Climate, water and land-use of the Omo-Turkana Basin: opportunities and challenges for sound natural resources management

Authors: Stefaan Dondeyne[1], Gladys Kangi[2], Ine Rosier[2], Henok Kassa[3], Jos Van Orshoven[2]

Authors' affiliations:

[1] Department of Geography, Ghent University, Krijgslaan 281 S8, B-9000 Gent, Belgium

[2] Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, B-3001 Leuven, Belgium

[3] Department of Natural Resources Management, Mizan-Tepi University, PO Box 391, Mizan Teferi, Ethiopia

Abstract

With Lake Turkana at its centre, the Omo-Turkana Basin drains an area of ca. 148,600 km² which, in Ethiopia and Kenya, has huge potential for both hydropower energy and agricultural production. Still, the diverse climate, water, and land resources pose particular challenges for their sound management. In the highlands, the climate is cool and humid while hot and arid around Lake Turkana. The Omo River (Ethiopia) provides ca. 90% of the lake's surface water inflow. In the Ethiopian Highlands, *Nitisols* and *Vertisols* are extensively used for cropland, but deforestation and the conversion of agroforestry to cereal-based cropping lead to accelerated soil erosion. In the lowlands, the expansion of irrigated land results in reduced river discharges. Having no outlet, Lake Turkana is alkaline and slightly saline. A major concern is that a decrease in the lake's inflow may raise the water salinity and jeopardize the artisanal fisheries. Soil and water conservation measures are required in the highlands to safeguard agricultural production but also to minimize sediment load which would compromise the lifespan of the hydropower dams. A minimal inflow of water into Lake Turkana is required to avoid catastrophic salinization which requires monitoring of the irrigation water usage.

Keywords: Lake Turkana, deforestation, hydropower, irrigation, salinization, soil erosion

Klimaat, water en landgebruik van het Omo-Turkana bekken: opportuniteiten en uitdagingen voor een duurzaam landbeheer

Samenvatting

Met het Turkana meer in zijn centrum beslaat het Omo-Turkana-bekken een gebied van ca. 148.600 km² dat in Ethiopië en Kenia een enorm potentieel heeft voor zowel waterkracht-energie als landbouwproductie. Toch vormen de uiteenlopende klimaatomstandigheden, water- en landvoorraden bijzondere uitdagingen voor een goed beheer ervan. In de hooglanden (≥ 1200 m b.z.n.) heerst een koel en vochtig klimaat, terwijl het rond het Turkana meer heet en dor is. De Omo-rivier (Ethiopië) levert *ca*. 90% van de instroom van oppervlaktewater van het meer. In de Ethiopische hooglanden worden *Nitisols* en *Vertisols* op grote schaal gebruikt voor akkerbouw, maar ontbossing en de omschakeling van boslandbouwsystemen naar graanteelt leiden tot versnelde bodemerosie. In de laaglanden (< 1200 m b.z.n.) leidt de uitbreiding van geïrrigeerd landbouw tot verminderde debieten van de rivieren. Het Turkana meer, dat geen waterafvoer kent, is alkalisch en licht zout. Een belangrijk bezorgdheid is dat een vermindering van de instroom van water verzilting in de hand kan werken en de ambachtelijke visserij in gevaar brengen. In de hooglanden zijn maatregelen voor bodem- en waterbehoud nodig om de landbouwproductie veilig te stellen, maar ook om de sedimentbelasting te minimaliseren die de levensduur van de waterkrachtdammen in gevaar zou brengen. Een minimale instroom van water in het Turkana meer is vereist om catastrofale verzilting te voorkomen, hetgeen een nauwe opvolging vergt van het gebruik van irrigatiewater.

Sleutelwoorden: Turkana meer, ontbossing, waterkracht, irrigatie, verzilting, bodemerosie.

Climat, eau et utilisation des terres du bassin de l'Omo-Turkana: opportunités et défis pour une gestion durable des ressources naturelles

Résumé

Avec le lac Turkana en son centre, le bassin de l'Omo-Turkana couvre une superficie d'environ 148 600 km² présentant un énorme potentiel pour la production hydroélectrique et agricole en Éthiopie et au Kenya. Cependant, la diversité des ressources en climat, en eau et en terre pose des problèmes particuliers pour leur bonne gestion. Dans les hautes terres, le climat est frais et humide alors qu'il est chaud et aride autour du lac Turkana. Le fleuve Omo (Éthiopie) fournit environ 90 % des apports d'eau de surface du lac. Dans les hauts plateaux éthiopiens (≥ 1200 m d'altitude), les *Nitisols* et les *Vertisols* sont largement utilisés pour les cultures, mais la déforestation et la conversion de l'agroforesterie en systèmes de cultures dominé par les céréales entraînent une érosion accélérée des sols. Dans les basses terres (<1200 m), l'expansion des terres irriguées entraîne une réduction des débits des cours d'eau. N'ayant pas d'exutoire, le lac Turkana est alcalin et légèrement salin. Une diminution de l'apport d'eau au lac risque d'augmenter la salinité et de mettre en péril la pêche artisanale. Des mesures de conservation des sols et de l'eau sont nécessaires dans les hautes terres pour préserver la production agricole mais aussi pour minimiser les charges de sédiments qui compromettraient la longévité des barrages hydroélectriques. Un apport minimal d'eau dans le lac Turkana est nécessaire pour éviter une salinisation catastrophique, ce qui exige un suivit de l'utilisation de l'eau d'irrigation.

Mots clés : Lac Turkana, déforestation, hydroélectricité, irrigation, salinisation, érosion des sols.

Used abbreviations

a.s.l.	Above sea level
AHI	Aridity/Humidity Index
ET_0	Evapotranspiration
P	Precipitation
RSG	Reference Soil Group
WRB	World Reference Base for soil resources

Introduction

The Omo-Turkana Basin is an endorheic basin in East Africa that drains to the world's largest desert lake (Tebbs *et al.*, 2019). However, both fossilized zoogeographical remnants and former lake levels indicate that the Omo-Turkana basin was once directly connected to the White Nile (Kolding, 1992). The outlet was at the north-western end of the lake, where currently the elevation of the then sill is at an elevation of *ca*. 455 m a.s.l., i.e. about 90 m higher than the current lake level. The final decline from a high stand of 90 m above the present lake would have begun 5200 years ago (Bloszies *et al.*, 2015).

This transboundary basin encompasses highlands of mountainous plateaus and volcanoes as well as steep valleys and plains in the lowlands and spans an area of approximately 148,600 km², mainly between Ethiopia and Kenya. Lake Turkana falls in-between the northern dome forming the Ethiopian Highlands and a southern dome forming the Kenyan Highlands (Figure 1). Mount Elgon (4310 m a.s.l.) is the highest point of the basin and is located in the southwest on the border between Kenya and Uganda. The Omo River, which has its source in the Ethiopian Highlands where Mount Gurage reaches 3719 m a.s.l., contributes up to 90% of the inflow in Lake Turkana (Avery, 2010). Downstream from its confluence with the Gibe River, the Omo River runs through a steep and narrow valley before reaching the plains in the Lower Omo valley. When reaching Lake Turkana, the river forms a bird's foot type of delta. The delta forms lobes that protrude into the lake as the lake's currents are too weak to disperse the sediments. The Omo-Turkana Basin can be divided into (i) Omo-Gibe subbasin that covers *ca*. 70,120 km² and comprises of the Omo River and tributaries, and (ii) the remaining area draining straight to Lake Turkana that covers *ca*. 78,480 km², and with the Turkwel River and Kerio River as major rivers.

In the past, the basin's lowlands in both Ethiopia and Kenya had been given low priority for development. However, since the turn of the 21st century, dynamics have changed: hydropower dams have been built, irrigated agriculture is expanding, and consequently river flows have been altered. To contextualize this rapid development, we reviewed the literature on climate, water and land-use to obtain a basin-wide view of the opportunities and challenges towards sound management of the basin's natural resources. This review was initially drafted in the framework of the DAFNE project (https://dafne.ethz.ch/) that aimed at developing a "Decision Analytic Framework to explore the water-energy-food Nexus in complex transboundary water resource systems". The Omo-Turkana Basin was one out of two transboundary basins taken as study areas; the other one being the Zambezi River Basin in southern Africa. As the range of topics is wide, a snowball strategy was followed to identify key papers and reports. When specific information was lacking as e.g. on climate characteristics, soil geography, variation in water level and size of Lake Turkana, the occurrence and extent of irrigation schemes, or trends in land-use and deforestation, we analysed publicly available data that was compiled in the course of the project. We build on prior insights and knowledge acquired through research in and around the basin, most particularly in the upper reaches of the Omo-Gibe subbasin around Jimma and Mizan Tefferi and the surroundings of Arba Minch in Ethiopia, and along the Turkwel and Kerio rivers in Kenya.

