Examining the role of land use and precipitation on the water quality of Lake Tana, Ethiopia.

Brian S. Kim
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The University of Texas at Austin

Introduction:

The northern highlands of Ethiopia formed approximately 75 million years a flood basalt emplacement lifted up the region forming a large geographical dome. The elevation rarely falls below 1500 meters, although some regions can be as high 4550 meters. The highland is split into two portion, the northwestern and southeastern, with the Lake Tana residing in the former. The climate is dominated by tropical highland monsoons with most precipitation occurring between June and September (Mohamed et al., 2005). The northern highlands receive more precipitation than the lowlands with approximately 1200 to 2700 mm of rain annually, making this region particularly susceptible to soil erosion via runoff events. Additionally, there is an increase in the frequency of extreme rainfall events in recent decades (Osman and Sauerborn 2002; Seleshi and Demaree 1995).

Major deforestation occurred between 1957 and 1982 destroying around 94% of pre-existing natural forest cover. As of 1995, the largest uses of land are agriculture (77%) and grasslands for grazing (12%) (Zeleke and Hurni 2001). The primary row crops in Ethiopia are teff, maize, beans and sweet potatoes (Cochrane and Bekele 2018). Widespread deforestation in northern Ethiopia is largely a result of subsistence agricultural expansion, livestock grazing, and fuelwood harvest (Gelaw, Singh & Lal, 2014). In the wake of deforestation, agricultural land in Ethiopia can be degraded by soil erosion (Lemma et al. 20 17). In the northern highlands of Ethiopia, soil loss is primarily through rill erosion, with runoff forming channels in cropland, at rates between 1.46 - 9.02 t ha-1 yr-1 (Lemma et al. 2017). Due to repeated tillage and harvesting, much of the cropland in northern Ethiopia is characterized by low soil organic matter and high soil disturbance making it susceptible to transport of soil particles with storm runoff (Dagnew et al. 2017). Agricultural catchments in the region have shown significantly higher levels of runoff compared to grassland-dominated catchments (Dagnew et al. 2017). Soil nutrients including nitrogen (N), phosphorus (P), potassium and calcium are lost along with organic carbon via soil erosion in catchments across northern Ethiopia (Haregeweyn et al. 2008). Use of mineral fertilizers has been increasing in northern Ethiopia over the past decade in an effort to regain lost soil fertility (Haregeweyn et al. 2008).

