Spatio-temporal variability of Lake Tana Water quality derived from MODIS-based Forel-Ule Index: The role of hydrometeorological and surface processes

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1. Introduction

- The Forel-Ule (FUI) color comparator scale is introduced by François Alphonse Forel In 1890.
- He then proposed his color standard, a combination of a cyanometer and xan-thometer to classify the blue to green waters.
- The FUI scale is made of twenty-one colors across a hue gradient, from blue to green, yellow and brown (S. Novoa et al., 2013).

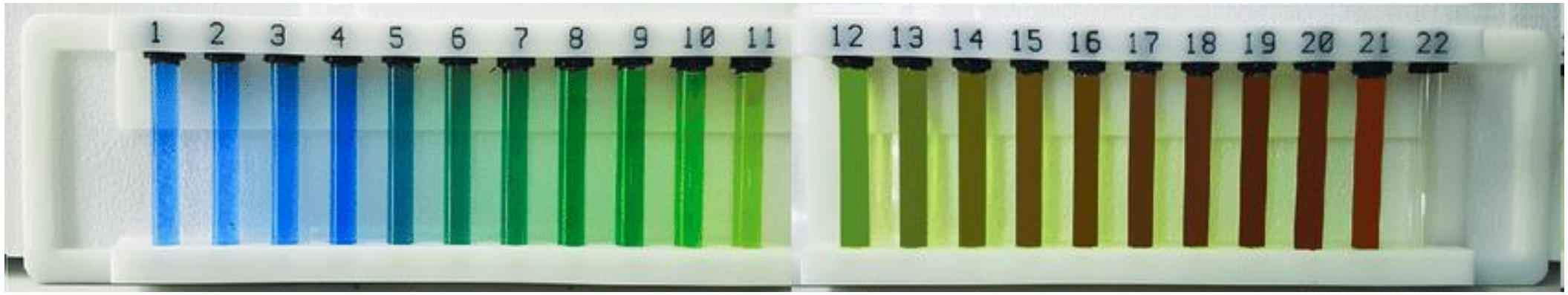

Fig. 1. Forel- ule color scale

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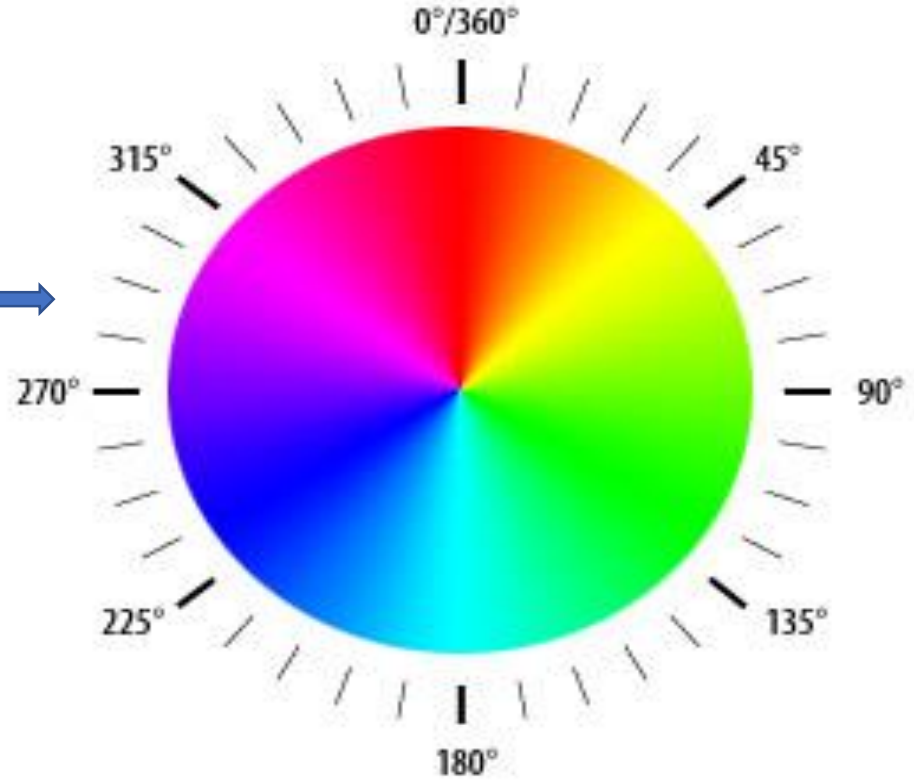
- Hue is the property of light which identifies color within the spectrum and visualized on a circle.
- It is measured in 360 degrees of a color circle: red is at 0°, green is at 120°, and blue is 240°.

Hue color range



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- ❑ Recently, the FUI scale is applicable to remote sensing data. (Wang et al., 2015)
- ❑ By characterizing the 21 FUI colors in terms of the (x,y) chromaticity standards of International Commission on Illumination (CIE1931)

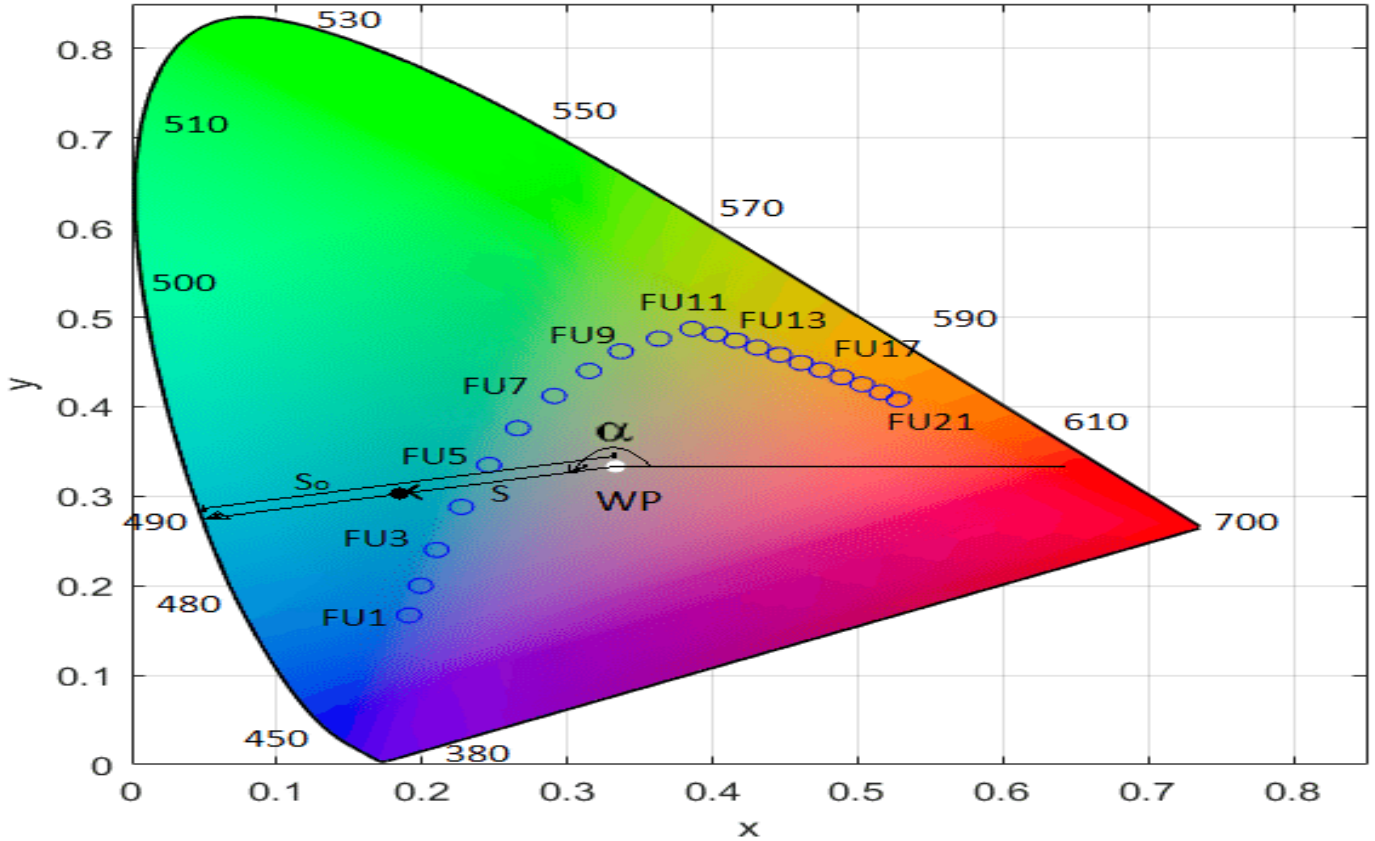

Fig. 2. x, y chromaticity coordinate and Forel Ule diagram.