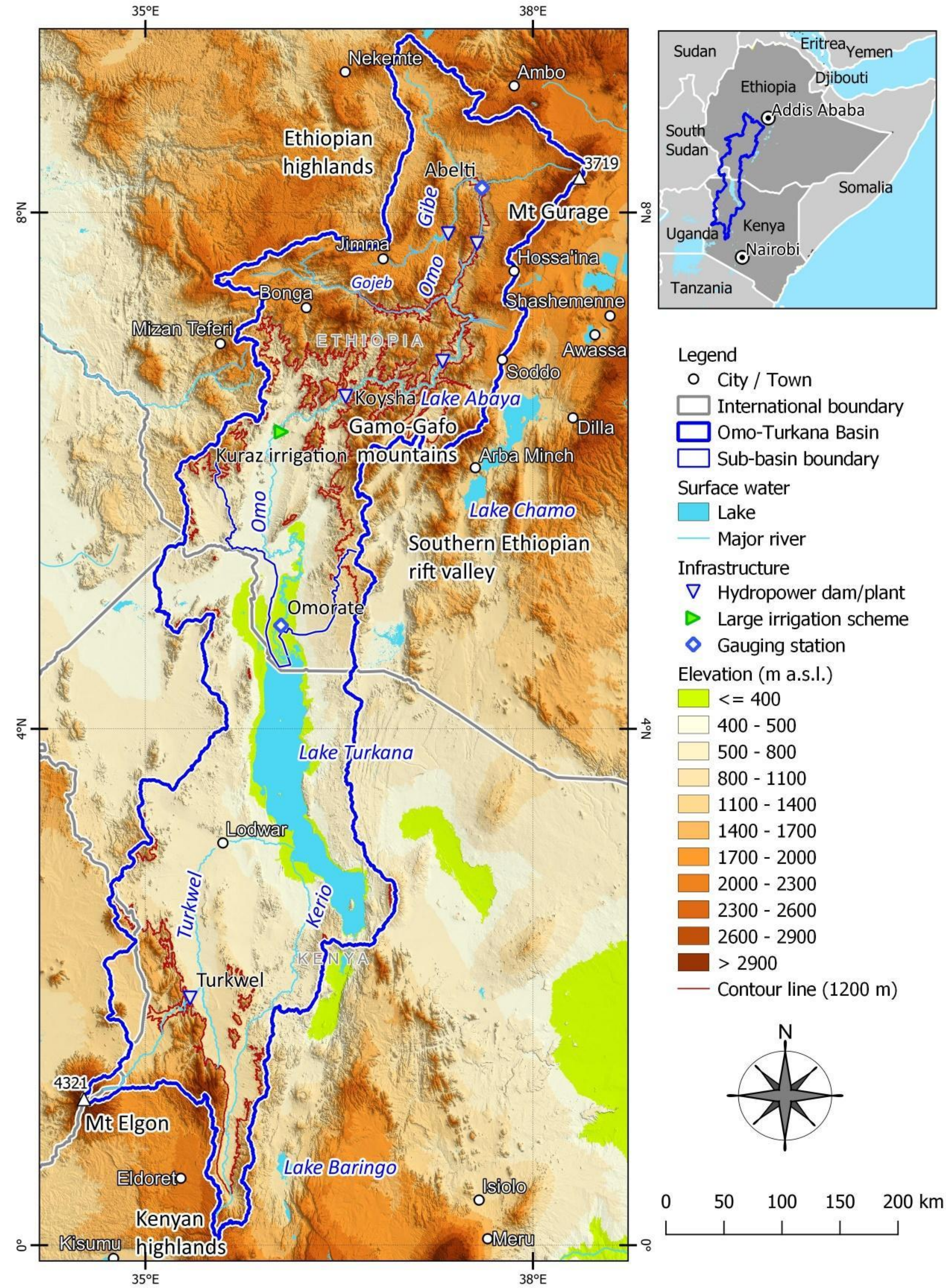

Figure 1 – Topography and major physiographic units of the Omo-Turkana Basin. At 4321 m.a.s.l, Mount Elgon on the border between Kenya and Uganda is the highest point in the basin while Lake Turkana at 365 m.a.s.l is the lowest point. [Authors' map, based on Global Multi-resolution Terrain Elevation Data 2010 - https://earthexplorer.usgs.gov/; Surface water based on the JRC Global Surface Water data - https://global-surface-water.appspot.com]

Climate

As is typical for tropical regions, differences between seasons in the Omo-Turkana Basin are principally determined by variation in rainfall and much less so by variation in temperature. The intra-seasonal variation in rainfall has often been attributed to the passing of the Intertropical Convergence Zone (ITCZ) (Fazzini *et al.*, 2015). However, the paradigm that the two rainy seasons occurring in Africa's equatorial regions are the result of the biannual equatorial passage of the ITCZ cannot be substantiated (Nicholson, 2017, 2018). However, the highlands in East Africa give rise to mesoscale convective systems that propagate westward and traverse the equatorial latitudes. Furthermore, large-scale phenomena such as the Madden-Julian oscillation and vertical cells over the Indian Ocean play a role in the timing and amount of the seasonal rainfall (Nicholson, 2017, 2018). Kenya, Tanzania, Uganda, Rwanda, and Burundi are all covered by a bimodal rainfall regime, with peaks in both the boreal spring and autumn. In contrast, in most of Ethiopia and Somalia, the rainfall peaks in the boreal summer (Yang *et al.*, 2015; Nicholson, 2017). The Omo-Turkana Basin, which connects these two zones through the topographic depression where Lake Turkana is located, is bound to have climate characteristics from both zones.

As the WorldClim data for 1970-2000 (Fick & Hijmans, 2017) indicate, the Ethiopian Highlands in the north, as well as the Kenyan Highlands in the south, have a cool and humid climate, while the central part of the basin surrounding Lake Turkana is hot and arid (Figure 2). The Aridity/Humidity Index (AHI) was proposed by the United Nations Environmental Programme (UNEP, 1992). It is calculated as the ratio of average annual precipitation (P) to reference (or potential) evapotranspiration (ET_0). Six climatic zones can be recognized using the Aridity/Humidity Index, ranging from humid ($AHI > 1$) in the highlands to hyper-arid ($AHI < 0.1$) around Lake Turkana (Figure 2b). Before reaching Lake Turkana in Ethiopia, the Omo River passes through humid and sub-humid terrain, followed by a semi-arid country. The Turkwel and Kerio Rivers in Kenya run across a huge area of semi-arid to arid land before reaching Lake Turkana in a hyper-arid region of the basin (Figure 2).

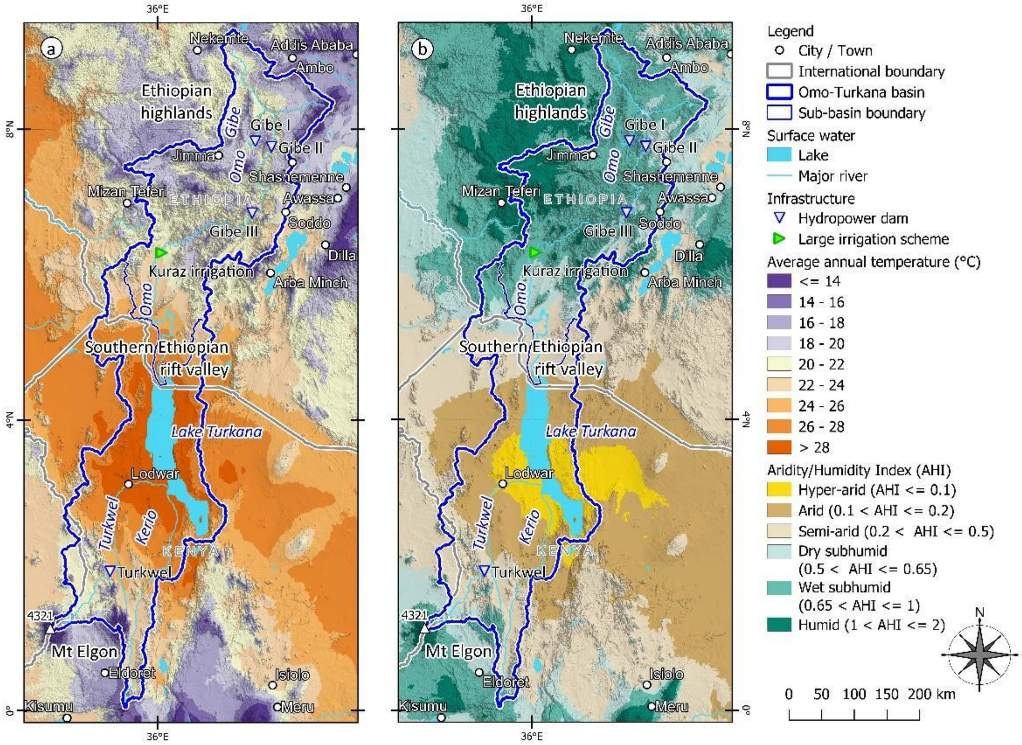

Figure 2 – (a) Average annual temperature and (b) Aridity/Humidity Index of the Omo-Turkana Basin and surrounding areas. The Ethiopian Highlands have a cool and humid climate, while the lower part of the Omo-Gibe subbasin in Ethiopia and the major part of the Turkwel-Kerio-Turkana Basin in Kenya have a hot and arid to hyper-arid climate. [Authors' map based on: WorldClim version 2.1 for Temperature - https://www.worldclim.org/ ***and Aridity/Humidity Index from Global Potential Evapotranspiration and Global Aridity Index -*** https://cgiarcsi.community/***; Global Surface Water from EC JRC/Google]***