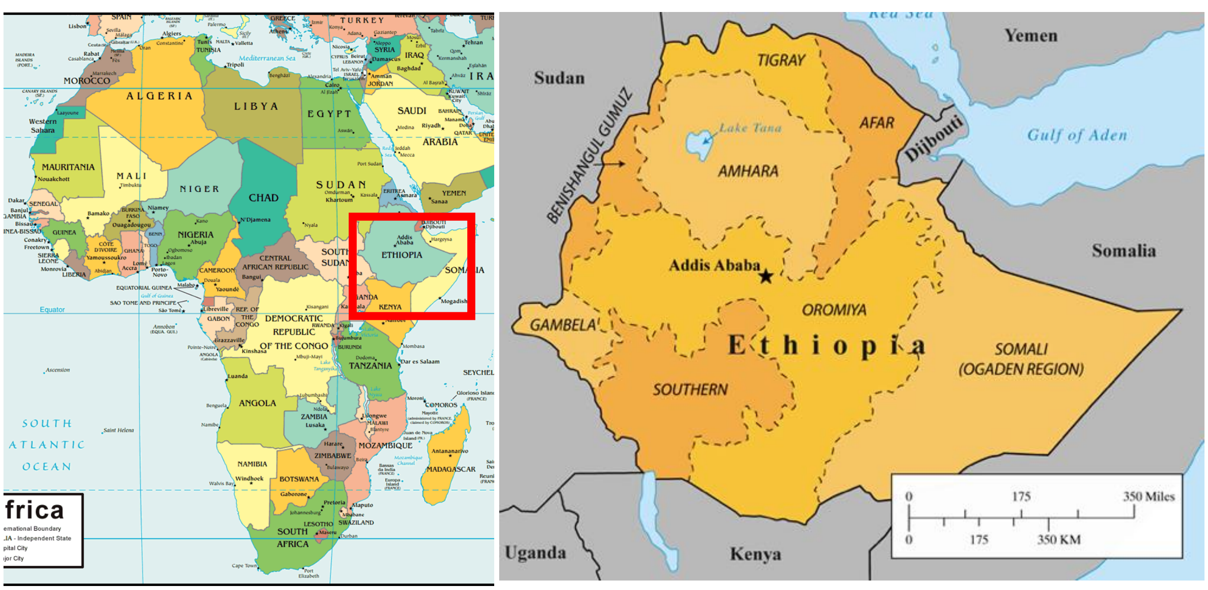

Figure 1. Map of countries in Africa with Ethiopia boxed in red (left). A map of Ethiopia with labeled subregions. Lake Tana is located in the Amhara region and is the largest lake in Ethiopia.

Lake Tana

Endpoint hydrologic systems, such as lakes, are integrators of anthropogenic change on the landscape (Williamson et al. 2008). Streams and lakes in heavily agricultural landscapes often experience elevated sediment and nutrient loads and an inability to process these excess nutrients. Across North America, Europe and New Zealand, there are many examples illustrating relationships between catchment land use and stream ecosystem function including nutrient spiraling metrics (Arango et al. 2008; Von Schiller et al. 2008; Matheson et al. 2011) and ecosystem metabolism (Bernot et al. 2010; FuB et al. 2017). Even in intensively farmed landscapes, restored floodplain and riparian buffers can enhance stream ecosystem functions such as nutrient removal (Arango and Tank 2008; Roley et al. 2012). However, in other instances agricultural streams function more like conduits to downstream systems rather than processors of nutrients (Royer et al. 2004; Sheibley et al. 2014).

In this region, access to clean water plays a crucial role in the livelihood and well-being of rural communities. In the surrounding urban areas, Lake Tana is used for cleaning, cooking, and human and livestock drinking by 2.6 million people (Makoni et al. 2004; Mazet et al. 2009). In spite of such dependency on this lake for access to freshwater, controls of water quality in these streams are poorly understood. In addition to basic resources such as drinking water, Lake Tana supports a large fishing industry of *Labeobarbus* and Nile tilapia that lands 1454 tons annually (FAO 2003).

Objective

Lake Tana has experienced an extreme change in land cover over the past several decades. This is turn has significantly impacted the soil erosion within the watershed affecting overall lake water quality. Using ArcGIS and historic time series, I aim to elucidate …

1. How has land use changed in the Lake Tana watershed over the past 20 years?
2. How has the change in land use affected Lake Tana water quality, specifically total suspended solids?
3. How has changes in precipitation within the watershed affected erosion and Lake Tana water quality?

Data and Methods

DEM: The Lake Tana basin, rivers and watersheds were based on the Aster Orthorectififed Digital Elevation Model (DEM) from 2000. Flow direction and flow accumulation were determined using ArcGIS tools and streams were defined using a flow accumulation threshold of 5000.

MODIS: Land cover data was derived from the MODIS/Terra and Aqua Combined Land Cover Type (MCD12Q1) and was acquired from the Land Processes Distributed Active Archive Center (LP DAAC). The database provided annual global land cover from 2001 to 2017. Within the MCD12Q1 data file I selected the Land Cover Type 1 classification scheme which consists of 17 unique groups (Evergreen Needleleaf Forest, Evergreen Broadleaf Forest, Deciduous Needleleaf Forest, Deciduous Broadleaf Forest, Mixed Forest, Closed Shrubland, Open Shrubland, Woody Savanna, Savanna, Grassland, Wetland, Cropland, Urban, Snow and Ice, Barren, and Water Bodies). For the purpose of this study, I excluded minor groups such as urban and snow/ice and broadened the categories to three major groups (forest, shrubland/savannas, and crop/pasture).

Each annual file was then masked to the watershed of Lake Tana and land cover distribution and change were determined based on differences of watershed percent for each category.

