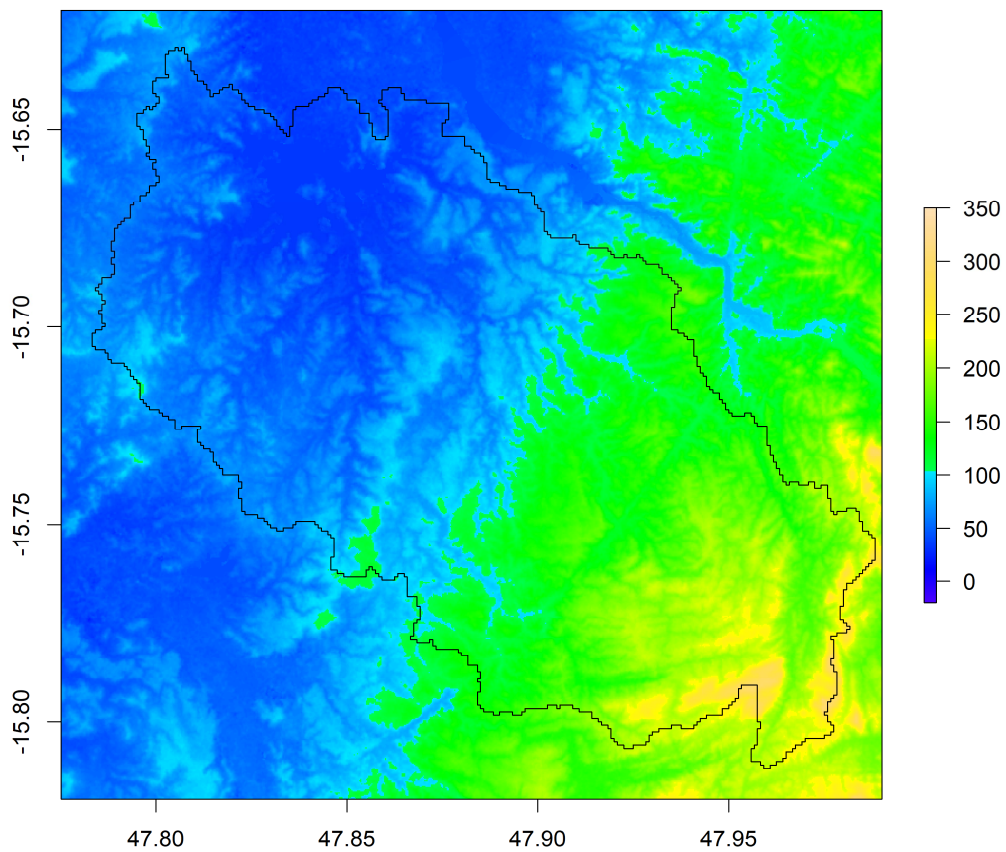
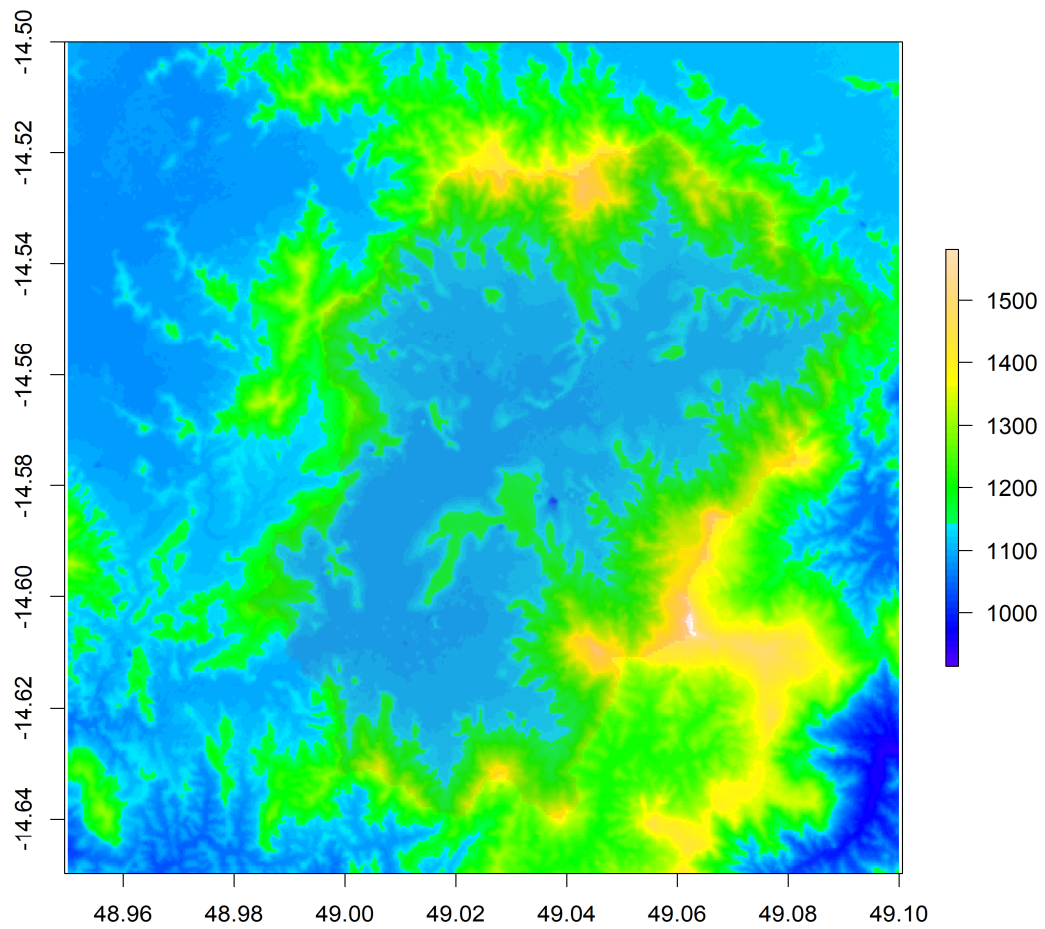


Figure 2. DEMs of the Lake Sofia catchment from ALOS data (above) and the Lake Tseny catchment from SRTM data (below).

NDVI is linked to the amount of solar radiation absorbed by the plant canopy for photosynthesis and correlates well with other biophysical parameters such as leaf area index, primary productivity of vegetation and vegetation cover.

2.2 Sentinel-2 data

Three indices were obtained from Sentinel-2 data:

- i) The Normalized Difference Vegetation Index (NDVI) which was calculated from the red reflectance (Sentinel band 4) and near-infrared reflectance (band 8); this variable was used to estimate vegetation cover in the erosion models.
- ii) The Normalized Difference Turbidity Index (NDTI), which was used to estimate turbidity in Lake Sofia and Lake Tseny
- iii) The Normalized Difference Chlorophyll Index (NDCI), which set was used to estimate chlorophyll content of the two lakes.

The equation for the NDTI is given by:

$$\text{NDTI} = (\rho_{\text{red}} - \rho_{\text{green}}) / (\rho_{\text{red}} + \rho_{\text{green}})$$

where ρ_{red} (Sentinel band 4) is the red reflectance and ρ_{green} (Sentinel band 3) is the green reflectance.

The equation for the NDCI is given by:

$$\text{NDCI} = (\rho_{\text{(red edge)}} - \rho_{\text{red}}) / (\rho_{\text{(red edge)}} + \rho_{\text{red}})$$

where $\rho_{\text{(red edge)}}$ (Sentinel band 5) is the red edge reflectance.

2.3 ESA land-cover data

Landcover maps at 10 m resolution were obtained from ESA and were resampled to 20 m to be consistent with other data (**Figure 3**).

A note on landcover

The landcover maps and NDVI data both suggest that vegetation in the lower parts of the catchments are more heavily influenced by humans than the upper parts. For the Lake Sofia catchment, agricultural crops are dominant in the lower area, while for the Lake Tseny catchment this is grassland. Both of these landcover classes have lower average NDVI values than woodlands and forests in the upper parts of the two catchments.

2.4 SRTM data

SRTM data were obtained at 30 m resolution. The vertical accuracy of SRTM data is reported to be between 4 and 8 m. An alternative DEM data set which is reported to have better vertical accuracy is the ALOS Global DEM produced at the Japan Aerospace Exploration Agency (JAXA). This latter data set was not used for this study because it contained pits with very low values in a couple of places, making topographic analysis such as stream detection very difficult. The SRTM data were resampled to 20 m resolution for the erosion risk analysis (**Figure 2**).

2.5 Meteorological data

Initially the Global Precipitation Climatology Project (GPCP) data were used to obtain rainfall measurements for the Lake Sofia catchment. The GPCP data is a blended product of satellite data and station data; the product is updated with a 3 to 4 month time delay. More up-to-date information is provided by the US National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center (NCDC) which is a repository for meteorological station data globally (Smith *et al.* 2011). The nearest station to the two catchments is Antsohihy; data from this station were used to estimate rainfall intensity for both catchments.