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- The color of natural waters has been measured globally since the 19th century by means of the Forel-Ule (FUI) color scale.(W. Ule et al., 1892).
- Remote-sensing reflectance from satellite-borne ocean color sensors is converted to FUI to identify water colors.(F. A. Fore et al., 1902).
- As water color is indicator of water quality, hue angle and FUI derived from remote sensing have been recently applied with success in the assessment of quality variability of lakes. (Liu, C. et al., 2017).

2. Study area

- Lake Tana is Located in Amhara region in the north-western Ethiopian highlands, with 84 kilometers length, 66 kilometers width, maximum depth of 15 meters, and an elevation of 1,788 meters.

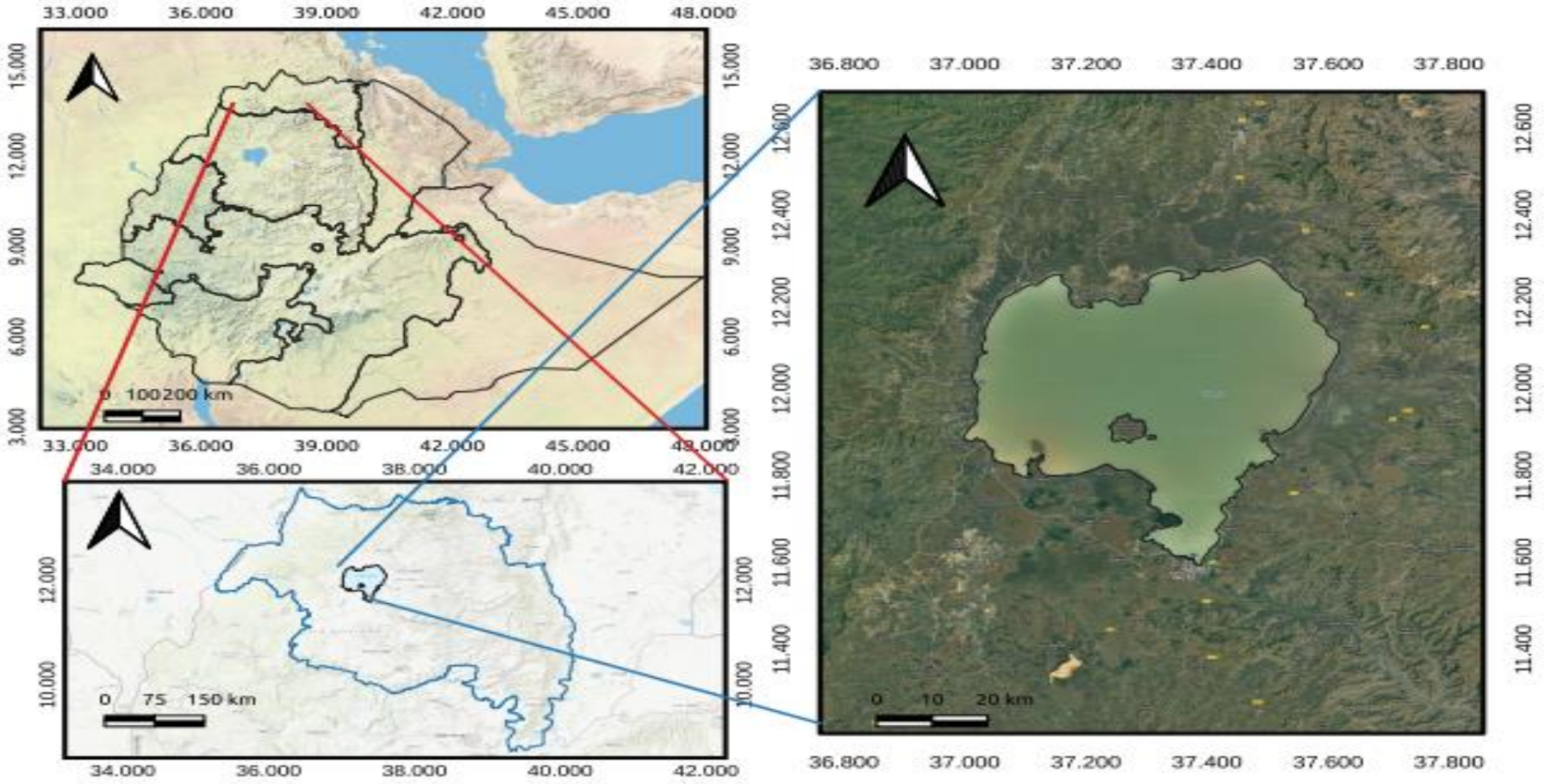


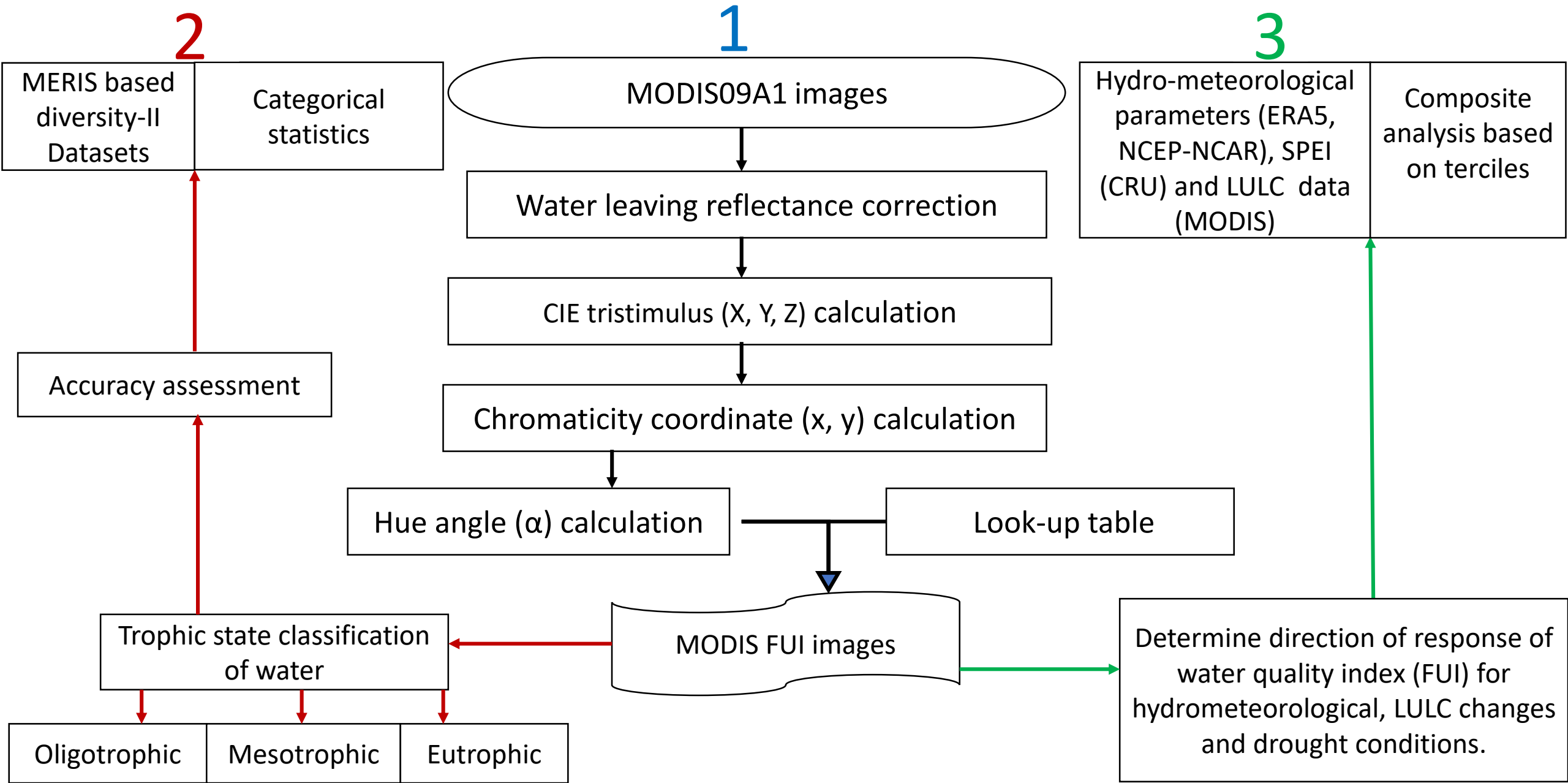
Fig. 3. Location Map of Lake Tana.