GPCC: Daily precipitation data was collected from the Global Precipitation Climatology Centre (GPCC). The GPCC creates the global precipitation map based on ~53,000 stations located throughout the globe including three in Ethiopia. Although this database provided 30 years of precipitation data, the 1° x 1° does not provide a very high resolution the Lake Tana watershed was represented by a single pixel (fig 2).

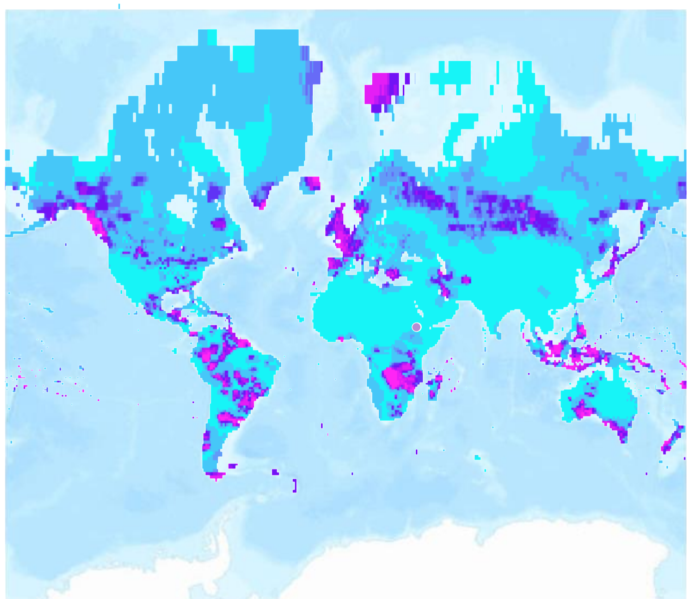

Figure 2. Raster file of global daily precipitation data from the GPCC.

TSS: Total suspended solids were derived from the MODIS-Terra satellite images. The dataset (MOD09GQ) provided almost daily, 250m resolution raster files based on near infrared (NIR) at 841-876 nm wavelength. To determine TSS, I utilized a model from Kaba et al. that calculated a linear regression (TSS = 2371 x pNIR – 62.8) by comparing NIR and land-sampled TSS which provided an R^2 of 0.95 (2013). Using this model, I determined TSS before, during, and after the rainy season during 2000, 2005, and 2010. One pitfall of this method however, is that due to the high chance of cloud cover during the rainy season, there can be large gaps in data continuity for a time series. To observe the effects of land cover on TSS I picked two points in Lake Tana to track the difference in TSS between the western and eastern catchments which have significant and distinct land cover differences.

Results

Watershed: Lake Tana is situated approximately 1800 meters above sea level, due to the fact that the highlands of Ethiopia are located on an elevated plateau. The lake is 3156 km^2 and the watershed is 15,096 km^2. The Lake Tana watershed is divided into three distinct regions (western, northern, and eastern). The major streams in the western basin converge into one river that drains the majority of this region covering a distance of almost 100 km. In the eastern basin, there are two primary rivers that drain into the lake that travels only 60 km and experiences a steeper elevation gradient. The northern region is ignored for the rest of the study due to its small catchment area and numerous inputs rather than a single discharge point.