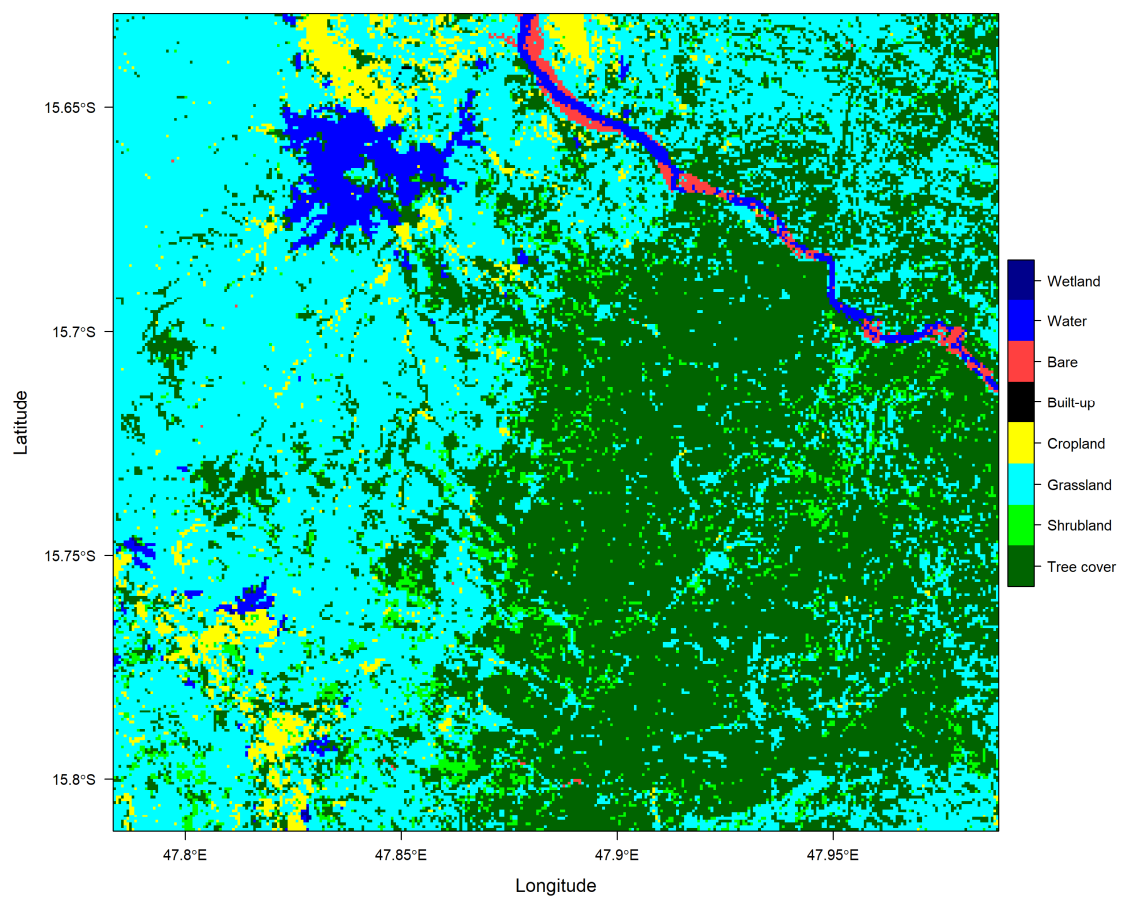
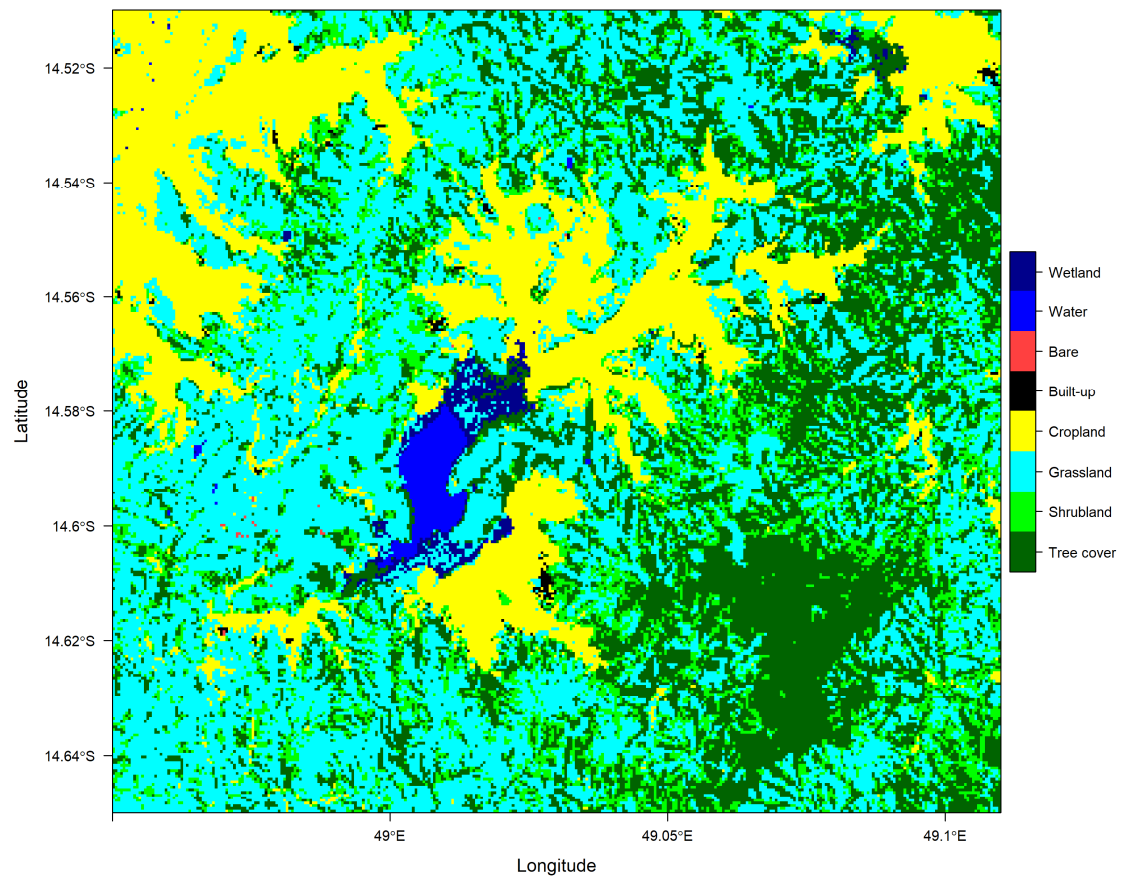


Figure 3. ESA land-cover map for the surrounding of Lake Sofia (top) and Lake Tseny (bottom)
Source: © (CCA 4.0) ESA World cover project 2021 / Contains modified Copernicus Sentinel data (2021) processed by the ESA WorldCover consortium (Zanaga et al. 2022)

3 Analysis

3.1 Trends in vegetation greenness

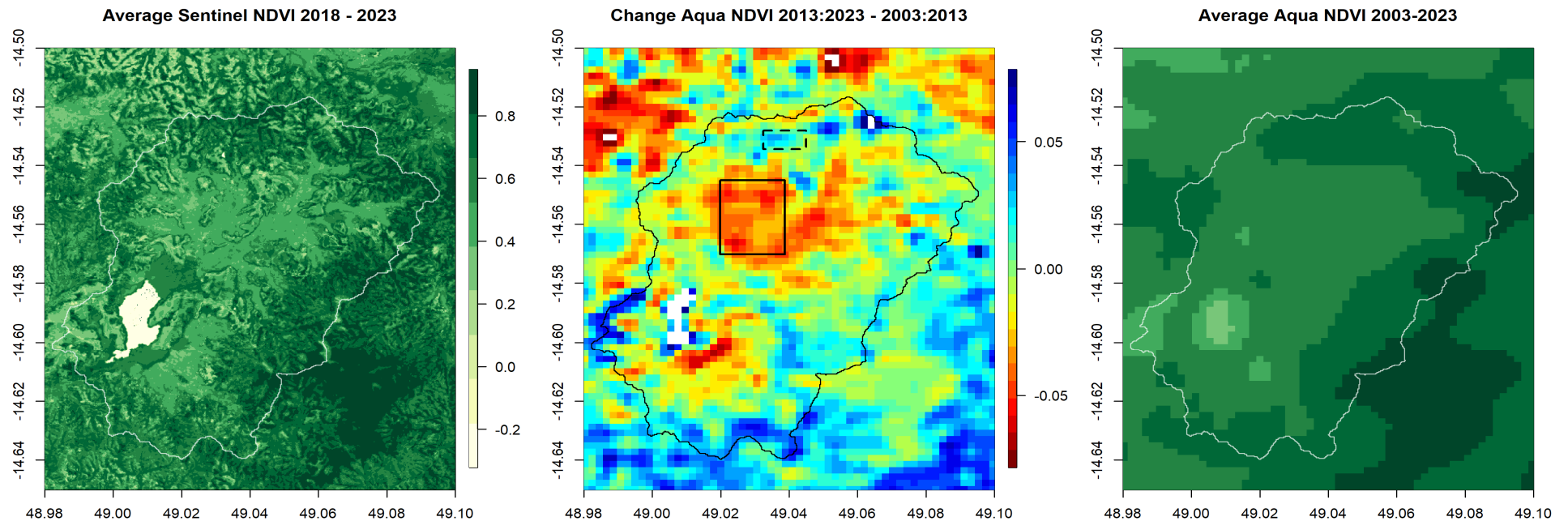


Figure 4. Spatial representation of NDVI for the Lake Sofia catchment

Left: Average sentinel-2 NDVI data 2016--2023.

Centre: Changes in MODIS Aqua 250 m NDVI data: difference between April 2013 - March 2023 and April 2003 - March 2013. The solid and dashed boxes indicate the locations of the averaged NDVI time series in Fig 3.3.

Right: Average MODIS 250 m NDVI data April 2003 – March 2023.

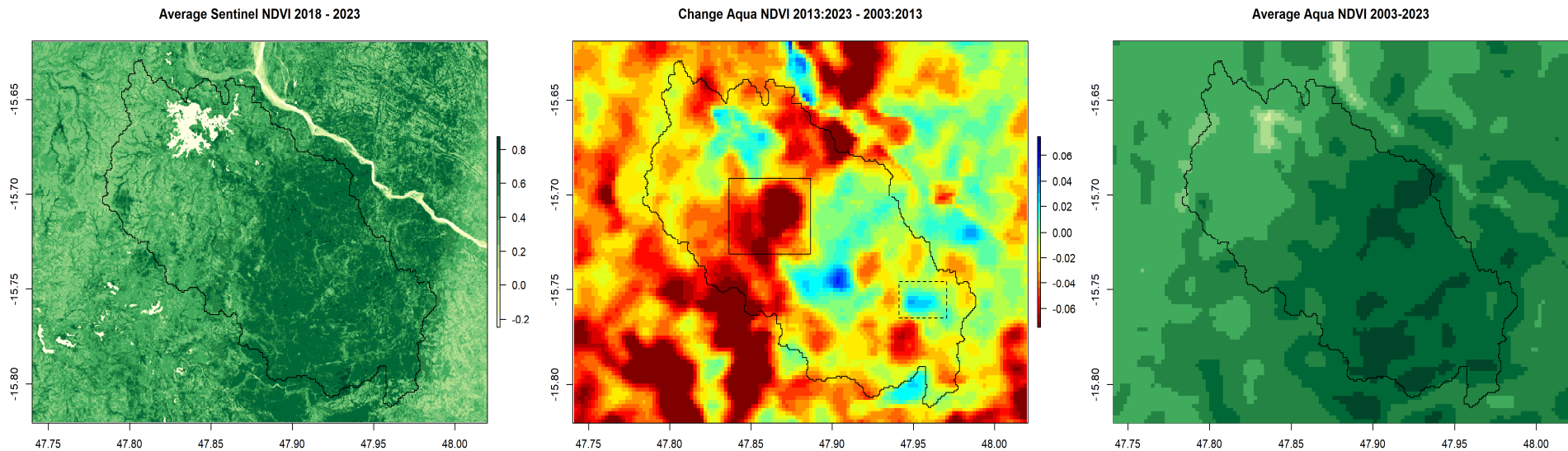


Figure 5. Spatial representation of NDVI for the Lake Tseny catchment

Left: Average sentinel-2 NDVI data 2016—2023

Centre: Changes in MODIS Aqua 250 m NDVI data: difference between April 2013 - March 2023 and April 2003 - March 2013. The solid and dashed boxes indicate the locations of the averaged NDVI time series in Fig 3.3.

Right: Average MODIS 250 m NDVI data April 2003 – March 2023.

The 250 m Normalized Difference Vegetation Index (NDVI) Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua data were measured globally at a daily time step in the early afternoon starting in 2002. The daily data were merged into 16-day composites by selecting the best pixel for every location. The 16-day composites were then filtered using a median filter applied to a $5 \times 5 \times 5$ window (five pixels in north–south direction, five east–west and five composites); this filter reduces noise in the data caused by atmospheric interference and cloud contamination, and fills in gaps where data were missing.

The data were used to analyse spatial and temporal variations in vegetation greenness. In the two catchments investigated, NDVI values tend to be lower in the lower parts of the catchments and higher in the upper parts. The lower parts of the Sofia catchment are dominated by agricultural crops, while those in the Tseny catchment by grassland (**Figure 3**).

The 20 m Sentinel NDVI data show a similar spatial distribution as the MODIS NDVI data, higher values in the mountains and lower values in agricultural regions and grasslands, but with much greater spatial detail (**Figure 4** and **Figure 5**).