3. Data sources

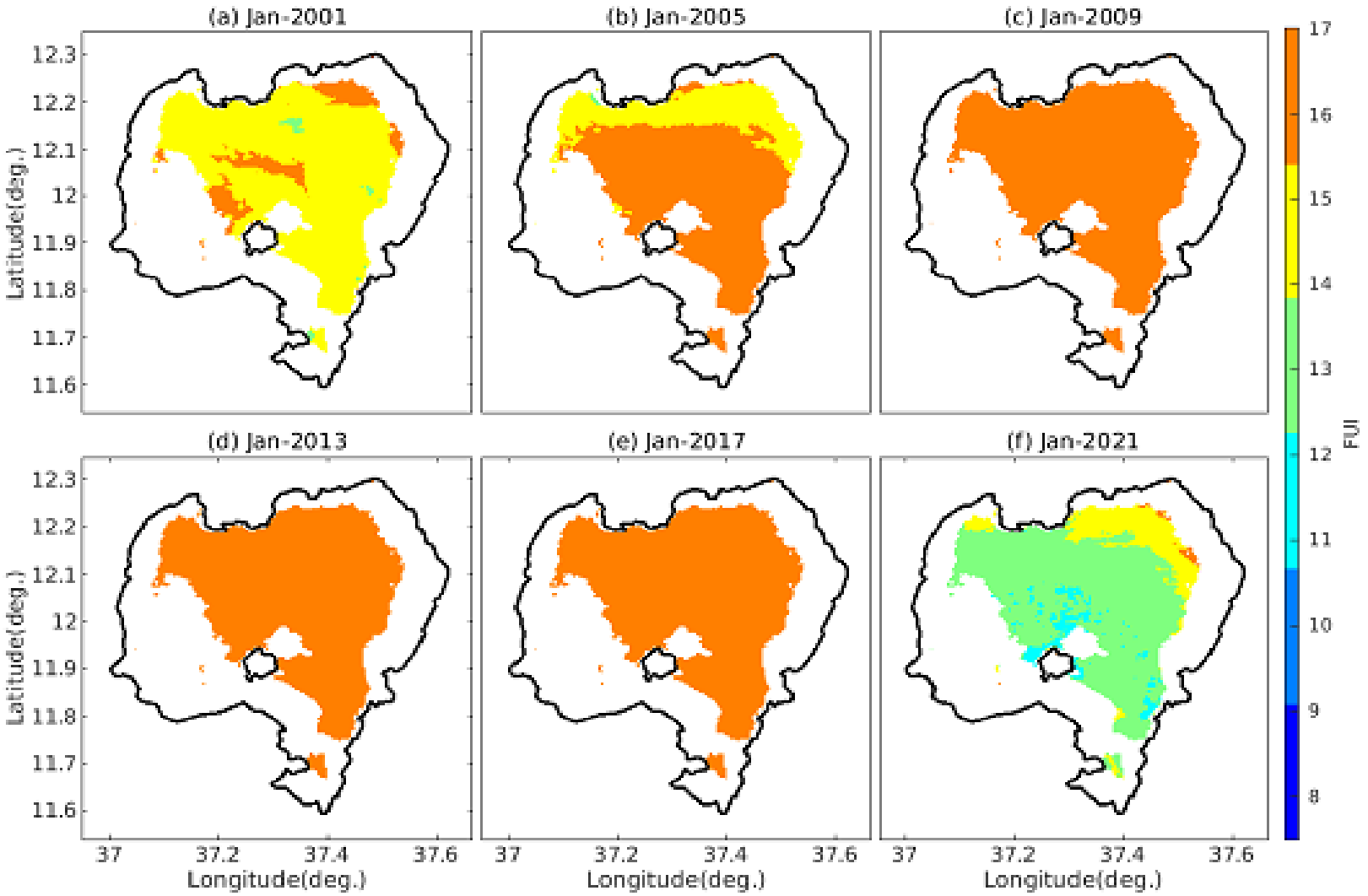
- Water surface reflectance (MOD09A1) from MODIS satellite.
- Diversity-II water quality variables from MERIS satellite .
- Land use and land cover change (NDVI & EVI) from MODIS satellite.
- Drought or SPEI data from Climatic Research Unit (CRU) model.
- Hydro-meteorological parameters from NCEP-NCAR and ERA5 models.

4. Methods

Flow chart of the overall research methods



5. Results and discussion



- During mid winter, FUI time series shows that it increased 2001 to 2005.
- Remained unchanged in 2009, 2013, and 2017.
- It started diminishing in 2021 reaching a value of 13 at the northern and central part of the Lake.

Fig. 4. Inter-annual FUI variability over the Lake Tana during mid winter.

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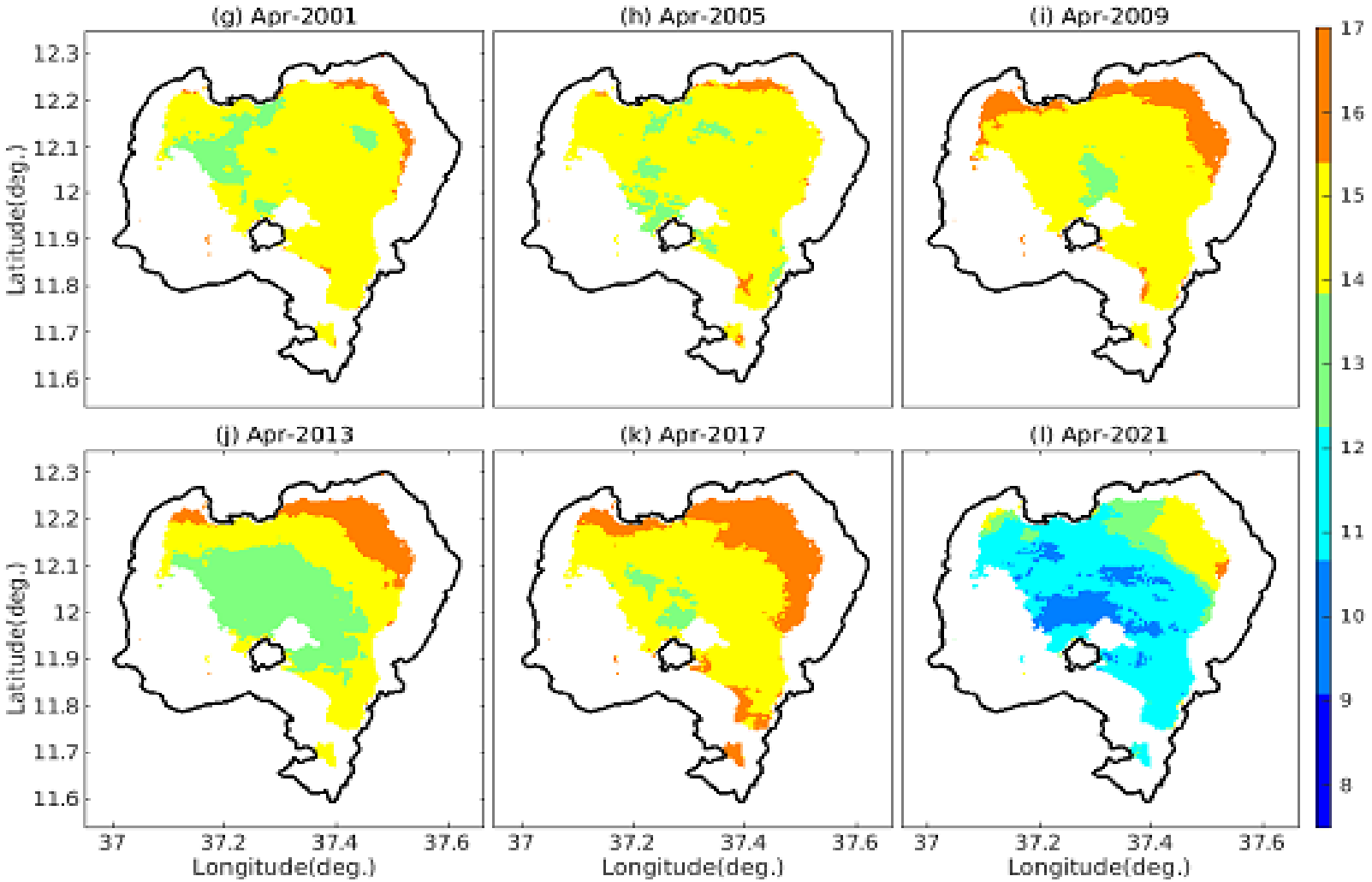

- In the mid spring month (April), the FUI over the Lake decreased except spikes in 2017 .
- The consistent decrease in FUI in spring FUI time series reveals that there are changes in the water quality drivers.

Fig. 5. Inter-annual FUI variability over the Lake Tana during mid spring.