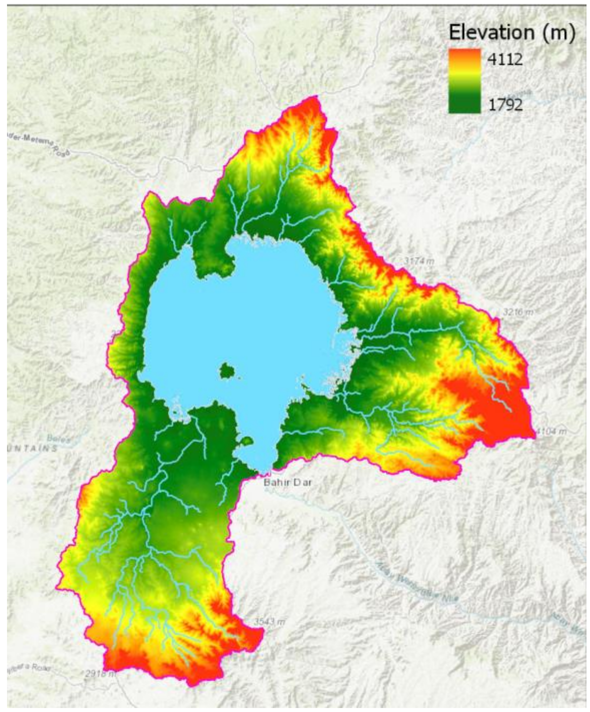

Figure 3. Elevation map of Lake Tana with major streams delineated.

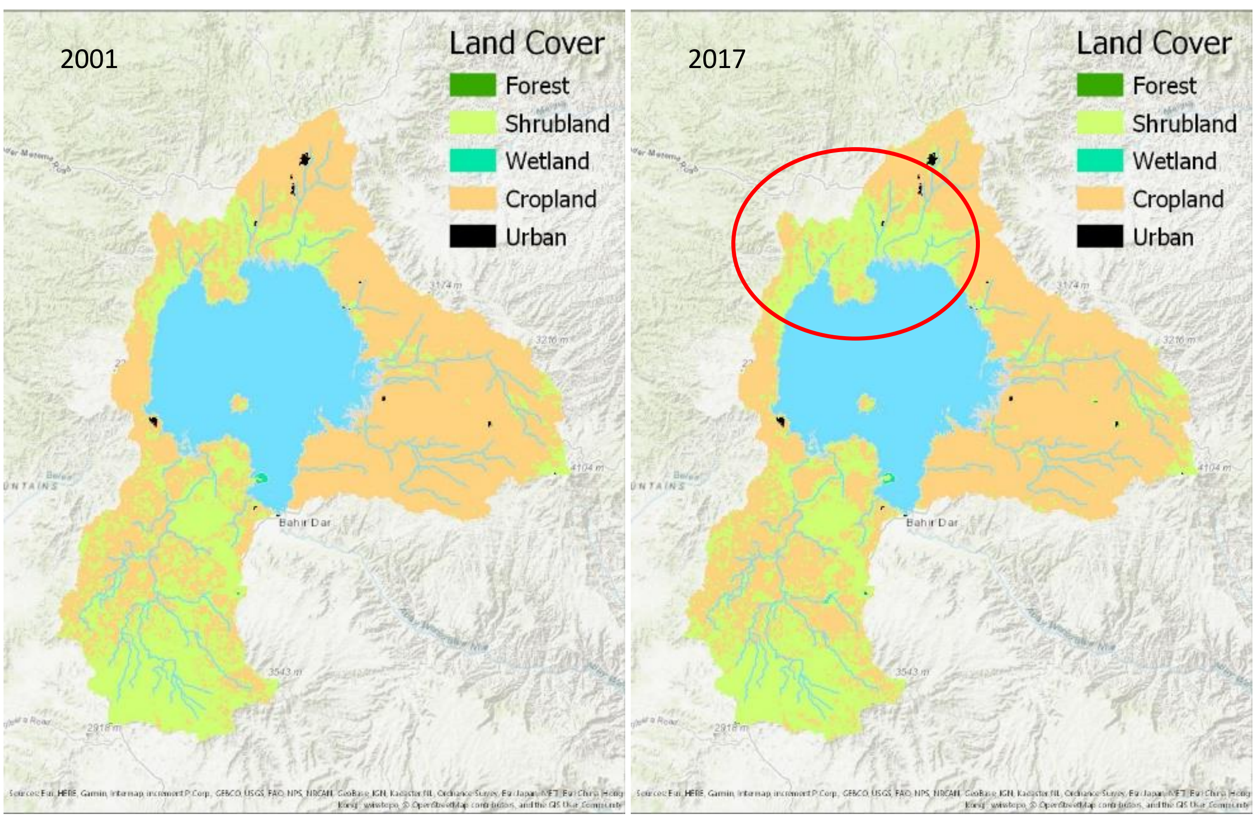

Figure 4. Land cover of Lake Tana watershed in 2001 (left) and 2017 (right). Region circled in red shows a region where there has been easily visible change in land cover.