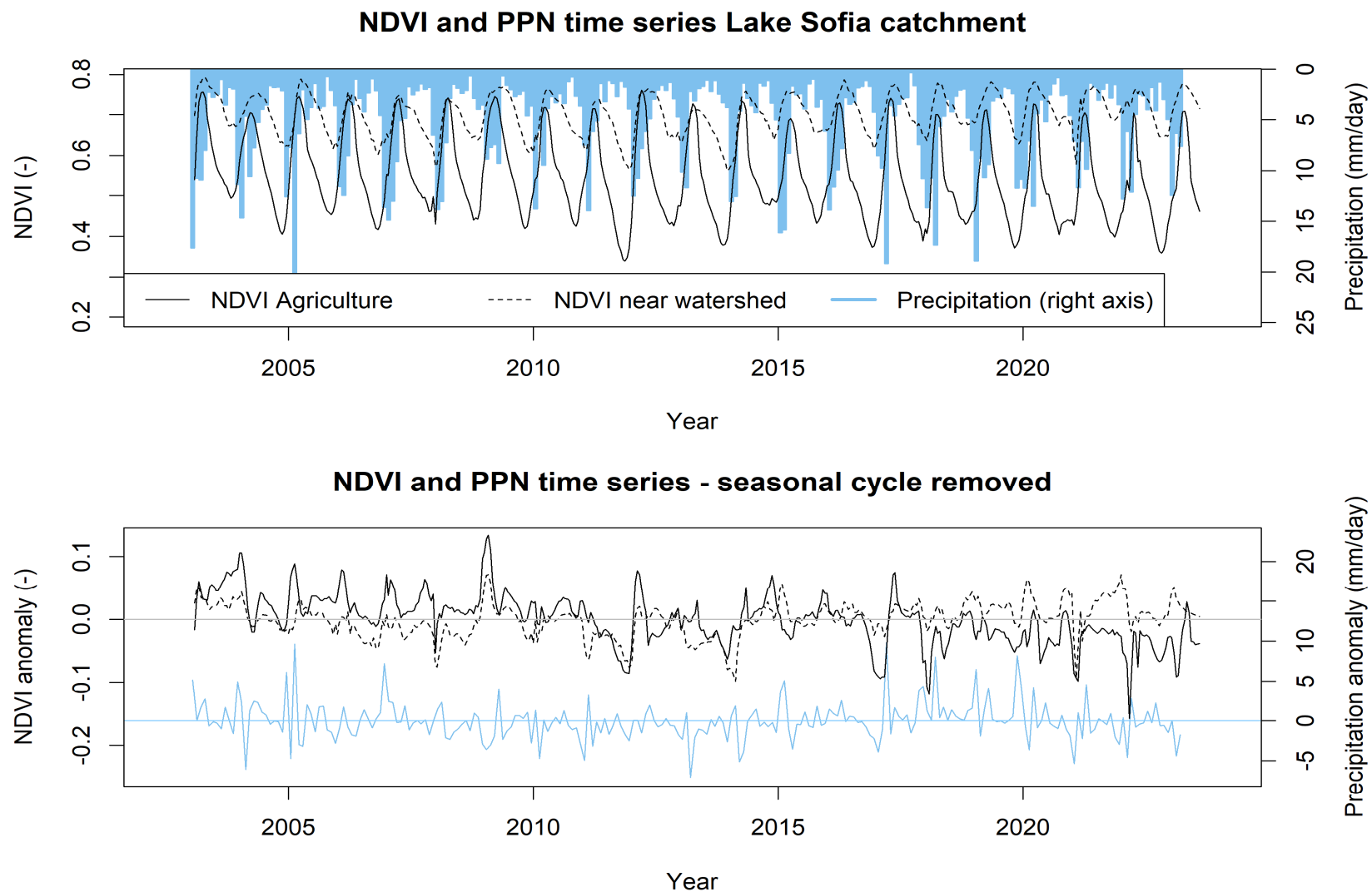


Figure 6. Temporal representation of NDVI and precipitation for the Lake Sofia catchment

Above: NDVI time series for the lower (solid line) and upper (dashed line) parts of the catchment, and time series from Global Precipitation Climatology Project (GPCP) $0.5^\circ \times 0.5^\circ$ data (blue bars; y-axis on the right is reversed). Notice a much shorter growing season for the lower part of the catchment.

Below: Anomaly time series (seasonal cycle removed) showing a gradual decline in NDVI in the lower part of the catchment whereas the rainfall time series and NDVI time series from the upper part of the catchment do not show a negative trend.

NDVI and PPN time series Lake Tseny catchment

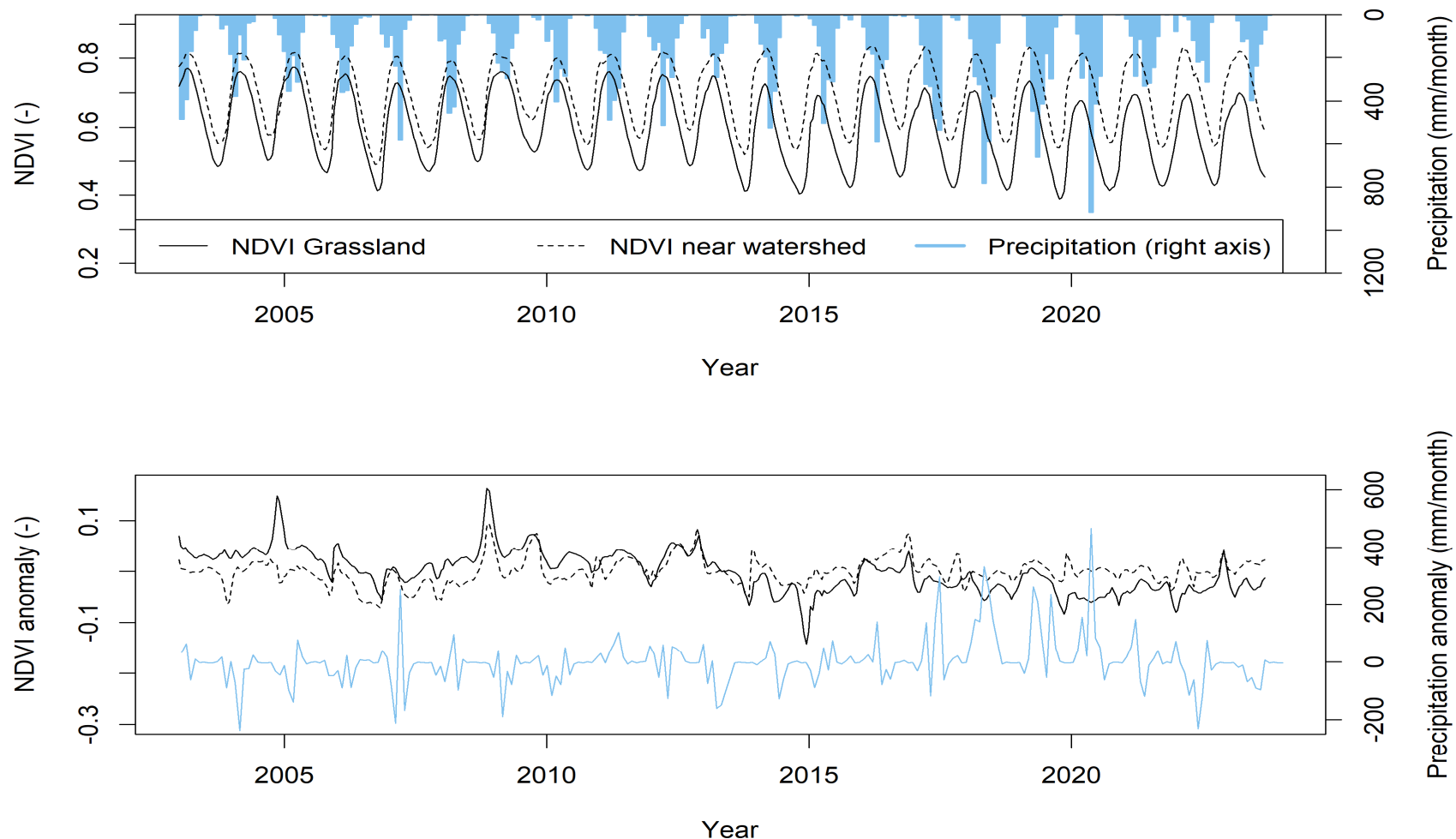


Figure 7. Temporal representation of NDVI for the for the Lake Tseny catchment

Above: NDVI time series for the lower (solid line) and upper (dashed line) parts of the catchment and precipitation time series from the Antsohihy meteorological station data (blue bars, the y-axis on the right-hand side is reversed). Notice a somewhat shorter growing season for the lower part of the catchment, however the growing season is longer than in the Lake Sofia catchment -

Figure 6).

Below: Anomaly time series (seasonal cycle removed) showing a gradual decline in NDVI in the lower part of the catchment whereas the rainfall time series and NDVI time series from the upper part of the catchment do not show a negative trend.

A considerable decline was found in the NDVI data from the lower parts of both catchments; by contrast, the upper parts showed no decline or in some cases a modest increase in vegetation greenness. The change over time was obtained by averaging the NDVI data for two periods, 2003–2013 and 2013–2023, and by calculating the difference (**Figure 4** and **Figure 5**).

Time-series for two areas in the two catchments, indicated in the maps in **Figure 4** and **Figure 5**, show detailed seasonal variations in NDVI for the lower parts in the two catchments where a decline in NDVI over time was found, and for the upper parts where vegetation remained stable or showed a slight increase over time.

The NDVI time series (

Figure 6 and **Figure 7**) show a short growing season in the lower parts of the Sofia catchment; it is shorter than the growing season in the upper parts of the catchment and also shorter than the growing season in the lower parts of the Tseny catchment. Anomaly time series, where the seasonal cycle is removed from the data, are indicated in the same figures and also show a clear gradual decline in NDVI values in the lower parts of both catchments.

The precipitation data are also include in

Figure 6 and **Figure 7**, and show that the wet season starts in November–December and ends in March–April. No trend in precipitation data can be found, meaning the trend observed in NDVI data is not caused by changes in climate and is most likely the result of land management practices.

3.2 Seasonal variations in lake turbidity

Lake turbidity was assessed using the Normalized Difference Turbidity Index (NDTI) derived from Sentinel-2 data. This index correlates reasonably well with the total sediment in suspension; for a range of open water bodies in the USA the correlation between these two variables was $r = 0.75$ (Sagan *et al.* 2020). Higher correlations can be obtained with other methods such as machine learning, but this requires an extensive data set for model training.

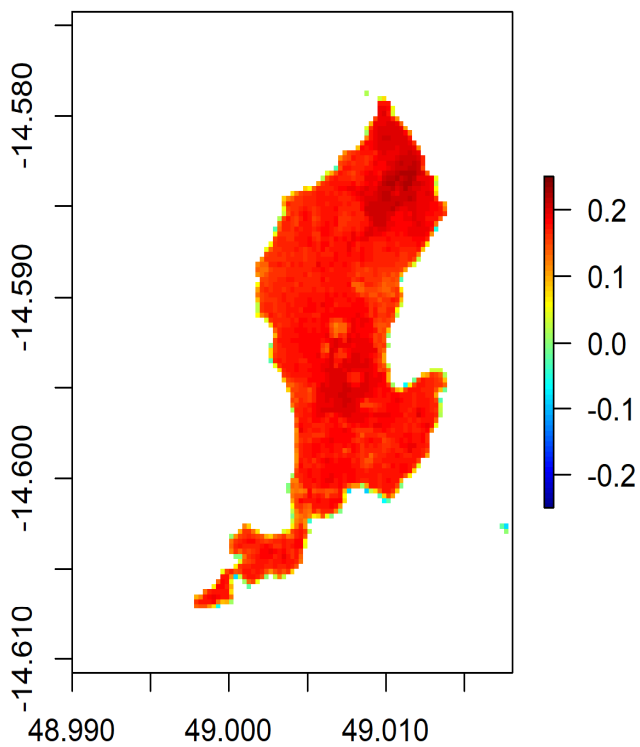
Sentinel-2 data are available from 2016; for this year one cloud-free image was found for both catchments. The Sentinel-2 data are available at higher frequency from the second half of 2018. The length of the Sentinel-2 data record is deemed too short for meaningful trend analysis, but can be used to explore seasonal and interannual variations.