The variation of the monthly precipitation and evapotranspiration data is illustrated for three stations in the Omo-Gibe subbasin and three stations in the Turkwel-Kerio-Turkana representing stations ranging from humid to hyper-arid climates (Trabucco & Zomer, 2019) (Figure 3). Although monthly rainfall follows a unimodal pattern in general, the precipitation maps show that around Lake Turkana, a first peak comes from March to May, when rainfall is higher than the preceding months, and a second peak occurs around October and November. In the highlands, where precipitation exceeds the actual evapotranspiration, infiltrating water gives rise to perennial streams as the Omo River. The length of a growing season is commonly defined as the months during which the precipitation exceeds half the reference evapotranspiration ($ET_0/2$) plus a period required to evapotranspire an assumed 100 mm of water from excess precipitation (or less if not available) stored in the soil profile (FAO, 1978; Jones *et al.*, 2013). As the data of Mizan-Teferi illustrates (Figure 3), in the humid zone of the basin the length of the growing period is 9 to 10 months. In the subhumid zone, as at the Kuraz irrigation scheme and in Eldoret, the length of the growing period is 7 to 8 months long. In contrast, in Omorate or at the Turkwel dam, which are in the semi-arid zone, precipitation merely exceeds $ET_0/2$ during one or two months. In the hyper-arid zone, as in Lodwar, monthly precipitation remains considerably below $ET_0/2$. The implication is that agricultural production can only take place when supplementary water is provided in these dry areas. In the lower Omo valley, farmers have been taking advantage of recurrent floods to practice flood-recession agriculture (Carr, 2017; Hodbod *et al.*, 2019b; Amos *et al.*, 2021). However, the construction of dams for both hydropower and irrigated agriculture reduces the occurrence of such floods.

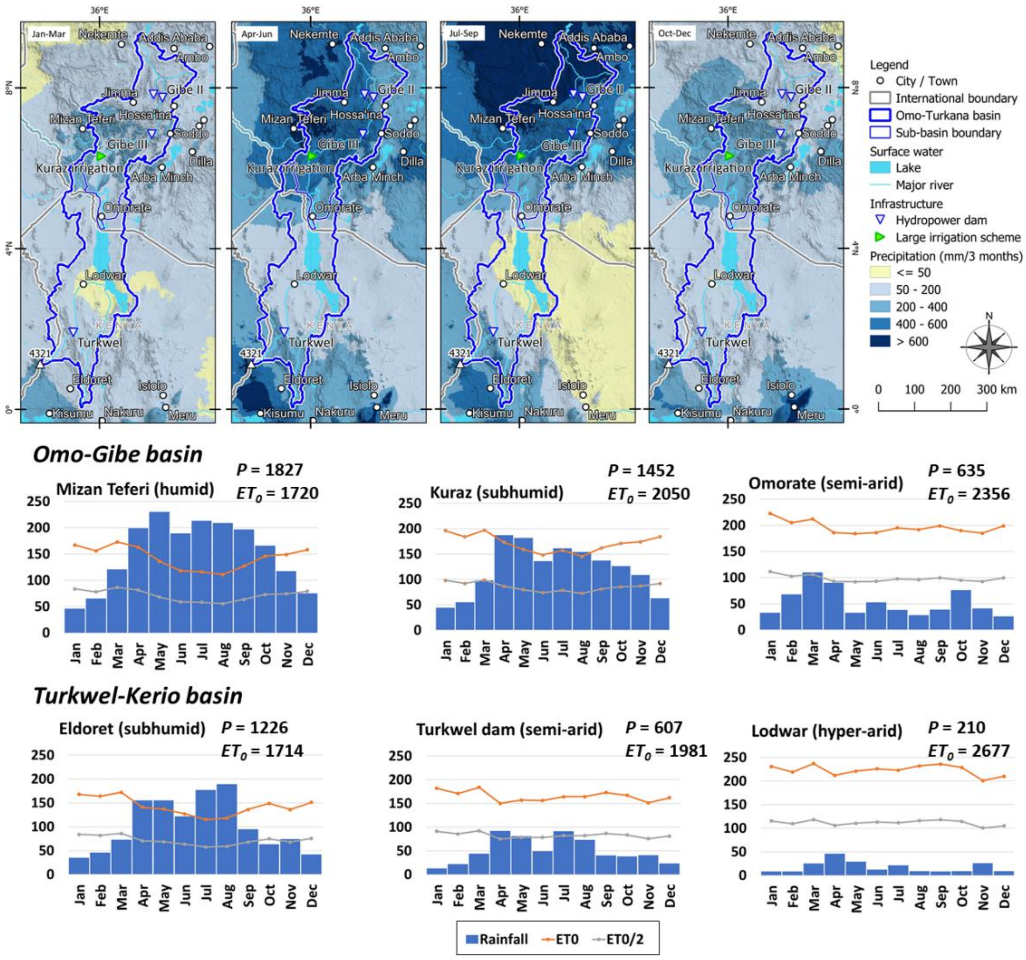

Figure 3 – Seasonal rainfall patterns over the Omo-Turkana Basin and surrounding areas. The peak of the rainy season is between April/May and Aug/Sep. Rainfall is markedly higher in the Ethiopian Highlands, and exceeds the Reference Evapotranspiration (ET_0). Precipitation remains low year-round around Lake Turkana. [Authors' map and graphs based on: Precipitation from WorldClim - https://www.worldclim.org/; ET_0 from Global Potential Evapotranspiration; Global Aridity Index - https://cgiarcsi.community/; Global Surface Water from EC JRC/Google]

Geomorphology and soils

The widespread occurrence of flood-basalts and the formation of the East African rift valley are key for understanding the geomorphology and soil geography of the Omo-Turkana Basin. Flood-basalts appeared already at the beginning of the breakup of Gondwana (*ca*. 320 million years ago). However, a more prolific outpouring of trap flood basalts took place during the Oligocene (*ca*. 30 million years ago). These basalts covered a low-relief land surface of modest elevation over more than 750,000 km² and predate the development of the East African rift valley, which began around the Miocene (22-25 million years ago) (Ebinger, 2005; Abbate *et al.*, 2015). The East African rift valley developed mostly during the Pliocene and early Pleistocene (*ca*. 6 to 2 million years ago). Besides the formation of the rift valley, this process went along with tectonic uplifting of the rift margins leading to the creation of the Ethiopian and Kenyan highlands. The rifting and tectonic activity were accompanied by widespread volcanic activity (Ebinger, 2005; Koptev *et al.*, 2016).

The Harmonised Soil Map of Africa (Jones *et al.*, 2013; Dewitte *et al.*, 2013), indicates 21 Reference Soil Groups (RSG) which occur in the Omo-Turkana Basin (Figure 4). In WRB, soils are classified into two hierarchical tiers with the "Reference Soil Groups" at the highest level (Schad & Dondeyne, 2016). The RSGs reflect dominant soil-forming processes or main soil regions and can therefore be regrouped accordingly. These features, together with these soil groups' major potentials and constraints for land husbandry are summarized in Table 1.

Tectonic uplifting, volcanism, and rift formation have led to a rejuvenation of the soils, leading to more fertile soil than one might expect. The highest parts of the Omo-Gibe subbasin are dominated by volcanic ejecta in which *Andosols* are formed. Generally, these soils have a high permeability for water and are therefore not very susceptible to water erosion while they have moderate to high chemical fertility. In the Turkwel subbasin, *Andosols* occur along with *Histosols* in the highest parts of Mount Elgon. *Histosols*, found in poorly drained areas, are soils dominated by organic material. Though the scale of the current soil map does not allow to indicate these, large swamps with *Histosols* are found north of the city of Bonga and along the Gojeb River in the Kafa Biosphere Reserve (Dresen *et al.*, 2015). These swamps retain large amounts of water and they play an important role in the hydrology.