Land Cover Change: Based on an initial visual analysis of the land cover maps from 2001 to 2017, it appears that there is no large significant change to land cover aside from minor variation in the region north of Lake Tana (fig 4). Due to the fact that the vast majority of deforestation already occurred several decades prior to 2000, it is not surprising that the change in tree cover or crop cover has not visibly changed in the past 20 years, at least in scale to what has previously occurred in the early 1900s. However, it is interesting to note that there is a significant difference in land cover between the western and eastern basins. While the western basin is predominantly shrubland scattered with cropland, the eastern basin is almost exclusively cropland. To better understand the minute changes that have happened within the watershed for the past 20 years, I determined the percentage of watershed for each of the land cover categories (fig 5). Based on the land cover maps, there is a clear increasing trend in the percentage of forest and shrubland/savanna and a distinct downward trend in the crop/pasture. Contrary to what was originally thought, it appears that forst cover in the Lake Tana watershed is increasing along with shrublands and savannas. One potential explanation for this increase is the implementation of a program called REDD+. The program to *reduce emissions from deforestation and forest degradation* (REDD+) is a global initiative born from the United Nations Framework Convention on Climate Change (UNFCCC) in 2005. The objective of the initiative was to mitigate greenhouse gases emissions from developing countries by implementing forest management programs. Figure 5, shows some support for this theory because the percentage of forest and