To investigate the seasonality of turbidity in the lakes during the year, the images from 2018 until 2023 were averaged by season, January to March, April to June, July to September and October to December (**Figure 8** and **Figure 9**).

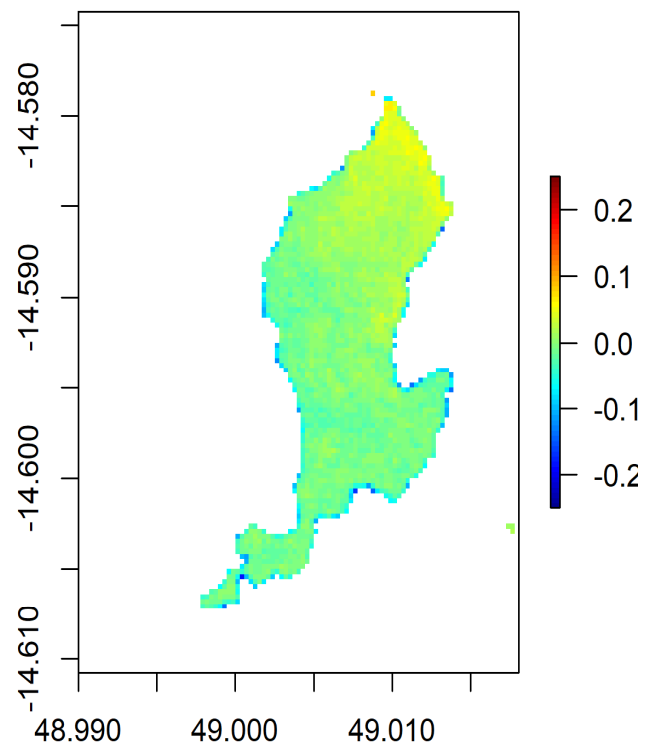
Analysis of seasonal lake NDTI data indicates that turbidity in both lakes was highest during the wet season (Jan-Mar and Oct-Dec) and lowest at the end of the dry season (July-Sept). Throughout the year turbidity values were much higher in Lake Sofia than in Lake Tseny. When exploring the spatial distribution of NDTI in Lake Sofia, the highest values tend to occur in the northern part (**Figure 8**).

Time series of turbidity in the lakes and of erosion risk in the catchments are considered below.

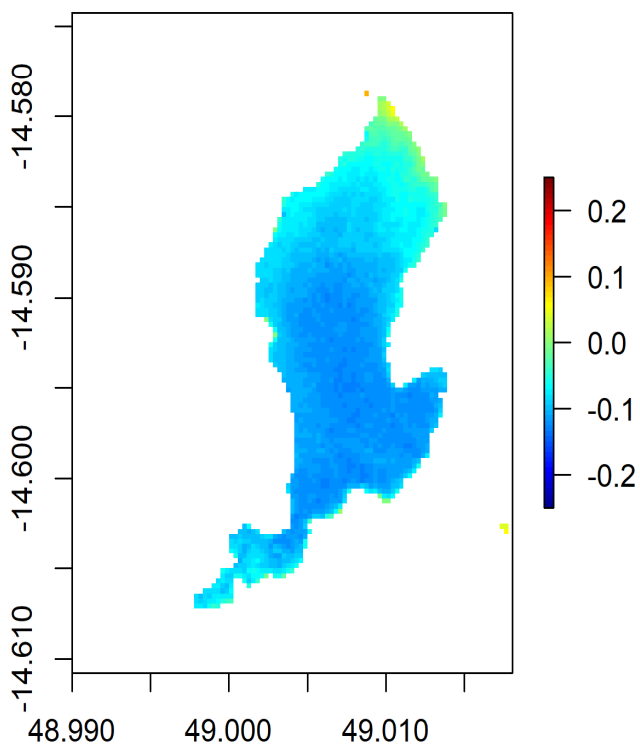
Median NDTI Months 1 - 3



Median NDTI Months 4 - 6



Median NDTI Months 7 - 9



Median NDTI Months 10 - 12

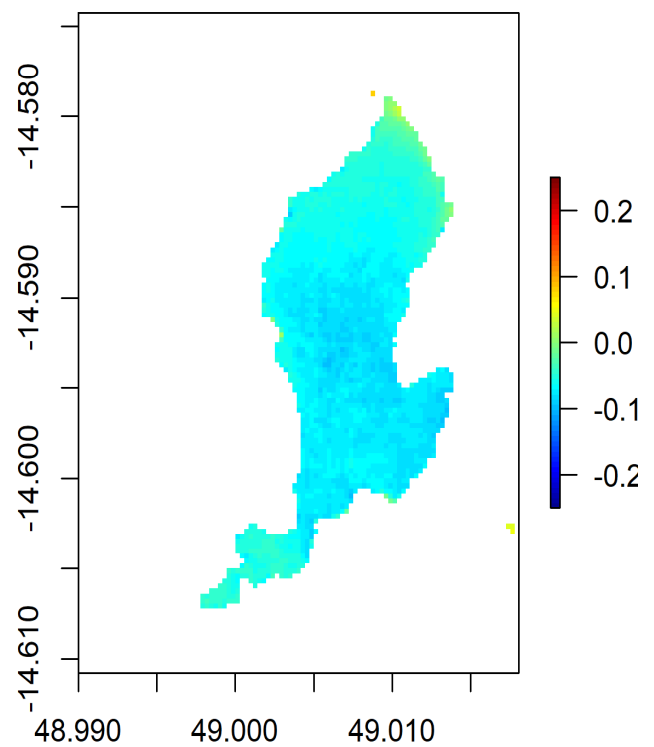


Figure 8. Seasonality in NDTI derived from Sentinel-2 data (2016 to 2023), Lake Sofia

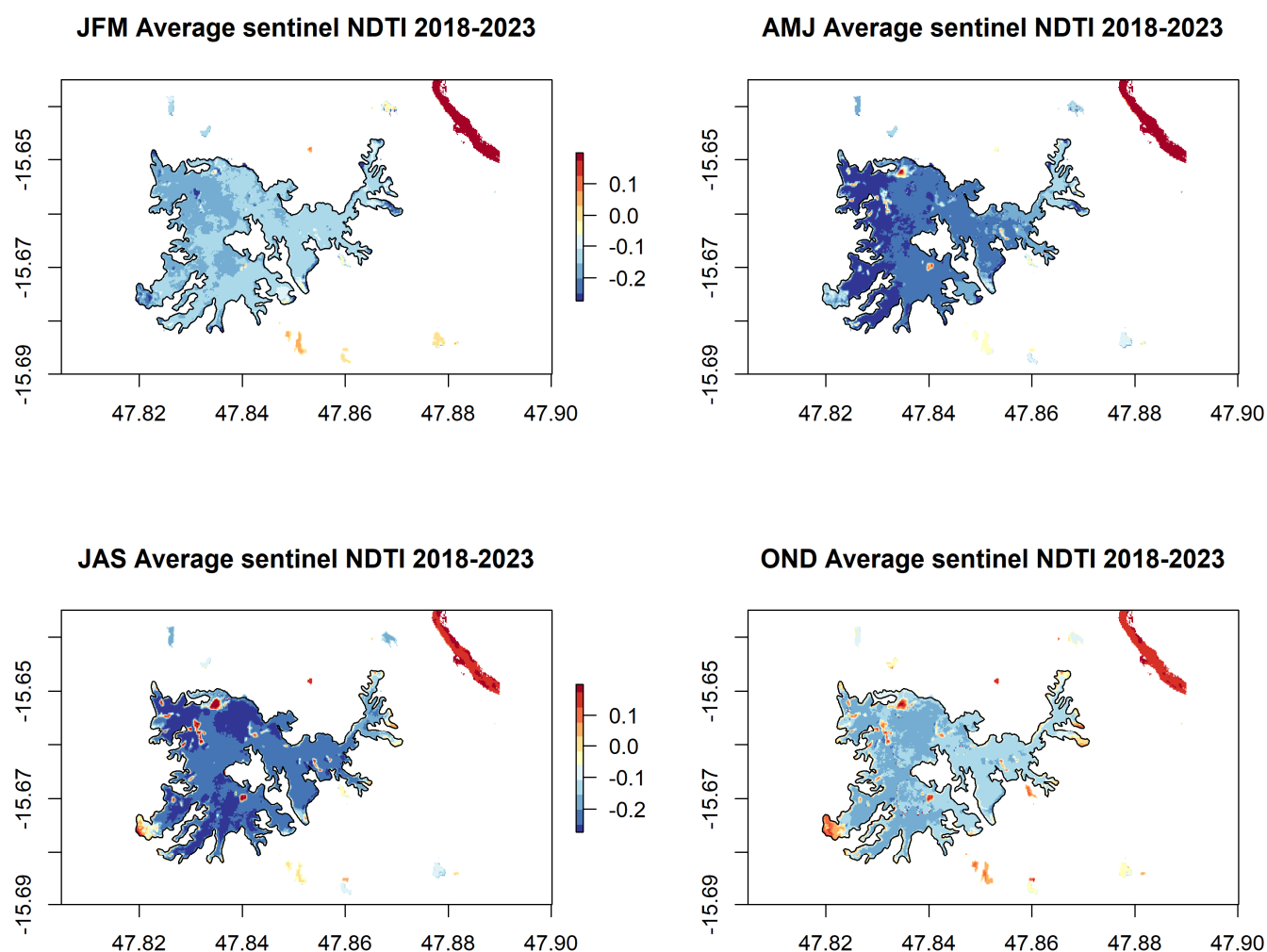


Figure 9. Seasonality in NDTI derived from Sentinel-2 data (2018 to 2023), Lake Tseny

3.3 Seasonal variations in erosion risk

For the estimation of erosion risk throughout the two catchments, the Fleming Kadhimi Scoring Model (FKSM; Fleming and al Kadhimi 1982) was modified. The original model requires five sources of information: Slope, rainfall erosivity, soil type, land-cover type and disturbance (**Table 1**).

Each criterion is converted into a risk score between 1 (lowest risk) and 5 (highest risk). The scores are then multiplied to obtain an overall risk score. The model takes into account the most relevant risk factors to erosion and shows spatial variability in erosion risk well.

Table 1. Summary of the Fleming Kadhimi Scoring Model (FKSM; Fleming and al Kadhimi 1982) criteria. The model is adapted in the current study: 'ESA cover' replaces 'Land cover' and 'NDVI' replaces 'Disturbance'.

Score	Slope (%)	Rainfall erosivity	Soil	Landcover	ESA cover	Disturbance	NDVI
1	0–2	$0 \leq F < 30$	Clay	Virgin forest	Forest	100 y	> 0.8
2	2–4	$30 \leq F < 50$	Coarse sand	Woodland	Shrubland	50 y	0.6-0.8
3	4–6	$50 \leq F < 70$	Medium sand	Pasture	Grass	Grazing	0.4-0.6
4	6–8	$70 \leq F < 90$	Fine sand	Agriculture	Crop	Annual crop	0.2-0.4
5	> 8	$F \geq 90$	Silt	Bare/Fallow	Bare	>1 in 1 y	< 0.2

Two modifications were made to the model in which remote sensing data were used to replace static maps; this allows exploration of temporal variability in erosion risk.