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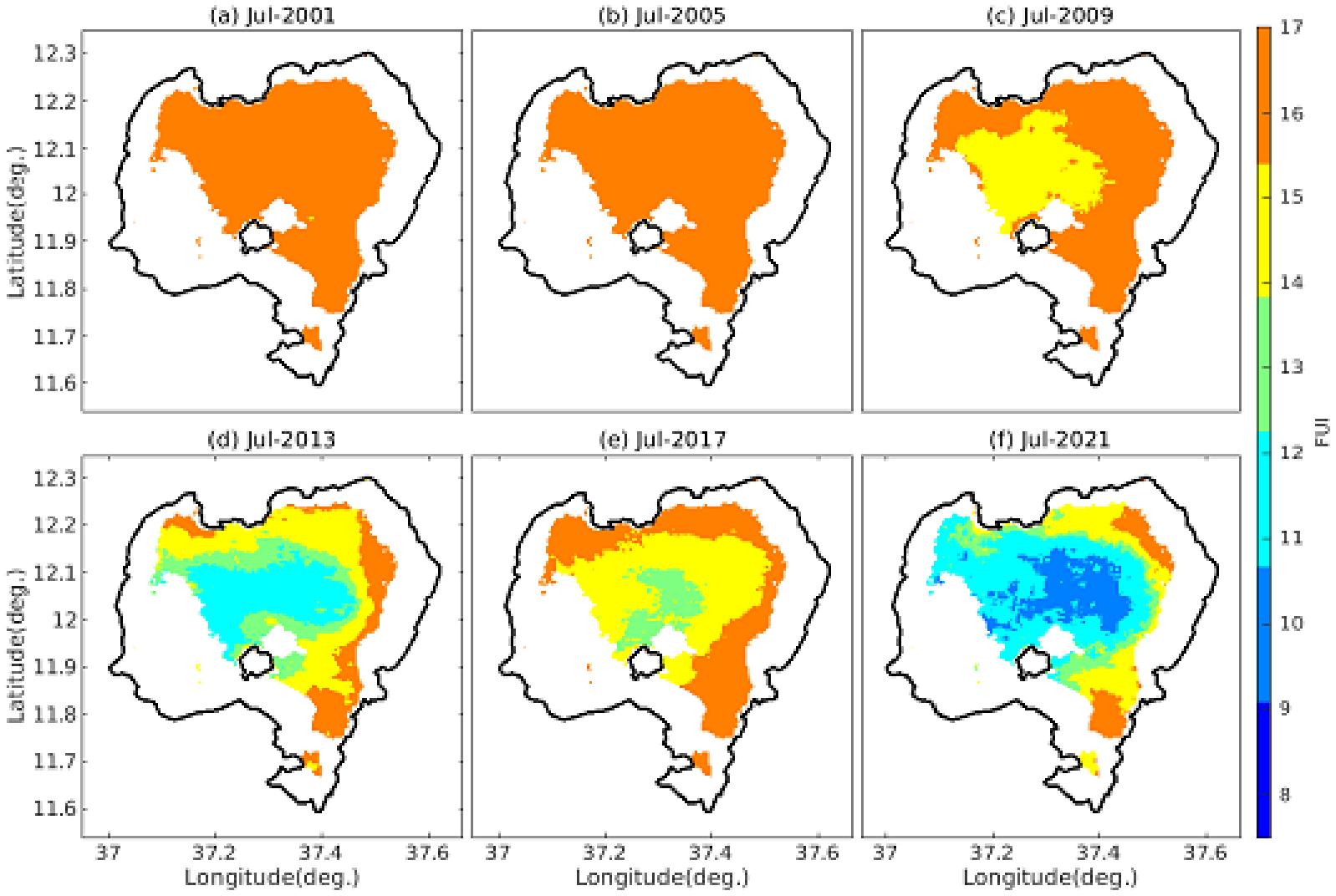

- The variability of FUI during mid summer month of July showed similar pattern of changes as in spring with a spike in 2017.
- It improves consistently from year to year.

Fig. 6. Inter-annual FUI variability over the Lake Tana during mid summer.

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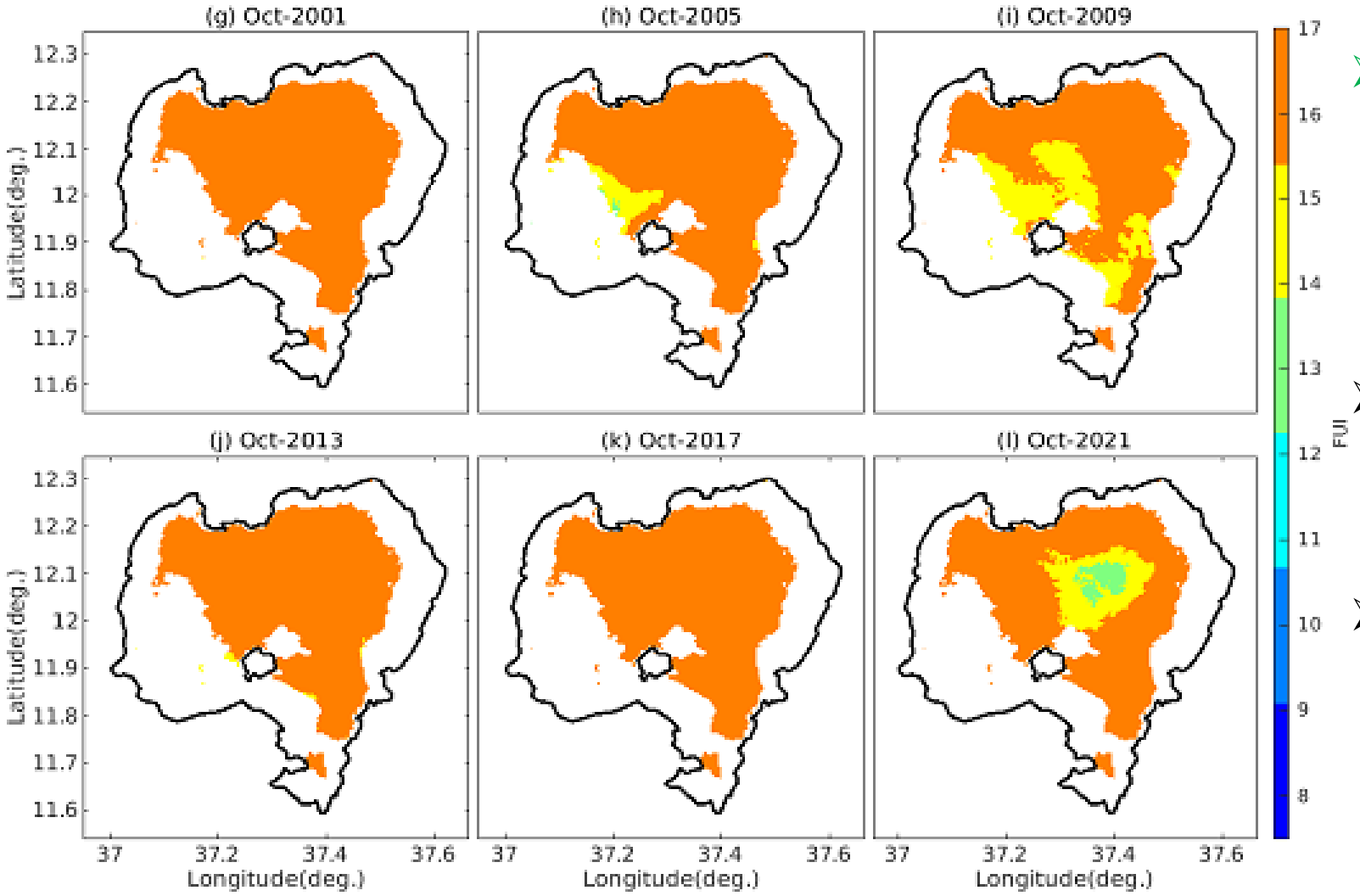
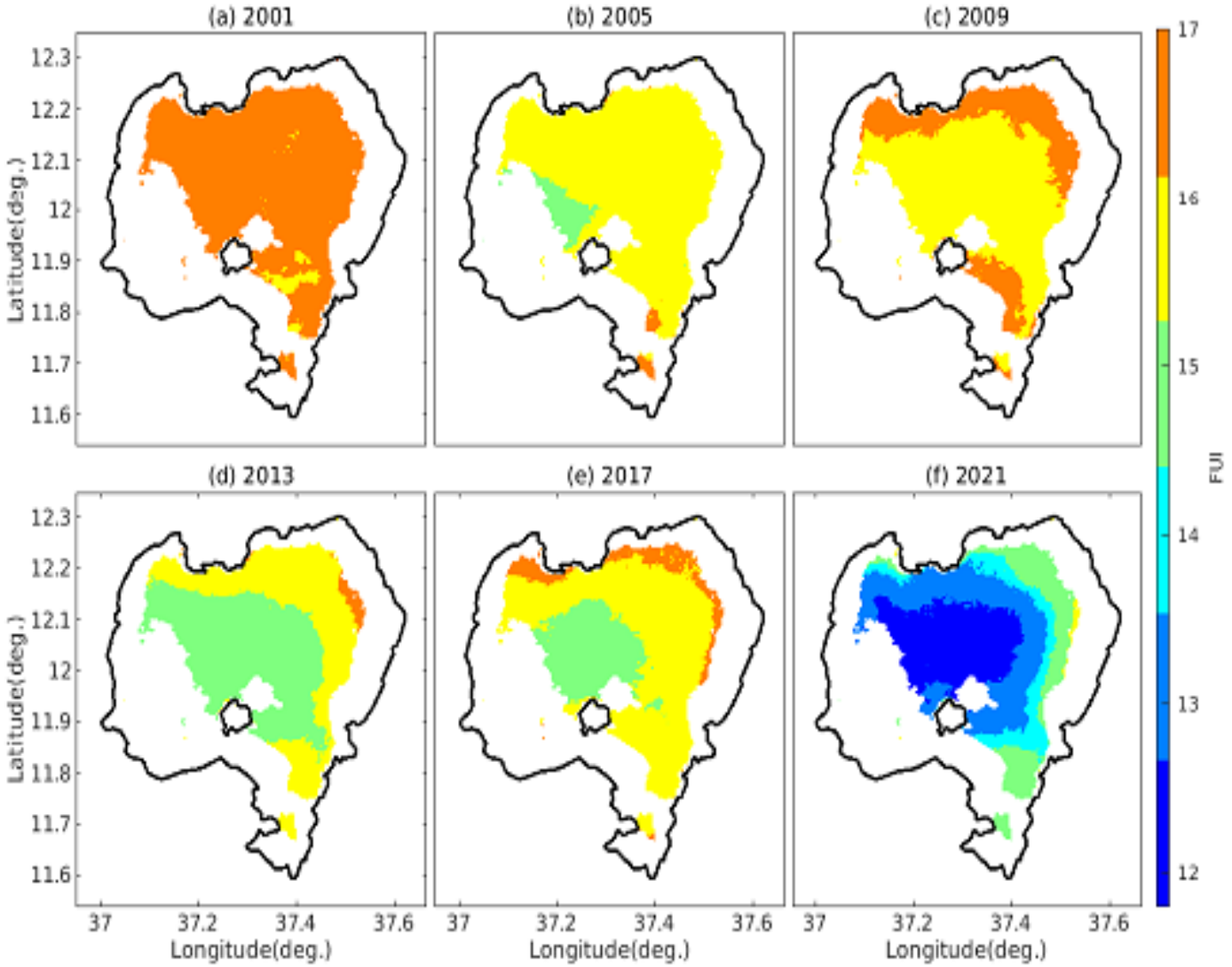