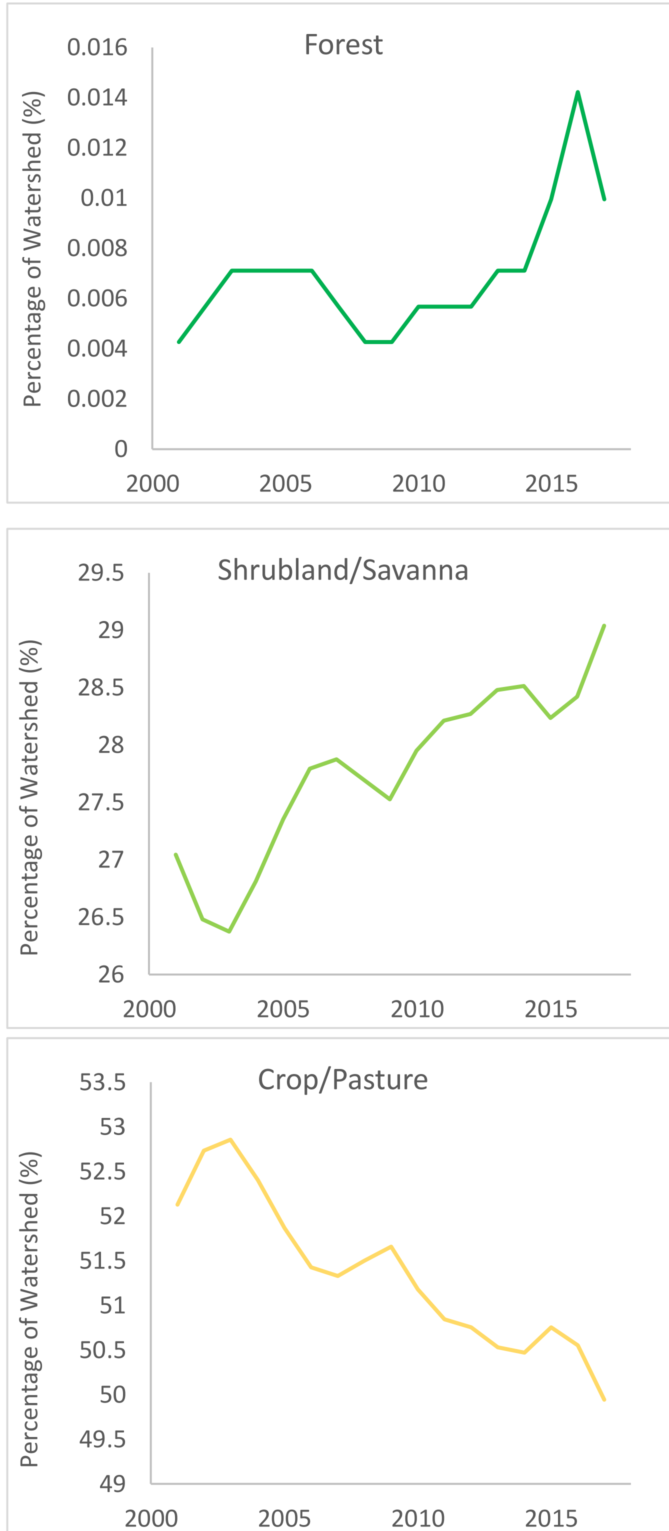

Figure 5. Percent of watershed for three different categories (top) forest (middle) shrubland/savanna, and (bottom) crop/pasture from 2001 to 2017.

shrubland/savanna begin to increase around 2005. Unfortunately, due to the lack of data prior to 2000 there is no reference to confirm whether the increase in forest cover was a product of REDD program in Ethiopia.

Precipitation: Based on the GPCC precipitation data, I did not find any evidence that strongly supports Osman and Sauerborn findings that the region has experienced more severe and frequent precipitation events. Although there are fluctuations in total annual rainfall, there is no distinctive positive trend suggesting increased precipitation (fig 6). Similarly, although the maximum 24-hour precipitation does fluctuate year to year, there is no obvious positive pattern.