Slope values were calculated from the SRTM DEM and converted into risk scores as set out in **Table 1**.

Rainfall erosivity (F) was calculated from monthly rainfall using:

$$F = \frac{\max P_{i=1..12}^2}{\sum P_{i=1..12}}$$

where F is the rainfall erosivity, and $P_{i=1..12}$ the monthly precipitation.

Rainfall erosivity values are high in areas where rainfall is highly seasonal, and low where rainfall is constant throughout the year. The seasonal rainfall erosivity is calculated from the maximum rainfall for the relevant 3-month period, rather than the maximum rainfall for the year as is done in the above equation. The rainfall erosivity is one value for the entire catchment.

Information on soil type was only available at coarse resolution (250 m) and in these data no differentiation between soil types was made for the Sofia catchment (the entire catchment consisted of silt), hence soil type was not considered in the calculations. Soil information can be incorporated if and when it becomes available.

ESA provides a global land-cover data set at 10 m resolution, and the classification units broadly agree with those used by Fleming and al Kadhimi (1982). The mapping of classification units from one scheme to the other is shown in **Table 1**, where the values in the original *Landcover* column were replaced by those in the *ESA cover* column.

A second adaptation made was the replacement of disturbance by vegetation cover (NDVI), since no information on the former was available. The idea behind this substitution is that where the canopy is well developed and vegetation cover is high, a leaf litter layer develops which, in addition to the vegetation, protects soil from erosion. Where vegetation is frequently removed or disturbed, cover by a litter layer is low and erosion risk high. Thus a low risk score was assigned to very high NDVI values and a high risk score to low NDVI values (**Table 1**). An advantage of this approach is that the risk score can be varied seasonally (**Figure 10**, **Figure 11**, **Figure 12** and **Figure 13**).

3.4 Average erosion risk by sub-catchment

The average erosion risk was calculated for each sub-catchments. This information can be used to identify suitable locations for the installation of measurement devices such as sediment traps, or to decide where to focus remediation measures. Note that the size of the catchment is of importance as well; a large catchment with an average erosion risk may contribute more to the sediment load in the lake than a small catchment with a large erosion risk.

The first step in the identification of sub-catchments was to detect the stream network; this was done with the Whitebox toolbox in the R environment (Lindsay 2016). The same toolbox was used to identify the sub-catchments from the locations of the outlets of the stream network.

Finally, for each of the sub-catchments the average annual risk score was calculated using the per-pixel values of the larger catchments.

Interestingly, for both catchments the highest average erosion risk scores are found in the western sub-catchments (**Figure 14** and **Figure 15****Table 1**).

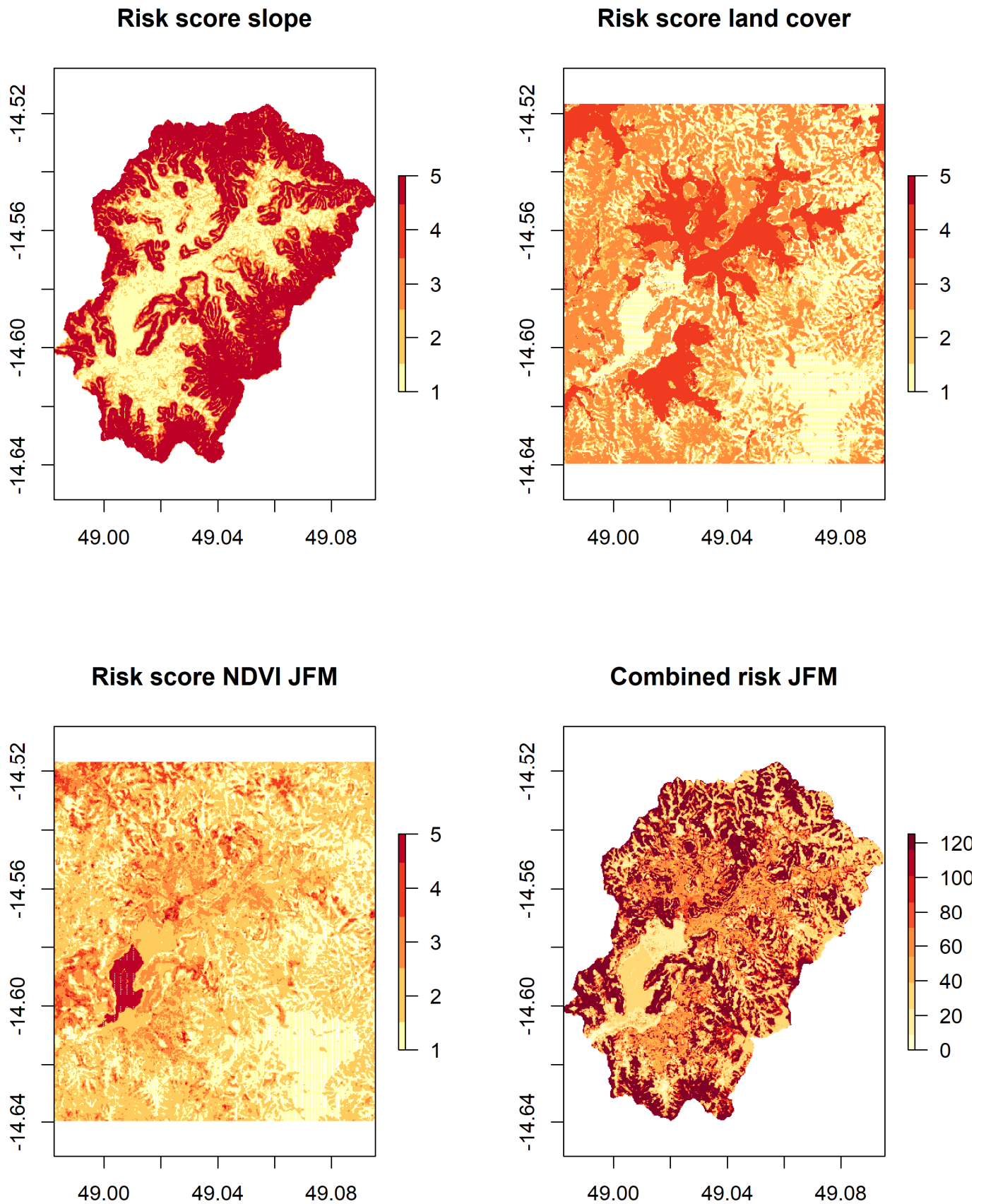
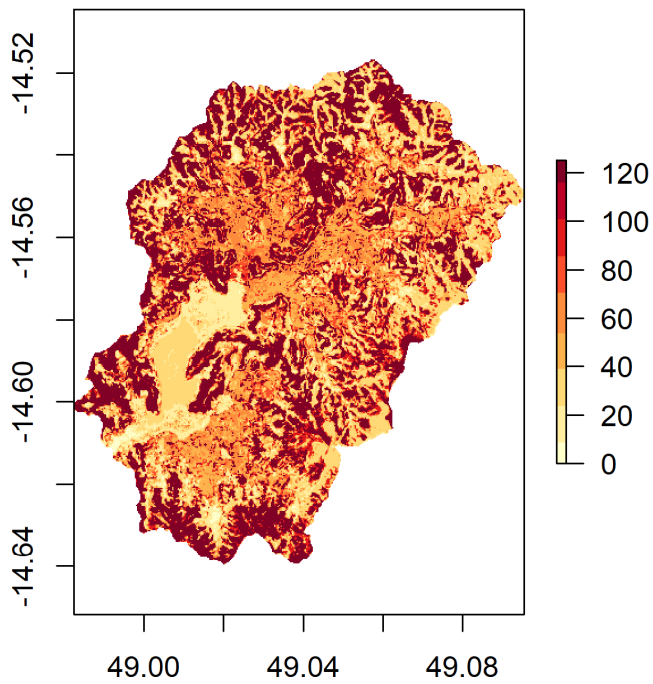


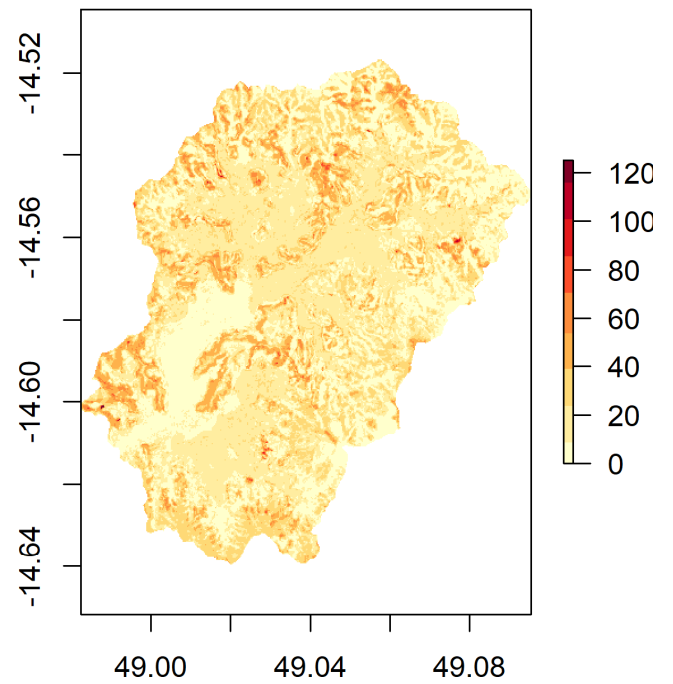
Figure 10. Spatial distribution of risk scores for the Sofia catchment

Note: Risk scores are shown for slope (top-left), land-cover type (top-right), NDVI for January until March inclusive (bottom-left) and the combined risk score which includes the score associated with rainfall erosivity (bottom-right).