Nitisols are the most widely mapped RSGs (Figure 4 a & b). These are deep, well-drained soils with high clay content (30-80%) and with kaolinite and (meta)halloysite as the dominant clay assemblage. Along with hematite, goethite, and gibbsite, minor amounts of illite, chloritized vermiculite, and irregularly interstratified clay minerals may be present. In the fine earth fraction, *Nitisols* contain 4% or more 'free' iron (Fe by dithionite-citrate extraction) and more than 0.2% 'active' iron (by acid oxalate extraction at pH 3) (Driessen *et al.*, 2001). These soils are typically formed from basaltic or volcanic rocks at mid-range altitudes and have a characteristically well-developed and strong soil structure. The chemical fertility of *Nitisols* is rather limited, but their very favourable physical properties make that these soils are suited for agriculture and are particularly well suited for arabica coffee (*Coffea arabica* L.) (Driessen *et al.*, 2001; Kassa *et al.*, 2017a). On similar parent material but at lower altitude, where the climate is warmer and has a pronounced dry season, *Vertisols* develop. Characteristic for *Vertisols* is the presence of smectite clays, which make the soil to shrink and crack when it dries and to swell when the soil is wetted (Figure 4 c & d). These soils have low workability as they are hard when dry and very sticky when wet. Moreover, the wide cracks formed during drying make them susceptible to pipe and gully erosion (Driessen *et al.*, 2001; Frankl *et al.*, 2012).

Weakly developed soils can be found at even lower elevations, especially at locations where soil erosion has occurred (*Cambisols*, *Regosols,* and *Leptosols*). In the driest areas soils are found where carbonates and soluble salts have accumulated (*Calcisols*, *Solonetz*, and *Solonchaks*).

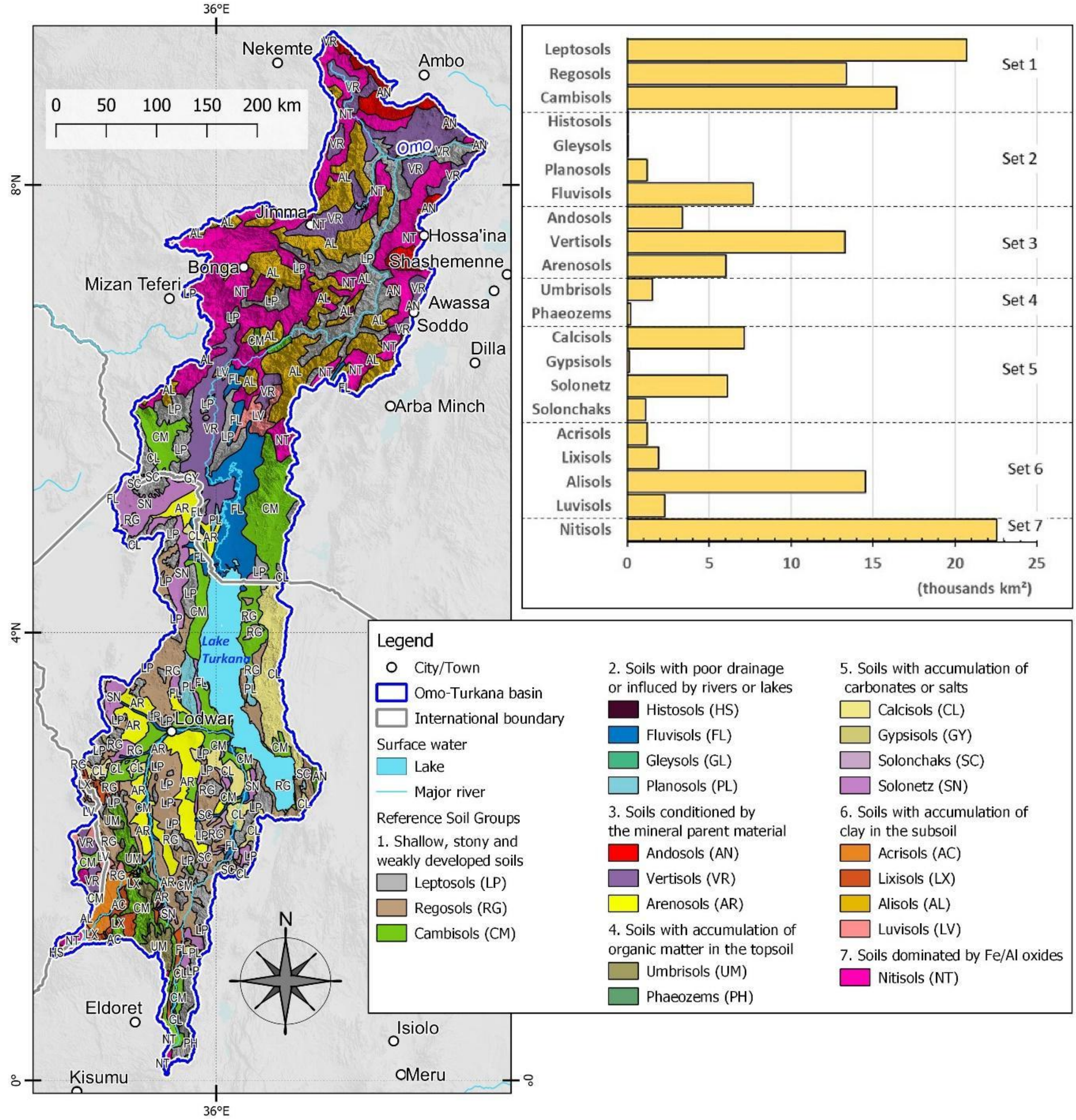

Figure 4 – Map of the dominant Reference Soil Groups (RSGs) of the Omo-Turkana Basin following the 2nd edition of WRB (IUSS Working Group WRB, 2007) and area of the mapping units of the dominant RSGs. See Table 1 for the principal properties, potential and constraints of each RSG [Authors' map and calculations based on: Dewitte et al., 2013; Jones et al., 2013]

Table 1 – Reference Soil Groups occurring in the Omo-Turkana Basin grouped into sets according to their dominant identifier and properties representing potential and constraints for land husbandry

	Reference Soil Groups	Principal identifier	Potential	Constraint
Set 1	Leptosols (LP), Regosols (RG), Cambisols (CM)	Weakly developed, shallow soils	Good chemical fertility	Limited soil depth (LP)
Set 2	Histosols (HS), Gleysols (GL), Planosols (PL), Fluvisols (FL)	Impeded internal drainage, or formed by river and lake deposits (FL)	Good chemical fertility	Water saturated; flooding, risk for salinization
Set 3	Andosols (AN), Vertisols (VR), Arenosols (AR)	Properties determined by parent material	Good water holding capacity and chemical fertility (AN, VR)	Susceptible to water erosion (AN, VR) Low water-holding capacity, low fertility (AR)
Set 4	Umbrisols (UM), Phaeozems (PH)	Humus rich surface horizons	Good infiltration capacity; good fertility (PH)	High acidity (UM)
Set 5	Calcisols (CL), Gypsisols (GY), Solonetz (SN), Solonchaks (SC)	Accumulation of carbonates (CL), sulfates (GY) and salts (SN, SC)	Good fertility (CL, SN)	Susceptible to water and wind erosion Alkalinity and/or high salt content
Set 6	Acrisols (AC), Lixisols (LX), Alisols (AL), Luvisols (LV)	Accumulation of clay in the subsoil	Good fertility (LX, LV)	High acidity (AC, AL)
Set 7	Nitisols (NT), Ferralsols (FR), Plinthosols (PT)	Highly weathered soils with high levels of aluminium and iron oxides	Good physical properties (NT, FR)	Susceptible to landslides (NT), low chemical fertility (FR, PT)

(Authors' own synthesis based on (Driessen *et al.*, 2001; Schad & Dondeyne, 2016)