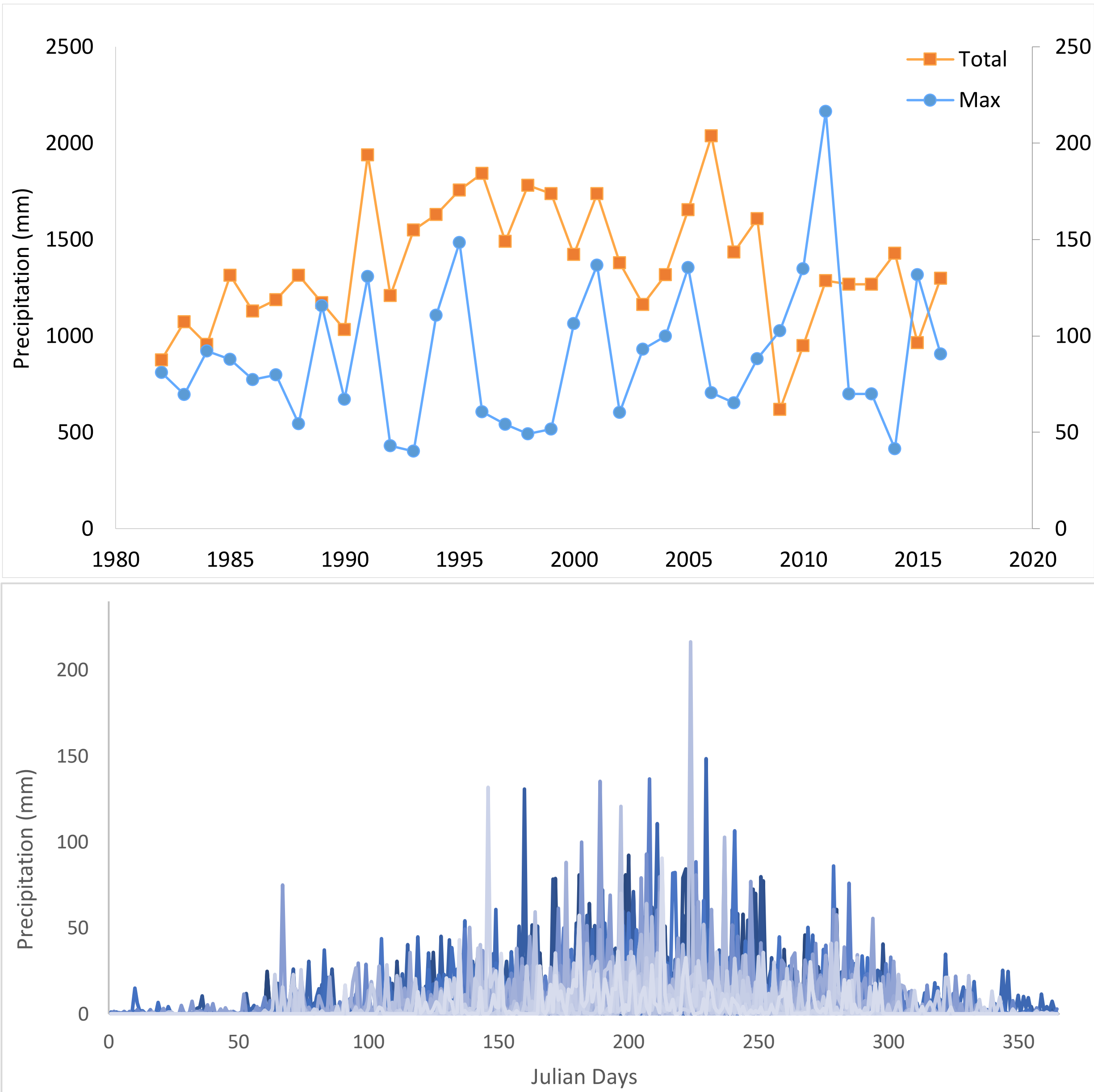

Figure 6. Total annual precipitation and annual 24 hour precipitation maximum from 1982 to 2016 (top). Daily precipitation from 1982 go 2016. The lines are colored from grey to blue in relation to 2016 to 1982.

The daily precipitation data shows us that the Lake Tana watershed experiences its dry season from early December to early March. The wet season last for 9 months extending from March to November with a gradual increase in intensity that peaks around mid-August. In addition to the gradual increase in precipitation till August, there are high precipitation events scattered between end of May till end of September (fig 6).

Total Suspended Solids: To determine the effects of land cover as well as precipitation I determined the total suspended solids for three different years 2000, 2005, and 2010. Total suspended solids were modeled for as many days as possible during the wet season which was dependent on cloud cover and availability of data. In all three years, the TSS signal for the eastern basin is consistently higher than those of the western basin. Furthermore, factoring in that the