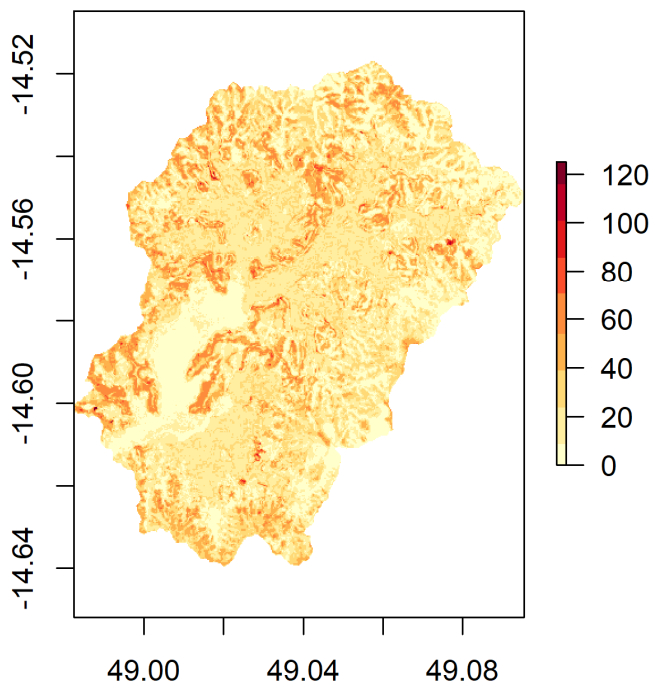
Combined risk JFM



Combined risk AMJ



Combined risk JAS



Combined risk OND

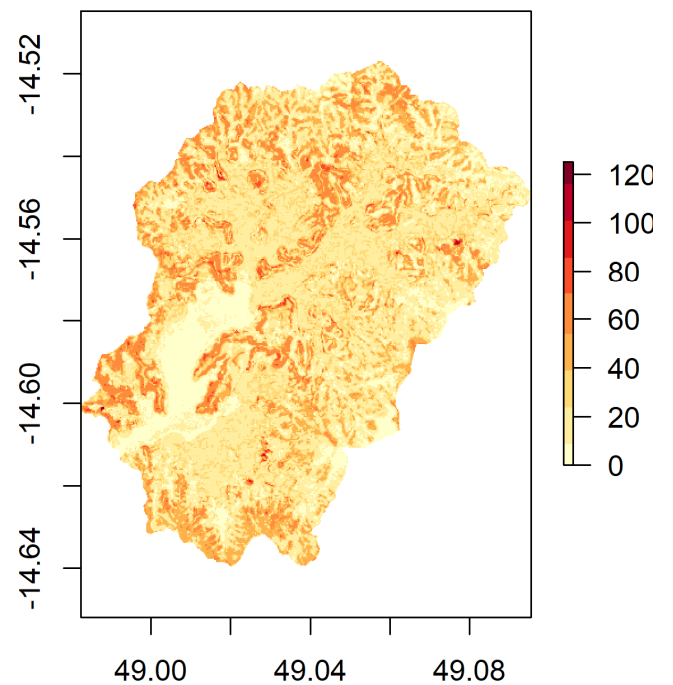


Figure 11. Seasonal variability in combined erosion risk score for Lake Sofia, by quarter

Note: The rainfall erosivity uses the maximum rainfall during each three-month period (Jan/Feb/Mar = JFM etc), whereas the NDVI risk score is based on the average of all NDVI images collected over the three months.

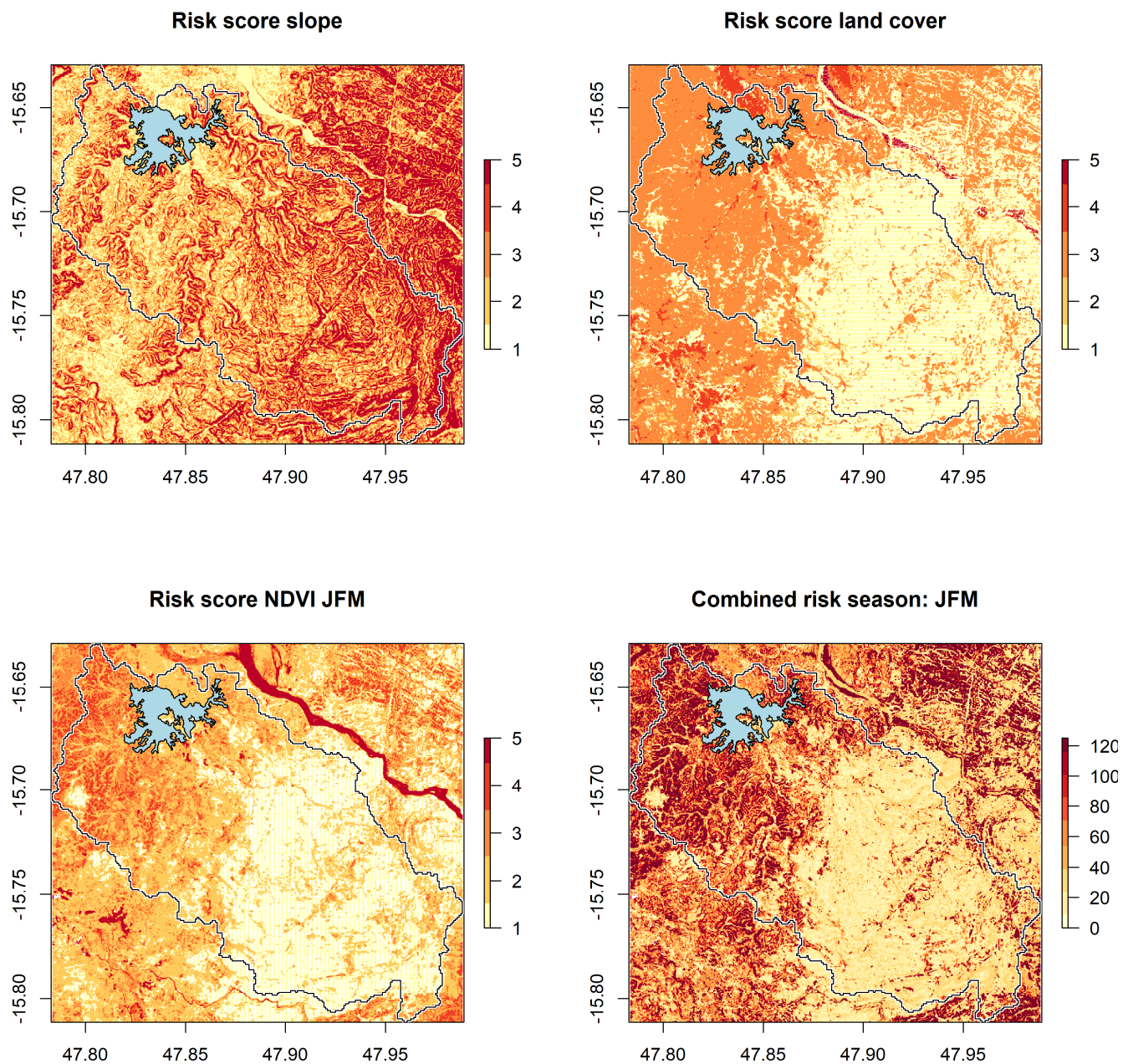


Figure 12. Spatial distribution of risk scores for the Tseny catchment

Note: Risk scores are shown for slope (top-left), land-cover type (top-right), NDVI for January until March inclusive (bottom-left) and the combined risk score which includes the score associated with rainfall erosivity (bottom-right).

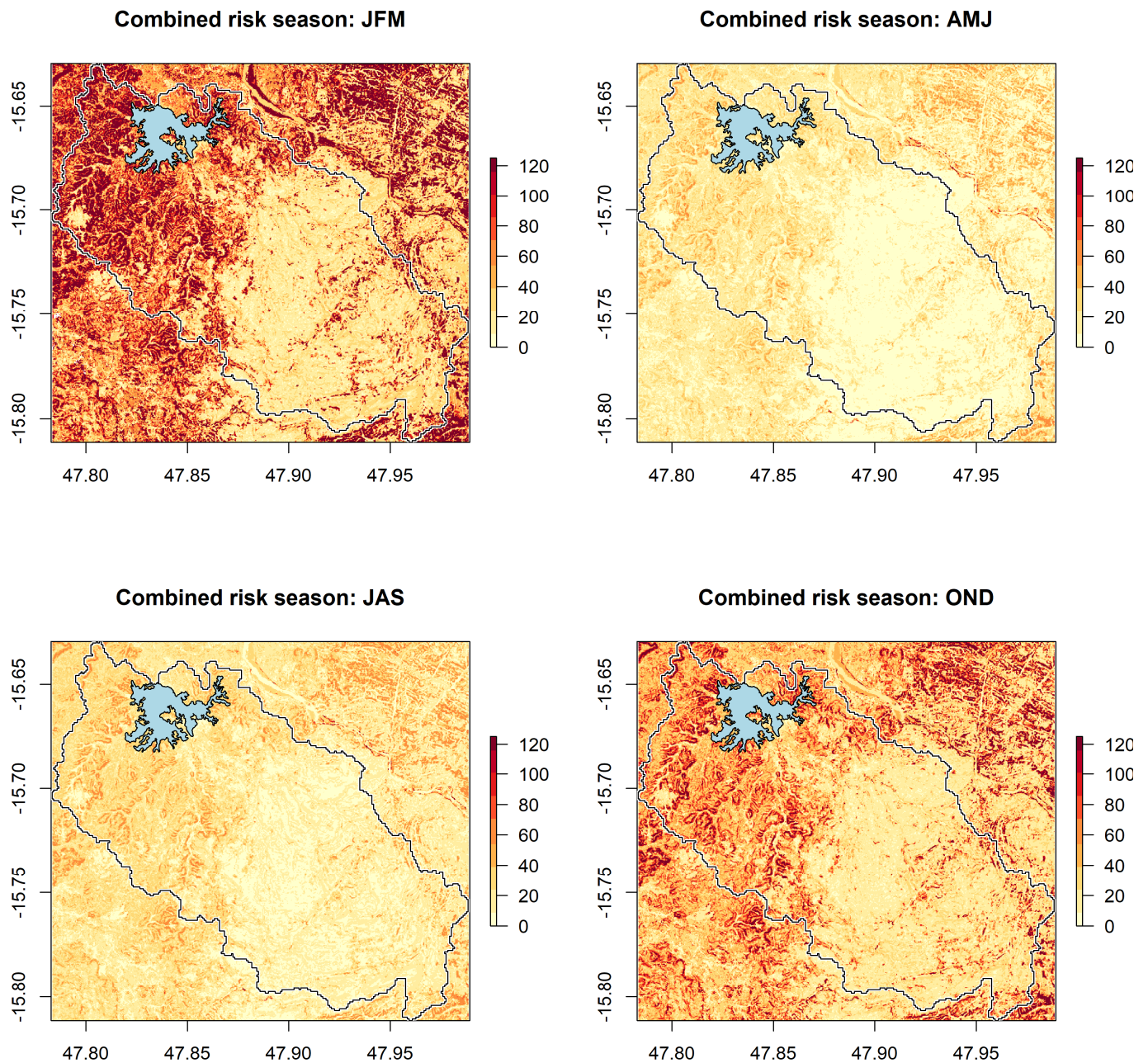


Figure 13. Seasonal variability in combined erosion risk score for Lake Tseny, by quarter

Note: The rainfall erosivity uses the maximum rainfall during each three-month period (Jan/Feb/Mar = JFM etc), whereas the NDVI risk score is based on the average of all NDVI images collected over the three months.