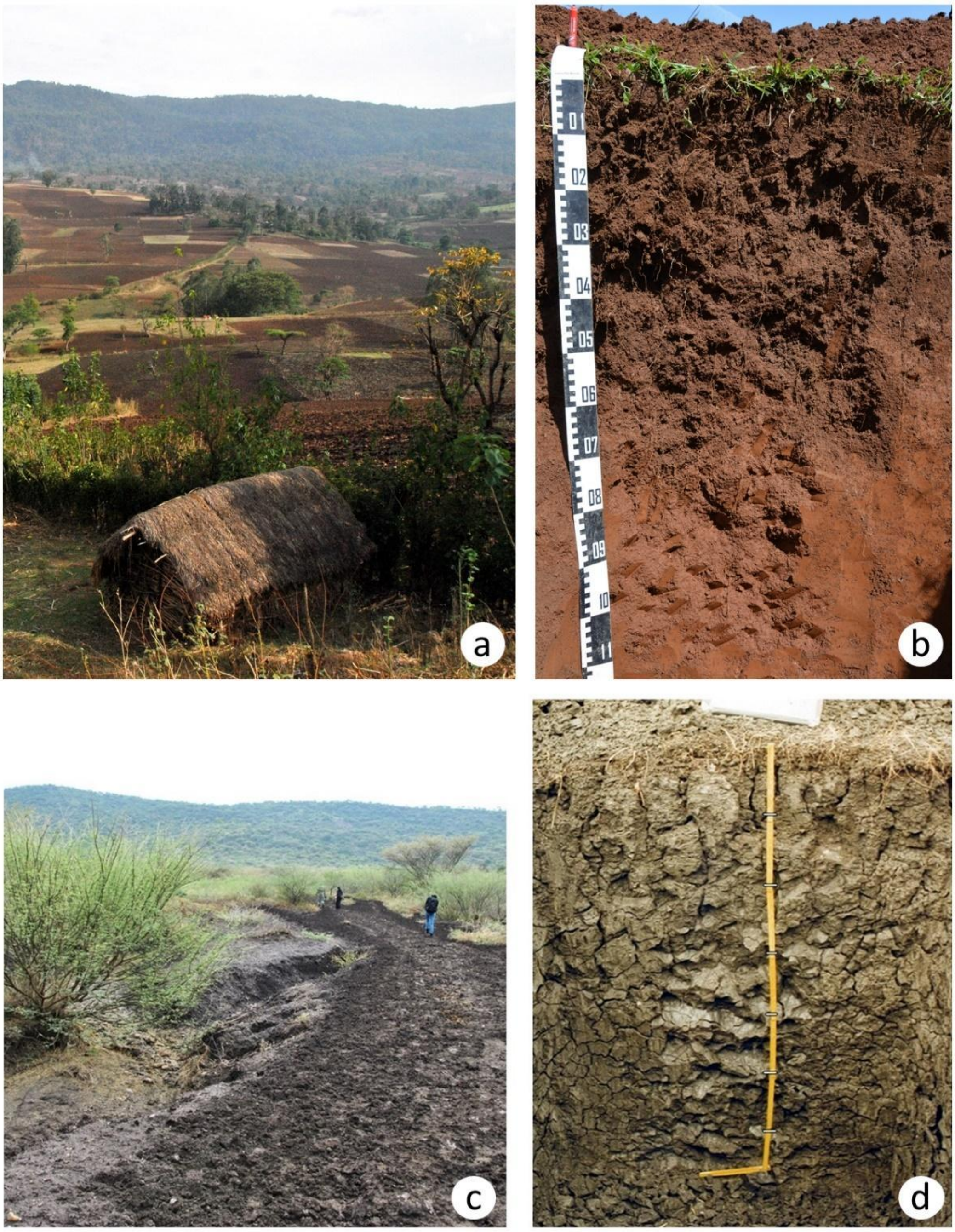

Figure 5 – (a) Landscape of Nitisols on the south-western Ethiopian Highlands (near Bonga); (b) a soil profile of a Nitisol showing its reddish colour is ascribed to Fe oxides. It owes its properties good for agriculture to its strong soil structure (Gamo-Gafo Mountains). (c) Gully erosion in a landscape of Vertisols in southern Ethiopian Lowlands (Nechisar National Park); (d) a soil profile with obvious cracks and slickensides formed by shrinking (when drying) and swelling (when wetting) of these soils dominated by smectite clays. These properties render these soils particular sensitive to gully erosion [Photos: S. Dondeyne]

Potentials and challenges for natural resource uses

Water resources

The main source of water for Lake Turkana is provided by the precipitation in the Ethiopian Highlands. The Omo River contributes 80 to 90% of the surface inflow in Lake Turkana while 6 to 10% of the surface input is provided by the seasonal Turkwel and Kerio Rivers together with the other littoral rivers (Yuretich & Cerling, 1983; Avery & Tebbs, 2018). The remaining inflow comes from rainfall above the lake, which has been estimated to be around 340 mm/year for the period 1993-2014 (Avery & Tebbs, 2018). At Abelti, in the upper reach of the Omo-Gibe subbasin (see Figure 1 for location), the mean annual flow is 190 m^3/s but between August and September peak discharges can be as high as 1000 m^3/s (Chaemiso *et al.*, 2016). There is a scarcity of data for the basin's lowest reaches with only one station which has been operational for four years (1977-1980) at Omorate. The average annual discharge upstream of the Omo Delta has been estimated to be between 500 and 800 m^3/s, or 15.8 to 25.2 km^3/year (Avery, 2012; Avery & Tebbs, 2018). Based on rainfall-runoff relations, the median annual discharge for 2004-2014 has been estimated to be 856 m^3/s, with an interquartile range of 143 m^3/s (HWRM-ETHZ, 2019). The Turkwel River flows from Mount Elgon's north-eastern slopes, first through the highlands that constitute the rift valley's shoulder, and then along the rift edges before reaching Lake Turkana (Adams, 1989). Average monthly discharges in the upper reaches of the Turkwel vary between 9.6 and 21 m^3/s while this decreases even further due to infiltration and evaporation losses in the lower reaches of the river (Stave *et al.*, 2005). The Kerio River runs along the fault lines in the rift valley and has various springs at the base of the escarpment separating the Kenyan highlands and the rift valley in which Lake Turkana is found (Cerling & Powers, 1977; Adams, 1989).

The average depth of Lake Turkana is 30 to 35 m, although the maximum depth is beyond 100 m (Odada *et al.*, 2003) and the lake's volume is estimated at 245 km^3. The lake level, and hence the lake volume, is, however, subject to significant seasonal and interannual changes (Yuretich & Cerling, 1983). Based on satellite images of 1990 to 2018, we determined the size of the lake with the Iterative Self-Organizing Data Analysis Technique Algorithm (ISODATA[1]) using Google Earth Engine (Gorelick *et al.*, 2017). The median lake area was 7,223 km^2, with a minimum of 6,978 km^2 in 1996 and a maximum of 7,536 km^2 in 2016.

Interannual fluctuations in the lake level for the period 1992-2020 are shown in Figure 6a. Variations in the Omo River's discharge cause seasonal oscillations in the lake's water level, with the lake level peaking in November. As a result, the delta is a tremendously dynamic environment that expands and contracts in response to changes in lake level and river sediment load (Figure 6b). When the Gibe

[1] ISODATA is an unsupervised spectral cluster classification approach for picture pixels. Each cluster represents a collection of pixels with comparable spectral properties. It is a modified k-means clustering algorithm, first determining the means of N arbitrary established number of clusters based on the bands' means and standard deviations in the input file. "N" is a number specified by the user, and essentially is the number of classes the user tries to. Each pixel is then assigned to the "nearest" cluster using a minimum distance criterion. The cluster means are then recalculated, and each individual pixel is compared to the new cluster means and allocated to the closest cluster a predetermined number of iterations (Irvin *et al.*, 1997; Rahman, 2015).

III reservoir was being filled, between January 2015 and January 2017, the level of Lake Turkana dropped by about 1.5 m (Figure 6a). This drop is within the range of the lake's natural variation, yet because of the high rainfall over the last years, the lake level was in 2020 higher than any time since 1992.