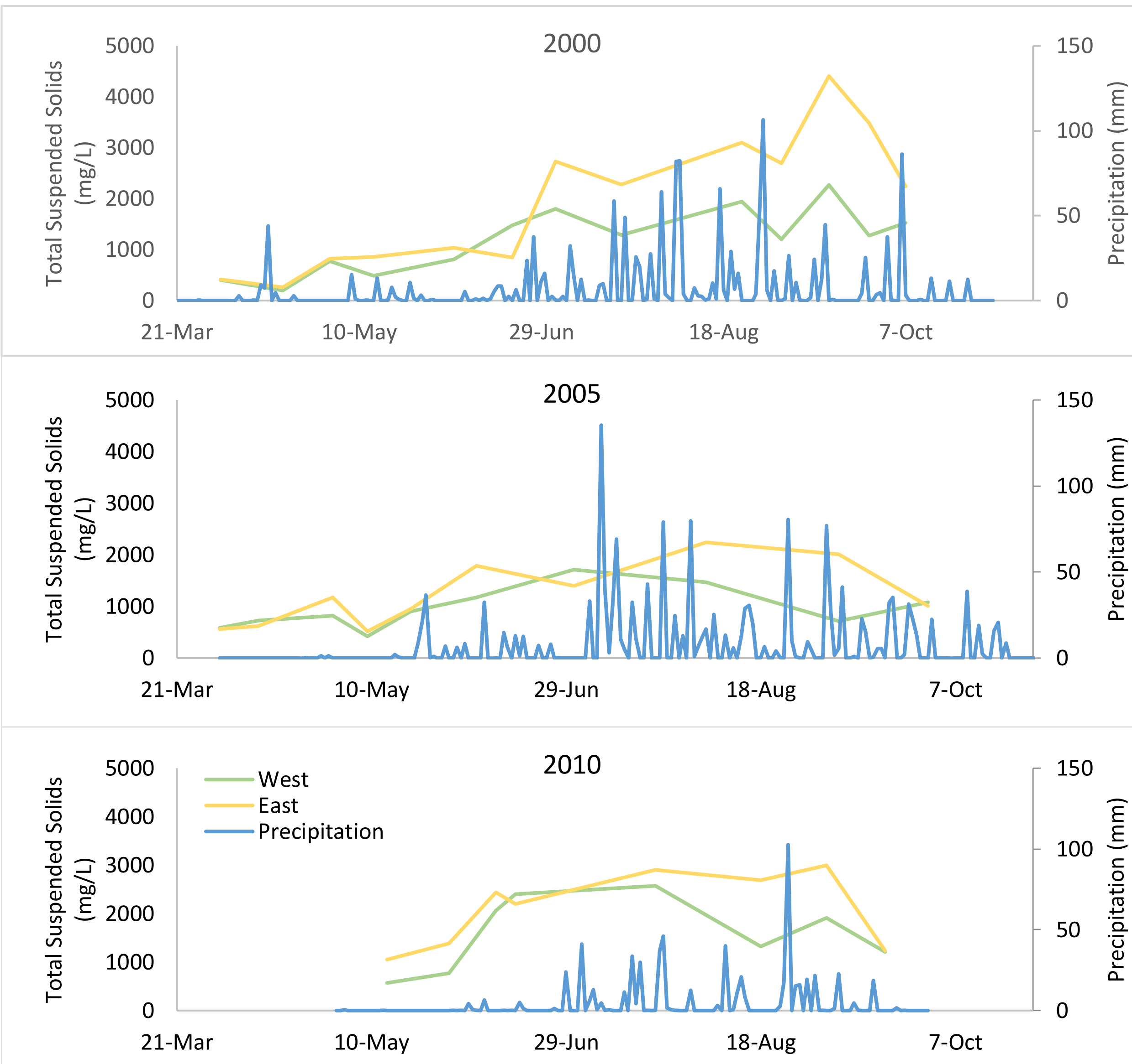

Figure 7. Total suspended solids (mg/L) in the western (green) and eastern (yellow) basins of Lake Tana overlaid with daily precipitation for the catchment.

western watershed covers a larger area than the eastern watershed, the discrepancy between the eastern and western TSS readings suggests a large influence of land cover on the transport of soils to Lake Tana. During strong precipitation events (Sep 3, 2000; Jul 12, 2005) show that eastern Lake Tana responded to higher increase in TSS compared to the western region. In addition to overall higher TSS levels, this suggests that the eastern watershed is less adept at responding to sudden precipitation events due to the lack of plant and root structure to retain soils during these intense episodes. In addition to the western watershed exhibiting lower initial erosion rates, the presence of shrubland land cover may contribute to shortening the effects of precipitation on TSS. After precipitation events (Aug 18, 2005; Aug 18, 2010) the western basin appears to decrease in TSS soon after the precipitation event whereas the eastern basin continues to exhibit high TSS for a longer duration of time.

Conclusion

Lake Tana in Ethiopia has undergone massive environmental changes for the past 100 years. Although the forest was decimated to less than 2% of initial forest cover, satellite data analysis shows promise that the forest is slowly recovering. Whether through the successful implementation of natural forest or developing a forest management strategy overall vegetation is has definitely increase in the past 20 years. More importantly, based on TSS models from the western and eastern lake basin, the presence of shrublands, savannas, and trees results in a significant decrease in TSS. Although the analysis of precipitation for the past 36 years did not support previous studies that suggest an increase in frequency and intensity, there is a clear link between precipitation and TSS in Lake Tana. Especially in situations like this. where environmental events happened several decades ago, utilizing GIS and satellite data can reveal a unique environmental history of these ecosystem.

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