- FUI do not show significant improvement during autumn except in 2021 over the central part of the Lake.
- The lack of consistency between the seasons in terms of FUI variability is linked to:
- The difference in the scale of variability of hydro-meteorological drivers during the different seasons.

Fig.7. Inter-annual FUI variability over the Lake Tana during mid autumn.

Selected annual mean FU Index maps



- In 2001, the Lake water have high FUI indicating the presence of highly turbid water.
- The water quality of the Lake shows a significant increase in 2005 in most part of the Lake compared to 2001.
- The improvement in water quality is continued into 2021 reaching FUI value of 12 over wider area of the Lake.

Fig. 8. Interannual spatio-temporal annual mean FUI variation over Lake Tana.

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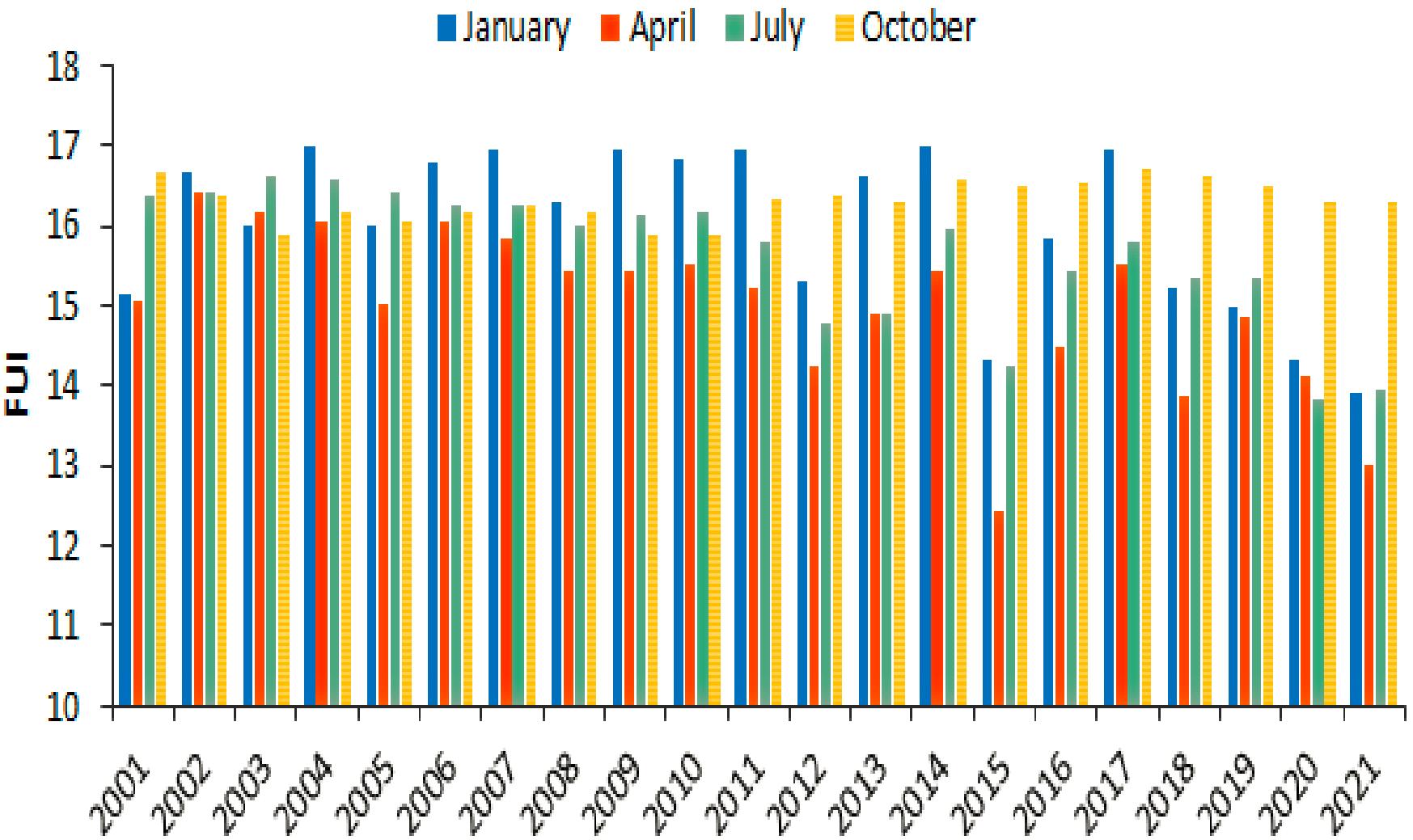

- The Lake wide mean FUI during the peak month of summer, winter, spring and autumn is in agreement with the observed FUI at pixel level.
- The Lake water quality shows a consistent improvement from 2001 to 2021.

Fig. 9. Lake wide inter-anuual monthly averaged FUI time series.