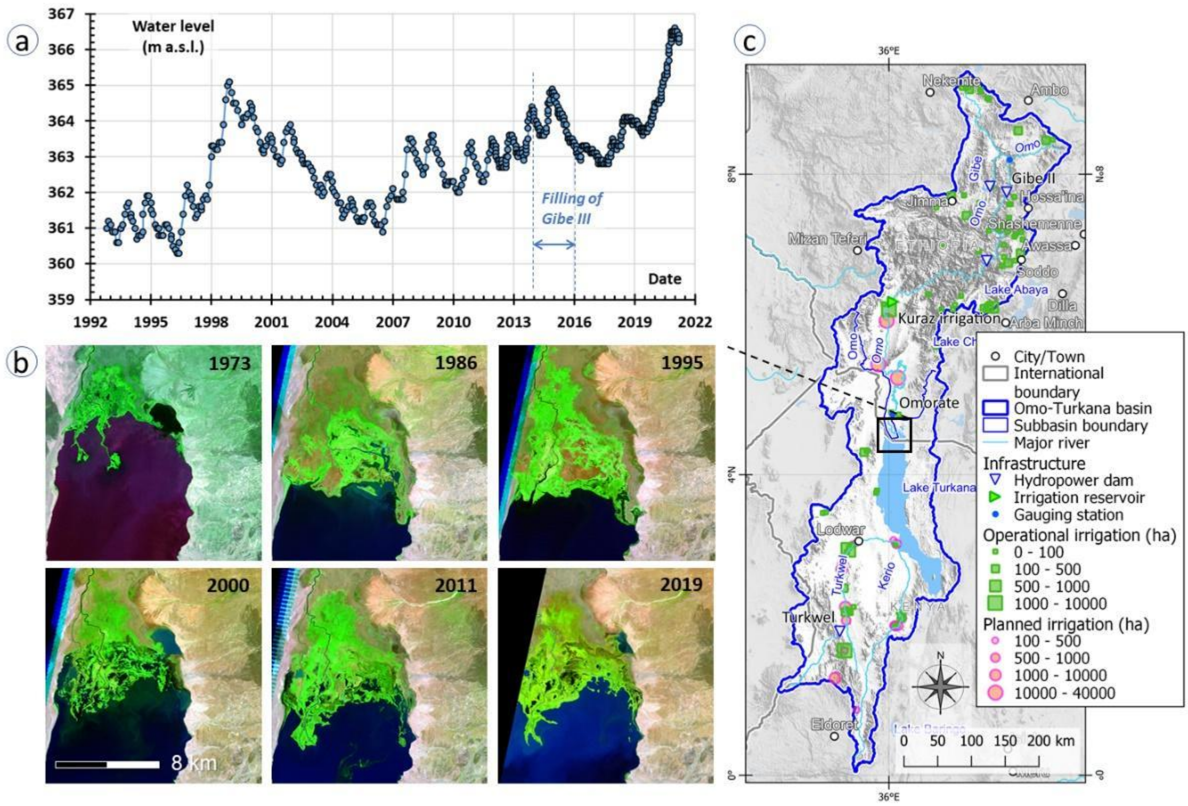

Figure 6 – (a) Fluctuation of Lake Turkana water level for the period Oct. 1992 to Mar. 2021. (b) Changes in extent of the Omo Delta seem to be affected by both fluctuation of the lake level and sediment load. (c) Sites with operational and planned irrigation schemes
[Authors' map based on: lake levels http://hydroweb.theia-land.fr*; satellite images* https://earthshots.usgs.gov/earthshots/Lake-Turkana*; irrigated areas: (Van Orshoven & Rosier, 2019); Global Surface Water from EC JRC/Google]*

The Omo River's perennial flow presents a tremendous potential for hydropower, as between the Gibe I dam and Lake Turkana the elevation descends around 1,300 m over less than 1,000 km . This potential has so far been realized in three hydropower plants: the Gibe I dam (184 MW), a bypass feeding a hydropower plant at Gibe II (420 MW), and the large hydropower dam at Gibe III (1870 MW), which was finished in 2016 (Zaniolo *et al.*, 2021). The Koysha hydropower dam (2160 MW), is a fourth dam and should be completed in 2023 (ENA, 2020). As the river discharges are much lower in the Turkwel-Kerio-Turkana subbasin, the potential for hydropower is markedly lower. Only one hydropower dam (106 MW) has been built in the Turkwel Gorge in the late 1980s, at the edge of the escarpment (Zaniolo *et al.*, 2021).

The three major rivers that directly feed Lake Turkana – Omo, Turkwel and Kerio – also supply water for irrigation schemes. Based on recent reports and detailed satellite imagery from 2018 accessible through Google Earth (Van Orshoven & Rosier, 2019), *ca*. 16,500 ha have been identified as being under irrigation of which 12,500 ha are in the Omo-Gibe subbasin and 4,000 ha in the Turkwel-Kerio-Turkana subbasin (Figure 6c). Eighty percent of the irrigation schemes in the Omo-Gibe subbasin are smaller than 100 ha, and are mostly in the basin's upper reaches. In the lower Omo valley, the Kuraz sugarcane irrigation scheme, the largest in the basin, covers already 7,000 ha. The state-owned Ethiopian Sugar Corporation started this irrigation scheme in 2011 and it is still under development. According to the company's most recent report (Ethiopian Sugar Corporation, 2019), the irrigated area has since expanded to 16,000 ha with another 14,000 ha of land made irrigable. Initially, the Ethiopian Sugar Corporation was given more than 245,000 ha of land, but when the quality of the land for sugarcane was re-assessed, this was first lowered to 175,000 ha and subsequently to 100,000 ha (Kamski, 2016; FDRE, 2018).

In the lower reaches of the Omo River flood-recession agriculture is a common practice and is of high importance to the livelihoods of the Dasanech people (Amos *et al.*, 2021; Kleinschroth *et al.*, 2021). Damming of the Omo River has however affected the continuation of the flood-recession agriculture and as a consequence, more people have settled in the northern parts of the Omo Delta (Amos *et al.*, 2021). As the extent of the flooded area decreases, evapotranspiration losses from flooding will also be reduced. However, the Global Surface Water data of the lower Omo valley indicates that not more than 4,000 ha is susceptible to seasonal flooding (Pekel *et al.*, 2016) and estimates of the areas which were actually recurrently flooded range between 500 ha and 2,000 ha (HWRM-ETHZ, 2019).

Lake Turkana is East Africa's most saline lake with a normal fish fauna; the water is alkaline (pH 8.6 – 9.4) and semi-saline (EC 3.5 mS/cm; TDS 2.5 g/l). The salinity level puts molluscs on the verge (Yuretich & Cerling, 1983; Ojwang *et al.*, 2018). Given the lake's endorheic nature, scholars have expressed alarm about the danger of rising salinity if additional water from the Omo River is used for irrigation. Increased salinity, it has been asserted, will alter the lake's ecology and imperil artisanal fishing, which directly benefits approximately 200,000 people (Avery and Tebbs, 2018; Hodbod et al., 2019a; Ojwang et al., 2018).

Predicting the impact on the fisheries of increased water abstraction is however a complicated matter. First, 40% of the catches are of Nile tilapia (*Oreochromis niloticus*), Nile perch (*Lates niloticus*) and catfish (*Synodontis schall*), which are species that hardly would be harmed by increased salinization. Other species could however be strongly affected (Gownaris *et al.*, 2015). Secondly, Avery and Tebbs, (2018) modelled the impact of several rates of water abstraction from the Omo River: with a 54% abstraction rate, the lake level would decrease by 15 m over 10 years, whereas at a 27% abstraction rate, the lake level would drop by 5 m. Gownaris *et al.* (2017) estimate that fisheries would decrease by two-thirds if water levels would drop by 25 m. However, the gross water requirements for the planned 100,000 ha irrigation scheme will vary from 1.1 to 1.9 km^3/year (Van Orshoven & Rosier, 2019). If, as a conservative estimate, we assume an annual average discharge of

500 to 800 m³/s, the abstraction will represent not more than 4% to 12% of the river discharge. Thirdly, changes in the water quantity will affect the water chemical balances as Ca^{2+} can precipitate as calcite, K^+ can lead to the formation of illite clays, and Na^+ and Mg^{2+} can be removed as exchangeable cations on smectites (Yuretich & Cerling, 1983). Smectites, as explained earlier, are clays that are characteristic of *Vertisols* which occur over vast areas in Omo-Gibe subbasin. Therefore, the assumption that a reduction in the lake's water volume would result in a dramatic increase in salinization as argued by Gownaris *et al.* (2017) or by Avery & Tebbs (2018) may not be correct. As predicting the outcome of these hydrogeochemical processes in a lake is very difficult, the proportion of water abstraction needs to be monitored as well as the evolution of the lake’s water quality.

Land-use and land cover change

Land-use in the Omo-Turkana Basin basin is a reflection of both climate variability and soil diversity. Large swathes of agriculture are found in the humid regions of the Ethiopian Highlands, particularly north and east of Jimma, whereas extensive tracts of montane rainforest can still be found south and south-west of Jimma (Figure 7a). According to the ESA land cover map of Africa (ESA CCI-LC, 2017), farmland covers 54% of the Omo-Gibe subbasin's highlands (≥ 1200 m a.s.l.), while forest and woodlands 31%. In the lowlands of the Omo-Gibe subbasin's, cropland constitutes only 3% while forests and woodlands fill the remaining 46% (Table 2). In the highlands of the Turkwel-Kerio-Turkana subbasin, cropland contributes for only 15% of the land cover whereas woods and woodlands cover 31%, with the remaining being predominantly shrubland or grassland. The lowlands are dominated by shrubland and grassland with forests covering only 5% and cropland only 2%. The driest arid parts of the basin are dominated by shrubland (22%) and grassland (43%).

Over the entire basin 1,140 km² of forest (i.e. 0.8% of the total area) was lost between 2000 and 2020 (Table 2). The Global Forest Change data (version 1.7, updated in 2019) (Hansen *et al.*, 2013) shows that deforestation is fragmented and particularly active in the forest areas of the highlands above 1,200 m a.s.l. of both the Omo-Gibe and the Turkwel-Kerio-Turkana subbasins (Figure 7; Table 2). Although deforestation is still relatively limited over the last decades it has been increasing with an average rate of 3.1 km² per year (Figure 7b). Between 1982 and 2016, deforestation in the highlands has outpaced forest regrowth, while interestingly, in the lowlands forest and woodland regrowth has been more important than deforestation (Kleinschroth *et al.*, 2021).