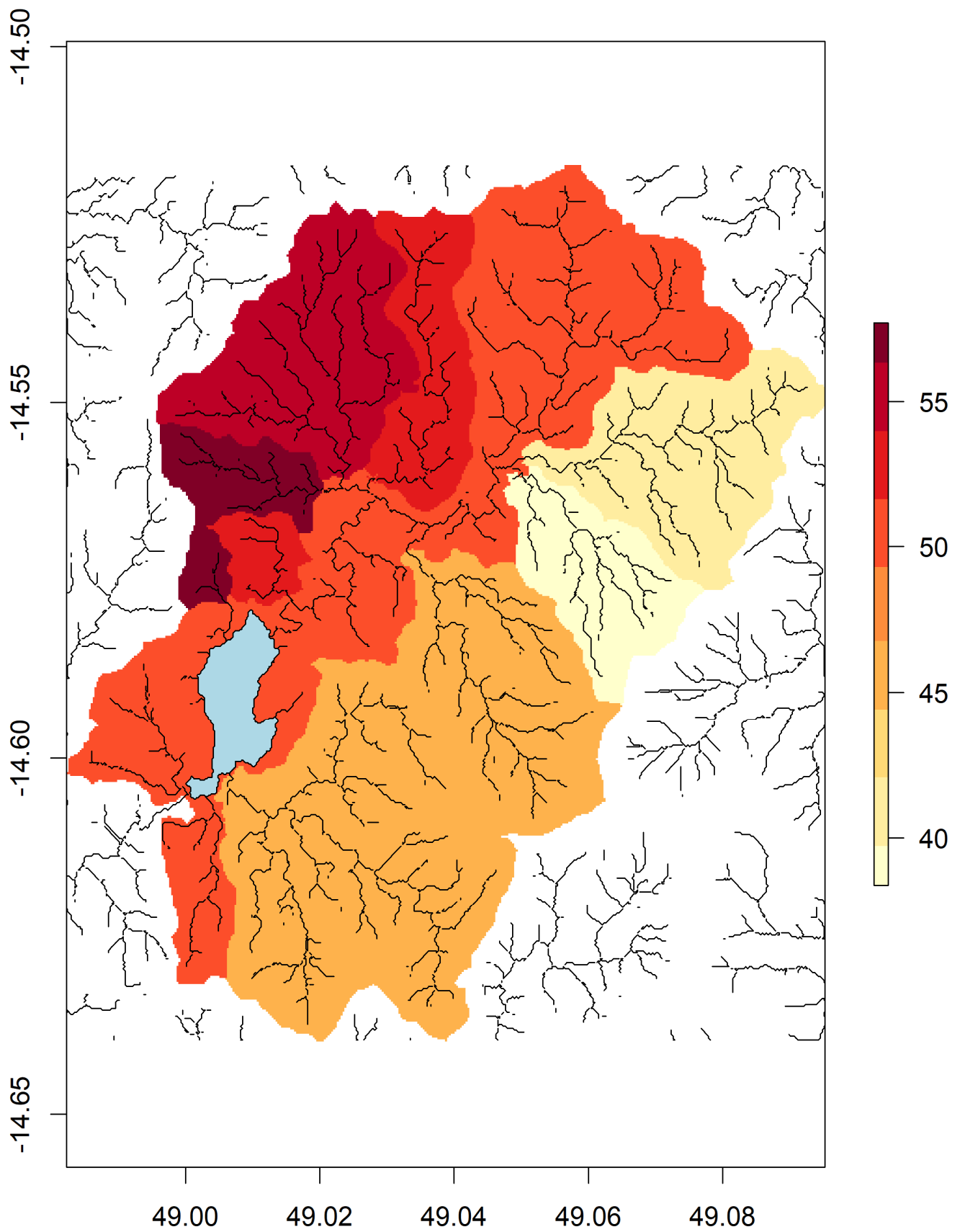


Figure 14. Annual risk scores averaged by sub-catchment for Lake Sofia

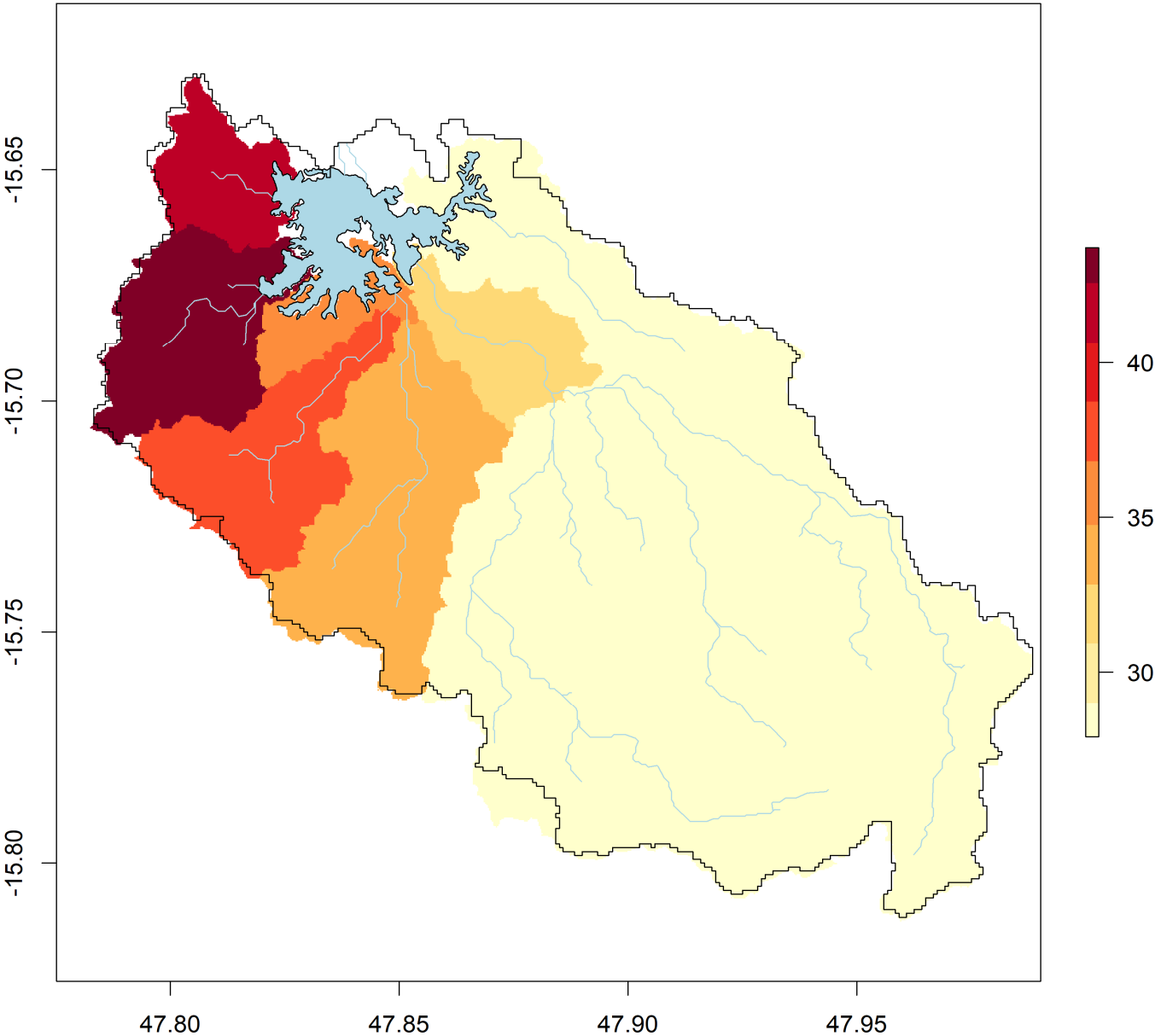


Figure 15. Annual risk scores averaged by sub-catchment for Lake Tseny

3.5 Comparison erosion risk and lake turbidity

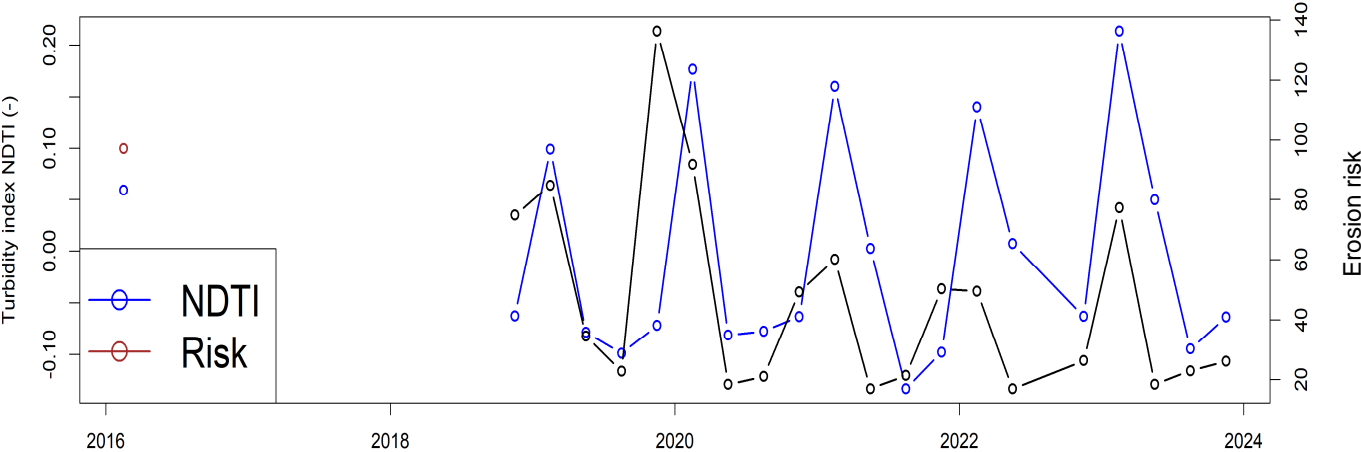


Figure 16. Seasonal risk scores for Lake Sofia catchment and turbidity values (NDTI) for the lake.

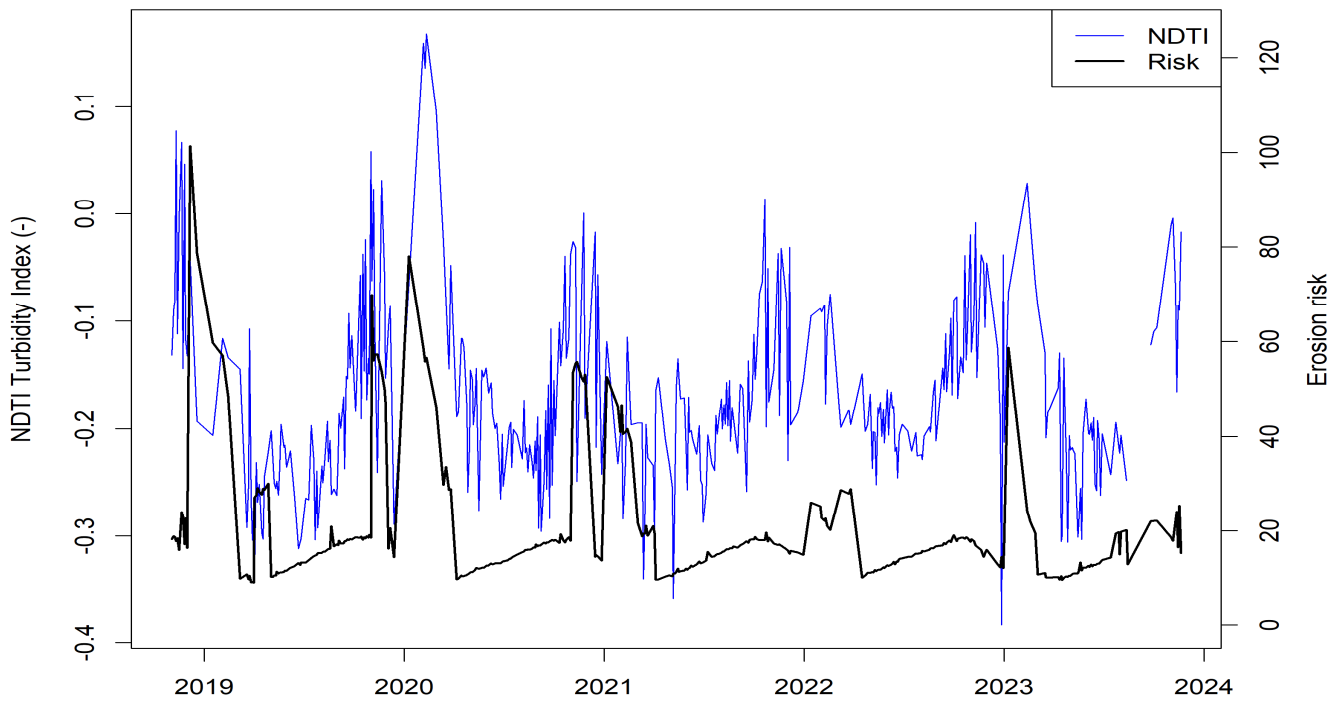


Figure 17. Seasonal risk scores for Lake Tseny catchment and turbidity values (NDTI) for the lake

Time series of average erosion risks for the two catchments were compared with the lake turbidity time series (Figure 16 and Figure 17). The time series for Lake Sofia have a seasonal time step, and for Lake Tseny the time step is monthly because the catchment is on the overlap between two adjacent satellite orbits and more images were available for as a result. Despite the difference in temporal resolution, both time series show a clear connection between high erosion risk in the catchments and high turbidity in the lakes.