5.1. Composite analysis

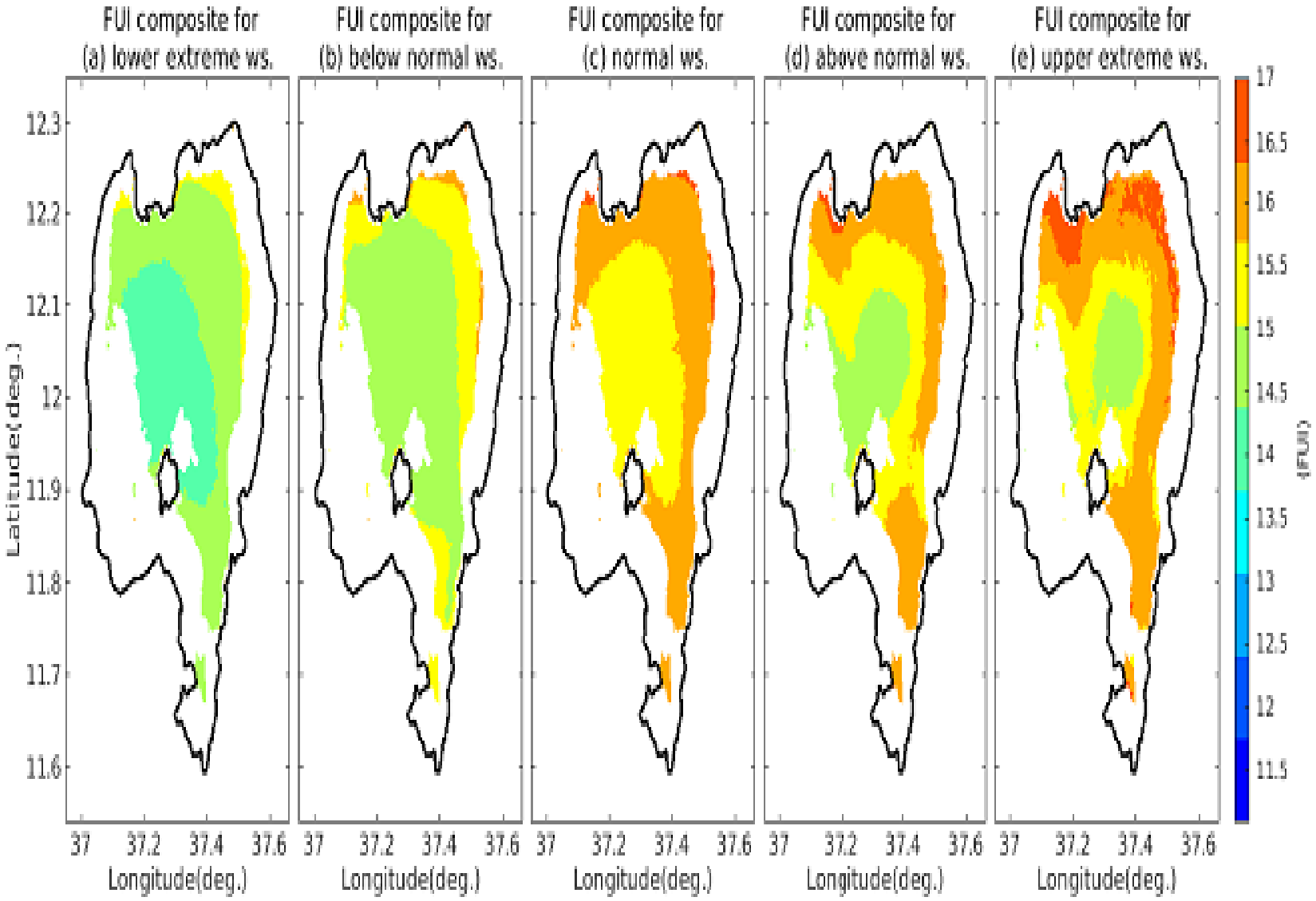

Fig. 10. FUI composites over Lake Tana belonging to the periods of below normal, normal, above normal, lower extreme, and upper extreme values of wind speed.

- Increasing wind speed is associated with decrease in water clarity (i.e., high FUI).
- Increasing wind speed enhances the blowing of algae.

↓

Accelerates the release of nutrients in to water bodies.

- Increasing wind speed changes surface water temperature by mixing the upper and lower water layers.

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Speeding up the volatilization and movement of contaminates on the Lake.

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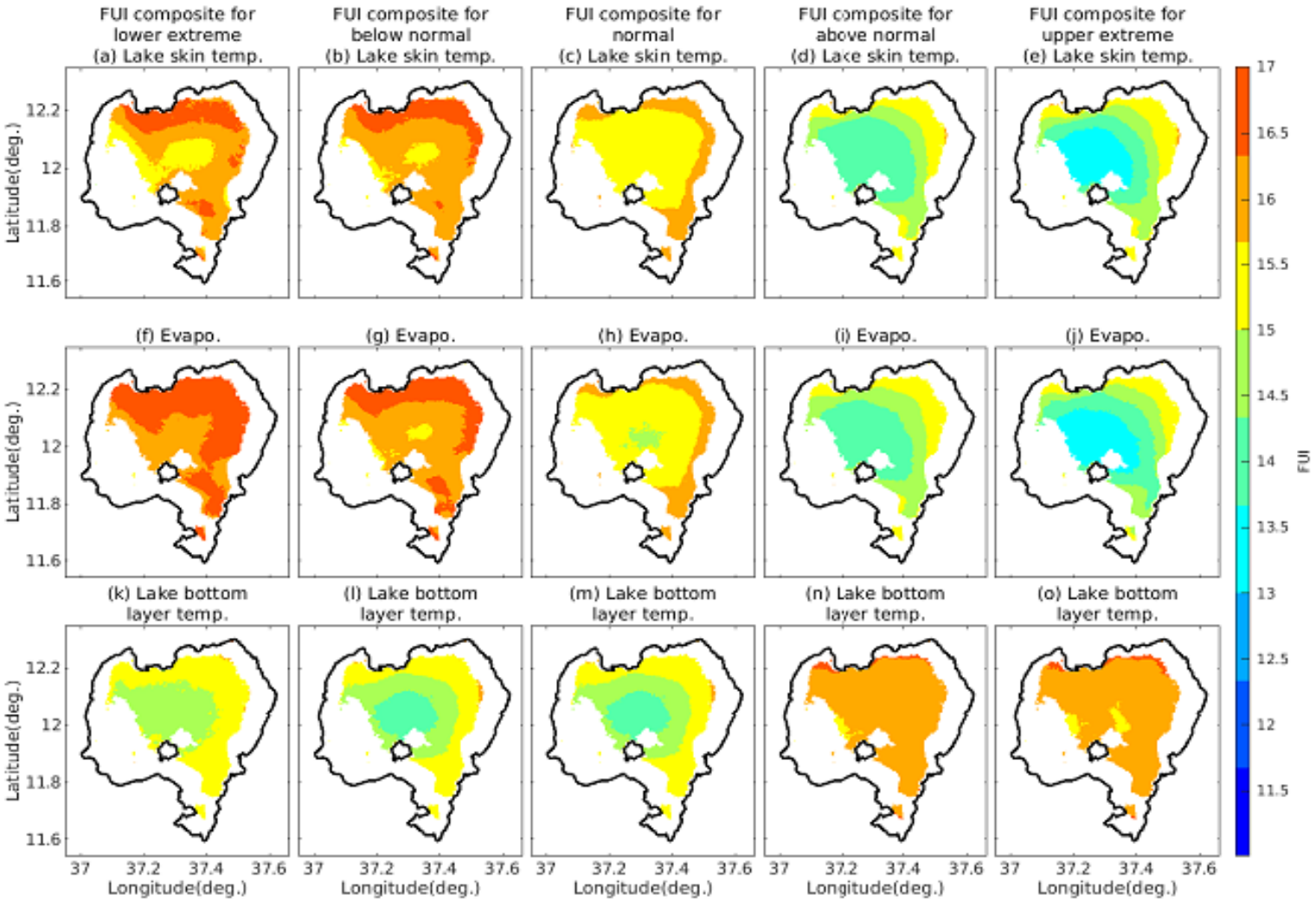

Fig. 11. FUI composites over Lake Tana during the periods of below normal, normal, above normal, lower extreme, and upper extreme values of skin temperature, lake bottom layer temperature, and evaporation.

FUI decreases with increase in Lake skin temperature & evaporation .

- Warmer temperature & increased heat diminishes:
  - Surface water viscosity,
  - Increases nutrient dispersion & stratification,
  - Speeds up the sinking rate of phytoplankton ,
  - Diminishes the accessibility of nutrients in inland water bodies.
- Increasing lake bottom layer temperature increases:
  - Microbial activity in soil and sediments at the bottom of the lake.
  - Resulting in a high phosphorus load on the surface of the lake.