South-western Ethiopia experienced a considerable increase in human population in recent decades, partly due to local population growth but also due to settlers from other regions of the country. As a result, the increased demand for agricultural land, firewood, charcoal, and timber is viewed as the primary cause of upland deforestation (Santos *et al.*, 2017; Getahun *et al.*, 2017; Dagnachew *et al.*, 2020). Furthermore, the local agroforestry systems where tubers such as false banana (*Ensete ventricosum* (Welw.) Cheesman) and coffee (*Coffea arabica* L.) are grown in partly cleared forest are being replaced by cropping systems dominated by cereals such as maize (*Zea mays* L.) (Reid *et al.*, 2000; Kassa *et al.*, 2017a). The conversion of forest and agroforestry to cropland leads to loss in both soil fertility and biodiversity (Kassa *et al.*, 2017b, 2018) and the annual sediment yield from cropland (17.0 ± 7.6 Mg ha^{-1}) is also four times higher than from comparable forest plots (4.0 ± 1.9 Mg ha^{-1}). Still, for forests 4 Mg ha^{-1} is high, and indicates a degradation of the forests, which has most likely to be attributed to livestock foraging in the forest (Kassa *et al.*, 2019).

These land-use changes present two major challenges to the basin's natural resource management. First and foremost, forest conservation and soil conservation, as well as agroforestry, should be supported wherever possible, particularly in the highlands. Soil and water conservation measures are crucial not just for sustaining agricultural output, but also for conserving aquatic habitats and, potentially, hydropower reservoir functionality. In southern Ethiopia, soil erosion caused by deforestation has been connected to reservoir sedimentation and increased nutrient concentrations in reservoirs and lakes. The Gibe I reservoir has been affected by siltation as initially the river sediment load entering the reservoir was 4.5×10^7 Mg/year, amounting to a loss of the reservoir capacity of 3.8×10^7 m^3/year (Devi *et al.*, 2008). Similarly, nitrate, sulphate, and total suspended solids concentrations in the Gibe I reservoir were found to be 2 to 5 times higher than international standards, with phosphate levels 50 to 90 times higher. Recent research on the nearby rift valley lakes, Lake Chamo and Lake Abaya also highlighted how lakes can be negatively affected by deforestation and soil erosion (Teffera *et al.*, 2017, 2019). Farmers in the Omo-Gibe subbasin are well aware of the potential benefits of soil and water conservation structures for minimizing surface runoff, soil erosion, and maintaining soil fertility, according to research. A questionnaire survey conducted with 201 households in the Omo-Gibe subbasin revealed that more than 80% of the respondents had suffered moderate to severe soil erosion (Wolka *et al.*, 2018). Stone bunds were frequently used where rock pieces were plentiful, and *Fanya juu*[2] and soil bunds were widely used when rock fragments were scarce. Damage to the soil and water conservation structures was attributed to runoff overtopping, livestock trampling, and agricultural activities. The majority of respondents said that labour shortage is a key difficulty in the building and maintenance of these structures (Wolka *et al.*, 2018). As high requirements of labour, shortage of land, and interference by cattle are the major factors impeding the adoption of soil and water conservation techniques, more efforts will be required to create site-specific soil and water conservation approaches. Farmers may particularly require incentives beyond the potential of enhancing their production system.

[2] *Fanya juu*, meaning “doing it up(wards)” in Swahili, entails digging out ditches along contour lines and depositing the soil uphill to make a ridge (Saiz *et al.*, 2016).

Table 2 – Area (km²) of land cover classes for the Omo-Turkana Basin and areas affected by deforestation (forest loss in km² and in percentage of the land cover class). Areas above 1200 m a.s.l. are considered as highlands, below 1200 m as lowlands.

	Omo-Gibe subbasin (km²)						Turkwel-Kerio-Turkana Basin (km²)						Total (km²)		
	≥ 1200 m a.s.l.			< 1200 m a.s.l.			≥ 1200 m a.s.l.			< 1200 m a.s.l.					
Land cover	Area	Loss	(%)	Area	Loss	(%)	Area	Loss	(%)	Area	Loss	(%)	Area	Loss	(%)
Forest and woodland	14649	363	(2.5)	10327	130	(1.3)	4251	186	(4.4)	2989	38	(1.3)	32215	715	(2.2)
Shrubland	819	12	(1.5)	4131	10	(0.2)	4327	38	(0.9)	14284	12	(0.1)	23561	72	(0.3)
Grassland	6252	54	(0.9)	6317	9	(0.1)	3248	45	(1.4)	27839	10	(0.0)	43656	119	(0.3)
Cropland	25912	156	(0.6)	1204	8	(0.7)	2039	60	(2.9)	1482	7	(0.5)	30637	231	(0.8)
Flooded vegetation*	11	–	–	161	–	–	1	–	–	78	–	–	251	1	–
Sparse vegetation	–	–	–	71	–	–	4	–	–	2770	–	–	2845	–	–
Bare areas	18	–	–	21	–	–	6	–	–	7789	–	–	7834	1	–
Built-up areas	81	1	–	2	–	–	4	–	–	10	–	–	97	1	–
Open water	51	–	–	93	–	–	1	–	–	7366	–	–	7511	–	–
Total	47794	587	(1.2)	22327	157	(0.7)	13880	329	(2.4)	64605	67	(0.1)	148607	1140	(0.8)

*Aquatic or regularly flooded vegetation

Authors' calculation based on the 2016 ESA land cover map of Africa (ESA CCI-LC, 2017) and the Global Forest Cover data version 1.7 update 2019 (Hansen *et al.*, 2013)

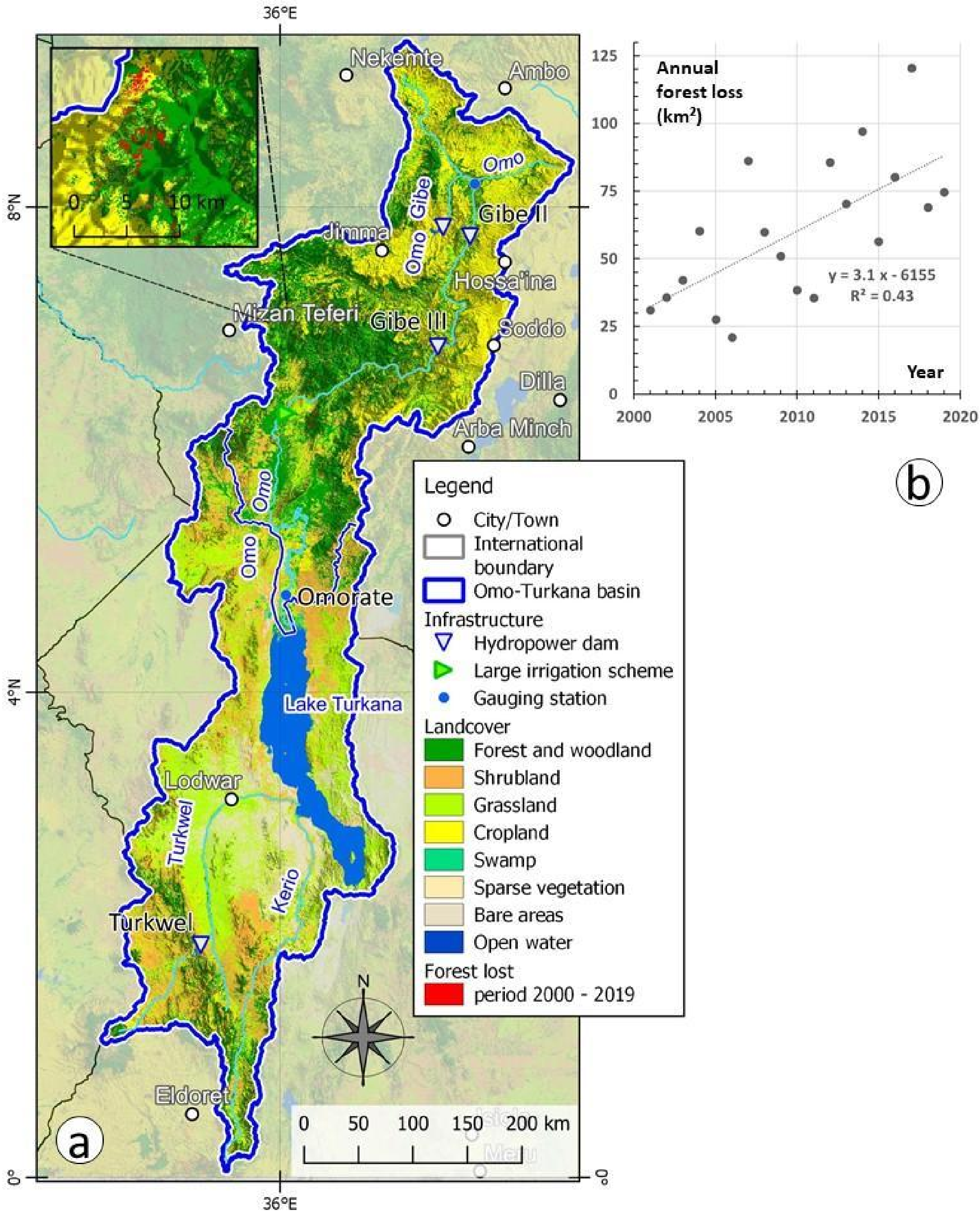

Figure 7 – (a) Land cover of the Omo–Turkana Basin. The inset illustrates the pattern of forest loss for the period 2000 to 2019; (b) Trend of forest loss between 2000 and 2019. While gross deforestation was on average 60 km² per year, the slope of the trend line indicates a steady increase of 3.1 km² per year. [Authors' map and calculations based on: ESA land cover map of Africa (ESA CCI-LC, 2017); Global Forest Cover data version 1.7 update 2019 (Hansen et al., 2013)]