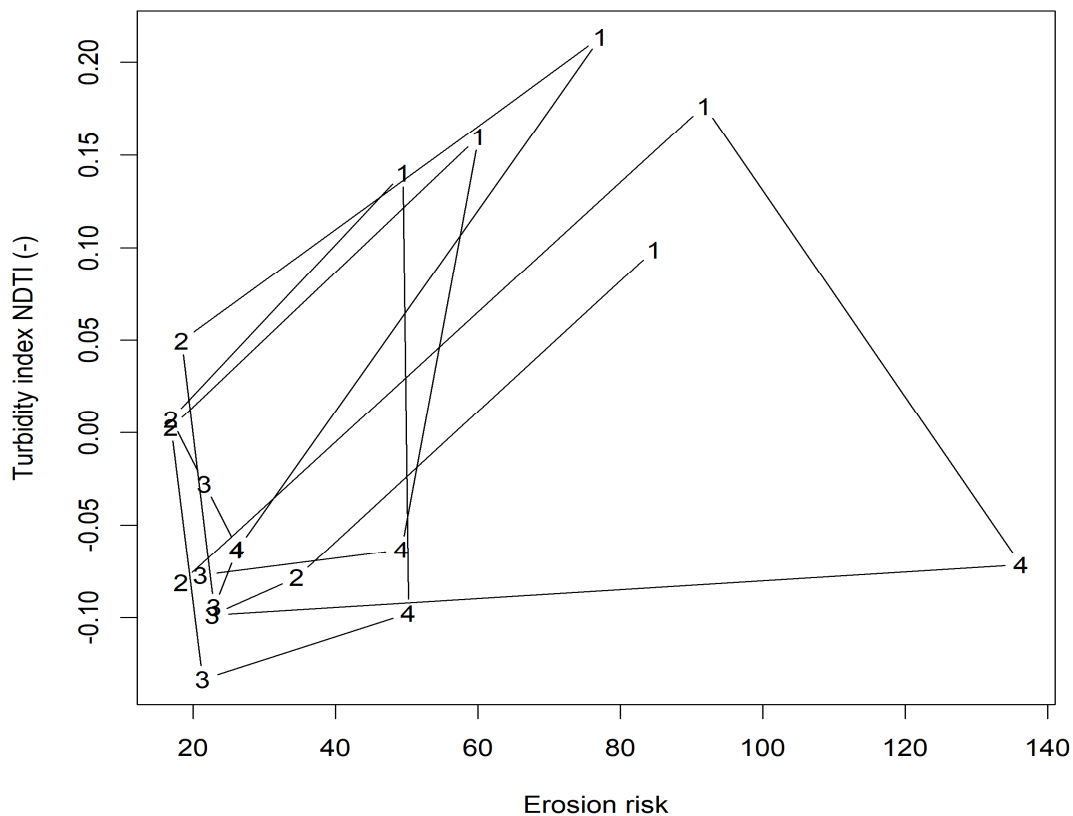


Figure 18. Hysteresis plot for catchment erosion risk and lake turbidity for the Lake Sofia catchment

Note: The numbers in the figure refer to the season (1 = Jan-Mar; 2 = Apr-Jun; 3 = Jul-Sep and 4 = Oct-Dec)

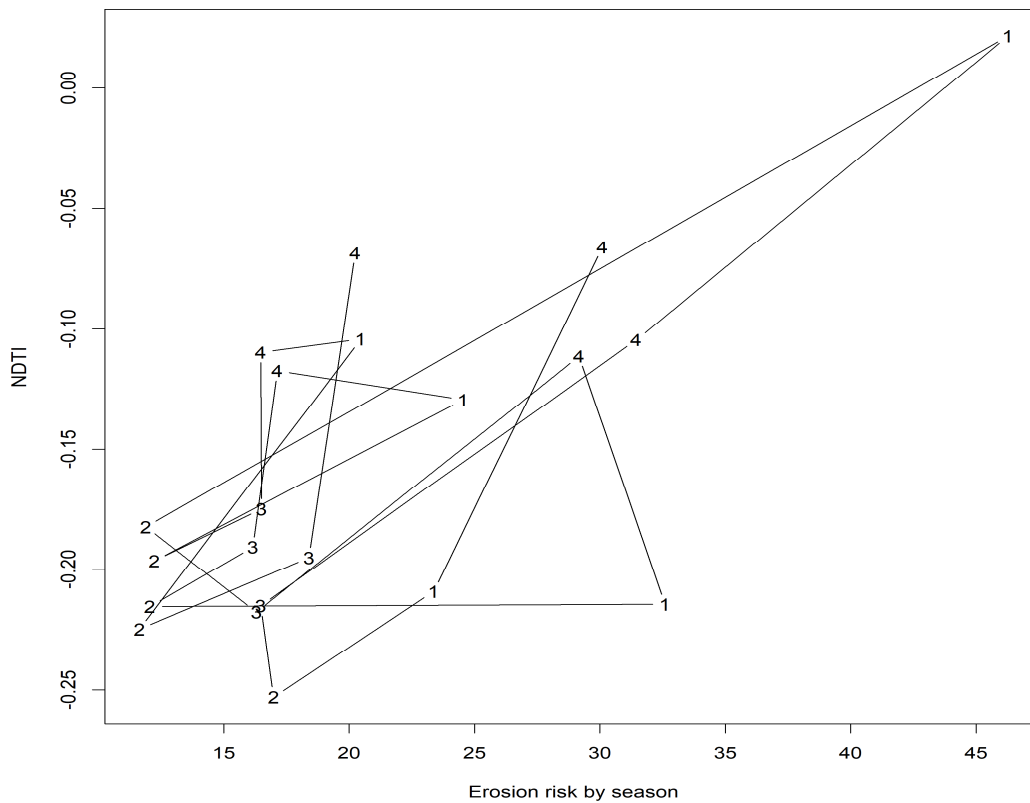


Figure 19. Hysteresis plot for catchment erosion risk and lake turbidity for the Lake Tseny catchment.

Note: The numbers in the figure refer the season (1 = Jan-Mar; 2 = Apr-Jun; 3 = Jul-Sep and 4 = Oct-Dec)

For Lake Sofia and for some years in Lake Tseny the erosion risk leads the turbidity, a lag between increased erosion risk in the catchments and increased turbidity levels in the lakes is to be expected since it takes time for sediment to be transported. In Lake Tseny, for years when both erosion risk and turbidity are relatively low, a short lag time between the two processes is found. The hysteresis loops (**Figure 18** and **Figure 19**) illustrate this difference between the two lakes further: for the Lake Sofia catchment the hysteresis is pronounced; high values in both erosion risk and turbidity occur during the rainy season, whilst during the first part of the dry season turbidity values are still high and take time to respond to the decline in erosion risk. For Lake Tseny the hysteresis is not as clear, indicating a short response time between a change (positive or negative) in erosion risk and a change in lake turbidity (**Figure 17**).

For some years the turbidity in Lake Sofia starts to pick up at the start of the rainy season possibly because of early rainfall (**Figure 16**).

4 Discussion

4.1 General observations

The present analysis strongly suggests that by far the biggest source of sediment into the lakes is from erosion and transportation by water. Firstly, this conclusion is supported by the link between seasonal variation in erosion risk and lake turbidity, where high rainfall and hence high runoff are associated with high turbidity. Secondly, this conclusion is also supported by the difference in lake turbidity and erosion risk in the two catchments; both are higher in Lake Sofia. Thirdly, if wind was the biggest contributor, one would expect the turbidity to be higher during the dry season when soil is more exposed. Fourthly, if fish were the biggest contributor to lake turbidity one would expect it to be more constant throughout the year, unless there were a reason fish would be more disturbing of sediments during the rainy season.

While this last possibility would benefit from further exploration, it seems unlikely to account for anything but a small proportion of the observed lake turbidity, especially given the significant difference in turbidity between the lakes, both of which contain fish (especially tilapia, to which the sediment disturbing behaviour is currently attributed; see WWT 2022).

Additional observations:

- Turbidity is higher in Lake Sofia than in Lake Tseny, and the hysteresis is also more clearly developed in Lake Sofia (cf. **Figure 18** and **Figure 19**). The lag between erosion risk and time of minimum turbidity in Lake Sofia demonstrates that the high sediment load in Lake Sofia needs more time to settle than in Lake Tseny.
- Lake Sofia: large parts of the catchment appear to be contributing sediment. Since the source of sediment is diffuse, it may well be an option to look at promoting soil conservation measures in these, in addition to implementing other measures such as expanding the papyrus fields or capturing the sediment before it reaches the lake.
- Seasonality in lake turbidity: after influx during the rainy season the sediment settles during the dry season and the lakes become clearer. This suggests that if conditions in the catchment can be improved (ie, sediment flows reduced), then sediment levels should reduce reasonably quickly.
- The restoration of macrophyte populations in the lakes requires clear water so that light can reach the bottom where macrophyte seedlings can establish. Therefore the chance of success is better in Lake Tseny compared to Lake Sofia. Likewise, seedlings should have a period of low turbidity for as long as possible to establish. The early part of the dry season would therefore be the best time for planting, provided other phenological aspects did not tend to counter this.

4.2 Suggestions for further work

The following data used in the present analysis would benefit from checking and ground-truthing:

- The land-cover map should be checked at each site to confirm that it is broadly accurate, and that the landcover categories match with the ground conditions.
- The erosion maps could also be ground-truthed, e.g. by installing sediment traps at the outlet of various sub catchments and grading them as low, middle and high erosion risk.
- Verification of decrease in crop yield in Lake Sofia catchment and of evidence of increased grazing pressures in Lake Tseny catchment, to see if these are in line with the observed decrease in NDVI. Field vegetation mapping, crop yield data, agricultural income data, interviews with local farmers, or records of the number of grazing animals could all help confirm whether this trend is correct.
- It would be useful explore the suitability of Sentinel-1 data or other synthetic aperture radar data to estimate when the Anjobony River overflows into Lake Tseny during the wet season, as this could be an important source of sediment that is currently not showing in the data used in this analysis.
- A soil map would be particularly helpful in strengthening the erosion risk model. If there is not great variability in soil type, this information would be similarly useful but would need to be confirmed with field research.

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The Wildfowl & Wetlands Trust (WWT) is one of the world's leading conservation organisations dedicated to saving wetlands for people and wildlife. Founded in 1946 by the pioneering conservationist Sir Peter Scott, WWT's vision is a world where healthy wetland nature thrives and enriches lives.

Our mission is to conserve, restore and create wetlands, save wetland wildlife, and inspire everyone to value the amazing things healthy wetlands achieve for people and nature. WWT has been working in Madagascar since 2010 and operates under an agreement with the Ministry of Foreign Affairs.

WWT Madagascar

LOT VT 74 (TER B)

Andohanimandroseza

101 Antananarivo

+261 32 62 154 16