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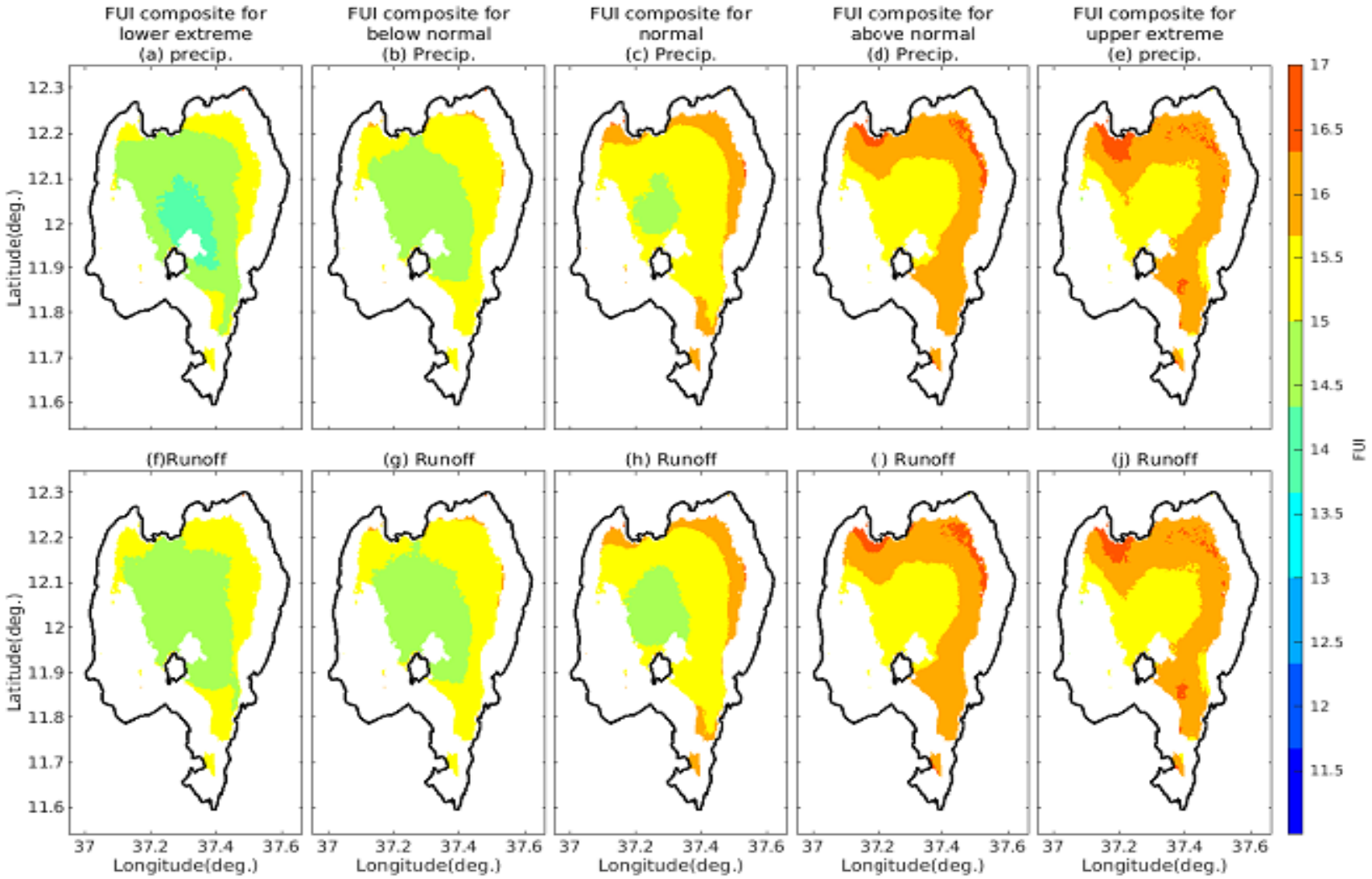

- FUI increases with increase in precipitation and runoff.
- Intense precipitation & heavy rainfall are responsible for:
  - High sediment transport,
  - Erosion and re-suspension,
  - Speeds up the mobilization of nutrients,
  - Collecting non-point pollutants (TN) and (TP),
  - Increases nutrient concentrations on the surface of water bodies.

Fig. 12. FUI composites over Lake Tana during the periods of below normal, normal, above normal, lower extreme, and upper extreme of precipitation, and surface runoff.

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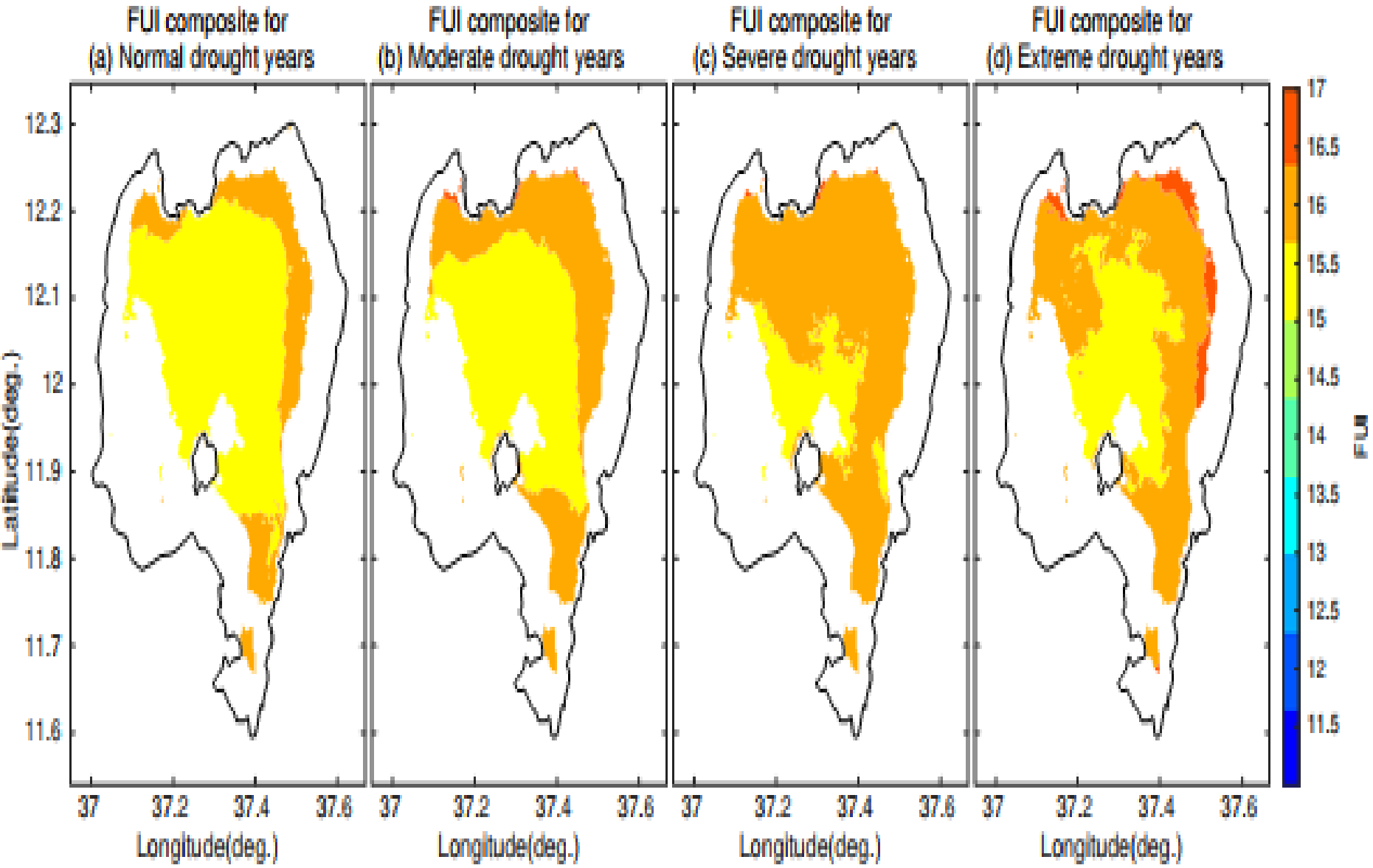

Fig. 13. FUI composites of Lake Tana during normal, moderate drought, severe drought, and extreme drought periods.

- FUI increases with increasing severity of drought events.

During drought years,

- Low inflow and maximum temperature:

Maximizes chl-a, concentration & algal bloom on the surface of the lake.

- Low inflow increases:

The concentration of suspended particles and turbidity by decreasing the amount of dilation.

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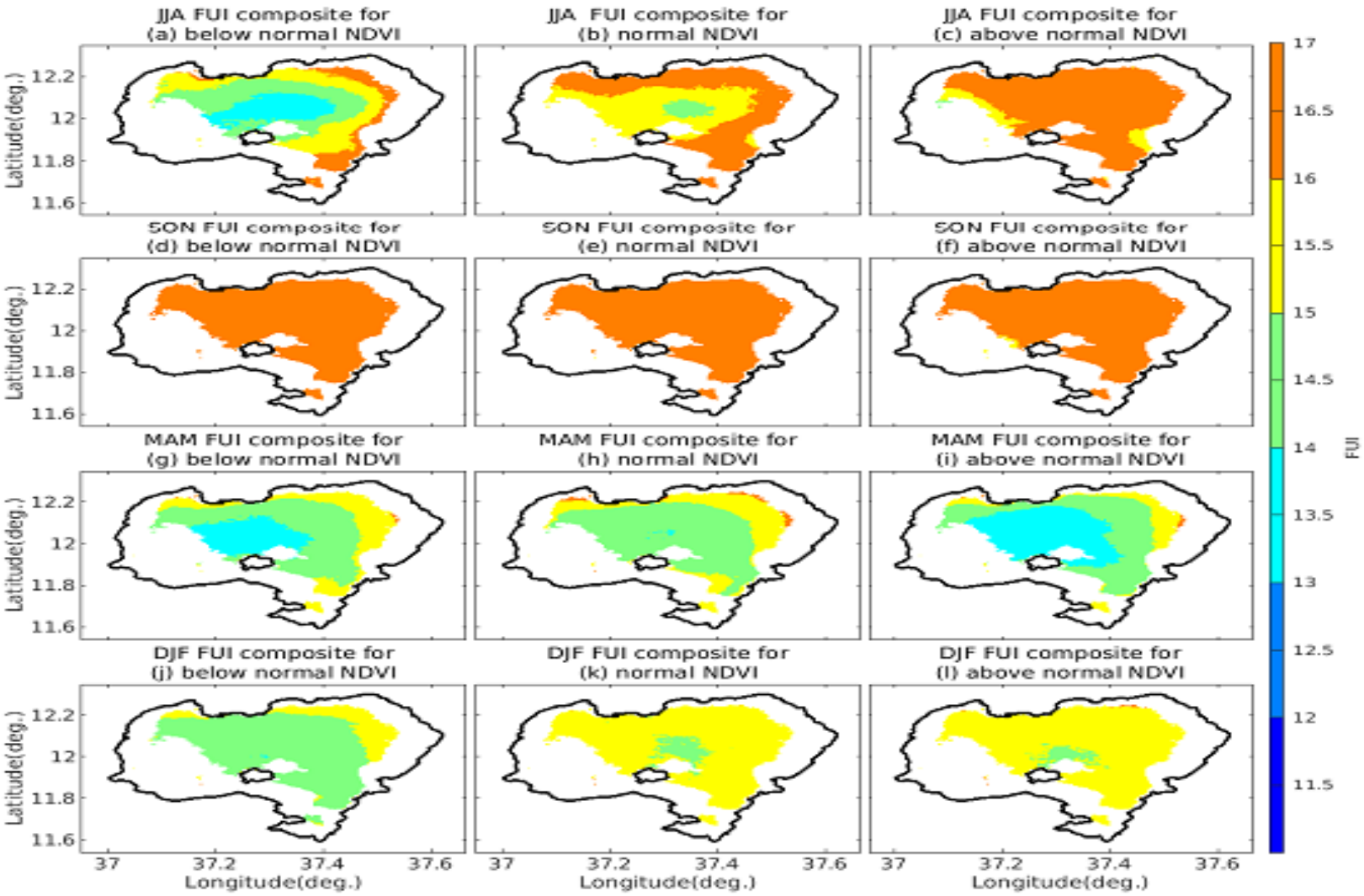

- During the summer season (JJA), FUI increases with increasing NDVI & EVI

This is due to the increment of the load of non-point source such as: total nitrogen (TN) and total phosphorus (TP) from high vegetation coverage.

- In autumn (SON), FUI is very high during all vegetation conditions (low, normal, and above normal NDVI and EVI values)

This is due to the high concentration of TN and TP during autumn on the surface of the Lake.

Fig. 14. Seasonal FUI composites of Lake Tana during below normal, normal and above normal normalized difference vegetation index (NDVI) months.

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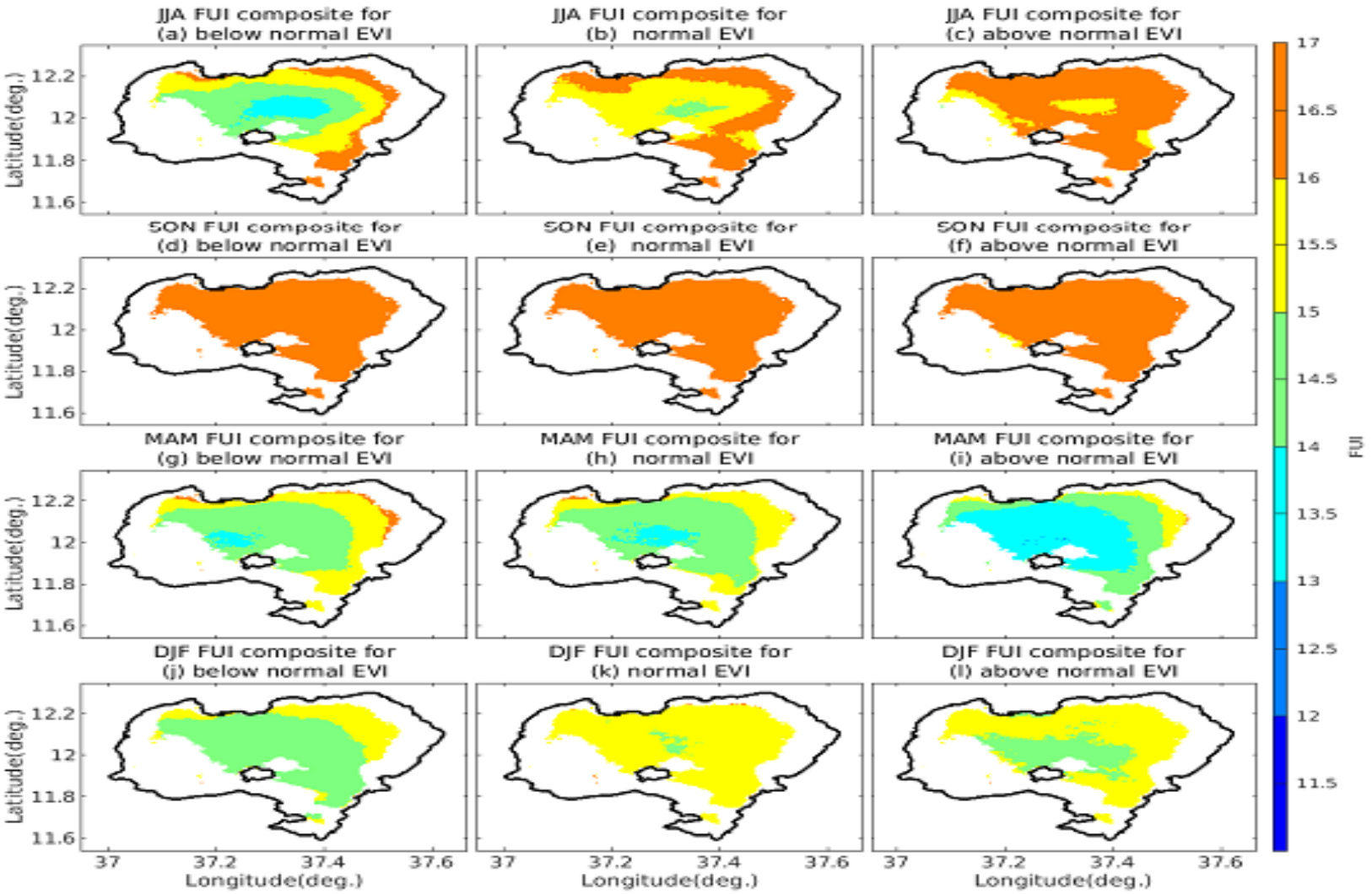

- In spring season (MAM), FUI decreases with increasing NDVI and EVI.
- During winter season (DJF), FUI increases with increasing vegetation index (NDVI).
- The quality of lake water improved during below and above normal EVI values.
- Where as FUI composite shows turbid lake water during normal vegetation condition.

Fig. 15. Seasonal FUI composites of Lake Tana during below normal, normal and above normal enhanced vegetation index (EVI) months.

6. Conclusions

- Optical property of inland water bodies is typically complex and variable.
- MODIS-based FUI, MERIS based Diversity-II datasets, CRU, ERA5 and NCEP-NCAR reanalysis datasets were employed.
- FUI is an attainable method for evaluating the quality of inland water bodies in large regions for a long time period.
- Lake Tana remained eutrophic during the study period from 2000-2021.
- FUI is influenced by meteorological, hydrological, and land use and land cover factors.

Acknowledgements

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Thanks a lot