Secondly, the Governments of Ethiopia and Kenya put great emphasis on expanding both large and small irrigation schemes (FDRE, 2016; Government of Kenya, 2018) but this expansion should be undertaken cautiously. Our analysis of the ESA land cover map (ESA CCI-LC, 2017), indicates that the planned 100,000 ha of sugarcane will be to the detriment of *ca*. 50,000 ha of tree cover, 35,000 ha of grassland, and 15,000 ha of shrubland. Irrigation schemes can contribute to more resilient livelihoods by improving food production and income while also reducing people's reliance on rainfall. However, they always result in increased demand for water. While water usage of large-scale irrigation schemes can be reasonably well estimated, budgeting the entire impact of smallholder irrigation schemes is as important but much more difficult. Smallholder irrigation is even more important in the driest parts of the basin, as along the Turkwel and Kerio rivers, where the expansion of irrigation has a strong bearing on the resilience of the basin's water resource system to droughts (Hirpa *et al.*, 2018).

Conclusions

The Omo-Turkana Basin encompasses a broad range of climate, water, and land resources with a high potential for hydropower and agriculture. The Ethiopian Highlands are particularly endowed with consistent rainfall and fertile soils allowing for good agricultural production. Less favourable soils – as the shallow or weakly developed soils (*Leptosols*, *Regosols*, *Cambisols*) or soils with carbonates and soluble salts (*Calcisols*, *Gypsisols*, *Solonetz*, and *Solonchacks*) – occur at lower altitudes and in the driest part of the basin.

The two key causes for concern to the sustainable management of water and land resources are the increasing deforestation and expansion of irrigated areas. Deforestation, combined with the conversion of agroforestry to cereal-based cropping systems, has been demonstrated to result in a loss of soil fertility, high rates of soil erosion, and increased sediment load in rivers in the highlands (≥ 1,200 m a.s.l.). Increased soil erosion causes eutrophication in downstream aquatic environments, as well as siltation of reservoirs. Irrigation schemes in the lowlands (< 1,200 m a.s.l.) are rapidly expanding, resulting in increased water abstraction from rivers. As high labour requirements, shortage of land, and interference by cattle are the major factors impeding the adoption of soil and water conservation techniques, these socio-economic factors ought to be taken better into account. Lake Turkana is particularly vulnerable to land-use changes in the Omo-Gibe subbasin because of its strong reliance on the Omo River for surface water intake. Reduced surface inflow could result in lower lake levels and increased salinization of Lake Turkana, posing a threat to artisanal fisheries and affecting the lake's biodiversity. We, therefore, call for better monitoring of water use by both large and small-scale irrigation schemes.

Acknowledgements

This paper is based on data and information gathered as part of the EU H2020 project DAFNE (Decision Analytic Framework to Explore the Water–Energy–Food Nexus) (grand no. 690268) and as part of Gladys Kangi's PhD research. Ms Kangi is benefiting from the University of Leuven's IRO PhD

fellowship (KU Leuven). The current paper is an adapted and shortened version of a book chapter (Dondeyne *et al.*, 2021).

References

Abbate, E., Bruni, P. & Sagri, M. 2015. Geology of Ethiopia: A Review and Geomorphological Perspectives. In: *Landscapes and Landforms of Ethiopia* (ed. Billi, P.), pp. 33–64. Springer Netherlands, Dordrecht.

Adams, W.M. 1989. Dam construction and the degradation of floodplain forest on the Turkwel River, Kenya. *Land Degradation and Development*, **1**, 189–198, (At: http://doi.wiley.com/10.1002/ldr.3400010303. Accessed: 11/2/2021).

Amos, S., Mengistu, S. & Kleinschroth, F. 2021. 1 Three decades of pastoralist settlement dynamics in the Ethiopian 2 Omo Delta based on remote sensing data. *Human Ecology*, 13.

Avery, S. 2012. *Lake Turkana and the Lower Omo: hydrological impacts of major dam and irrigation development*. African Studies Centre, University of Oxford. (At: https://www.africanstudies.ox.ac.uk/sites/default/files/africanstudies/documents/media/executive_summary_introduction.pdf. Accessed: 1/8/2020).

Avery, S.T. & Tebbs, E.J. 2018. Lake Turkana, major Omo River developments, associated hydrological cycle change and consequent lake physical and ecological change. *Journal of Great Lakes Research*, **44**, 1164–1182, (At: https://linkinghub.elsevier.com/retrieve/pii/S0380133018301540. Accessed: 4/8/2020).

Bloszies, C., Forman, S.L. & Wright, D.K. 2015. Water level history for Lake Turkana, Kenya in the past 15,000years and a variable transition from the African Humid Period to Holocene aridity. *Global and Planetary Change*, **132**, 64–76, (At: https://linkinghub.elsevier.com/retrieve/pii/S0921818115001265. Accessed: 18/1/2022).

Carr, C.J. 2017. The Dasanech of the lowermost Omo Basin: from adaptation to development debacle. In: *River Basin Development and Human Rights in Eastern Africa — A Policy Crossroads*, pp. 111–144. Springer International Publishing, Cham.

Cerling, T.E. & Powers, D.W. 1977. Paleorifting between the Gregory and Ethiopian Rifts. *Geology*, **5**, 441–444.

Chaemiso, S.E., Abebe, A. & Pingale, S.M. 2016. Assessment of the impact of climate change on surface hydrological processes using SWAT: a case study of Omo-Gibe river basin, Ethiopia. *Modeling Earth Systems and Environment*, **2**, 1–15, (At: http://link.springer.com/10.1007/s40808-016-0257-9. Accessed: 4/8/2020).

Dagnachew, M., Kebede, A., Moges, A. & Abebe, A. 2020. Land Use Land Cover Changes and Its drivers in Gojeb River Catchment, Omo Gibe Basin, Ethiopia. *Journal of Agriculture and Environment for International Development (JAEID)*, **114**, 33–56, (At: https://doi.org/10.12895/jaeid.20201.842. Accessed: 18/1/2021).

Devi, R., Tesfahune, E., Legesse, W., Deboch, B. & Beyene, A. 2008. Assessment of siltation and nutrient enrichment of Gilgel Gibe dam, Southwest Ethiopia. *Bioresource Technology*, **99**, 975–979, (At: https://linkinghub.elsevier.com/retrieve/pii/S0960852407002258. Accessed: 18/1/2021).

Dewitte, O., Jones, A., Spaargaren, O., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Gallali, T., Hallett, S., Jones, R., Kilasara, M., Le Roux, P., Michéli, E., Montanarella, L., Thiombiano, L., Van Ranst, E., Yemefack, M. & Zougmore, R. 2013. Harmonisation of the soil map of Africa at the continental scale. *Geoderma*, **211–212**, 138–153, (At: https://linkinghub.elsevier.com/retrieve/pii/S0016706113002401. Accessed: 9/5/2019).

Dondeyne, S., Kangi, G., Rosier, I., Kassa, H. & Van Orshoven, J. 2021. Climate, water and land resources: diversity, uses and changes. In: *The Omo-Turkana Basin: Cooperation for Sustainable Water Management* (eds. Lautze, J., McCartney, M. & Gibson, J.), pp. 11–36. Routledge, Abingdon, UK.

Dresen, E., Tegetmeyer, C., Mundt, F. & Dresen, M. 2015. *Final report: Mapping and analysis of wetlands and rivers at Kafa Biosphere Reserve*. geosysnet, Berlin. (At: https://www.kafa-biosphere.com/publications/. Accessed: 27/9/2021).

Driessen, P.M., Deckers, J. & Spaargaren, O. (Eds). 2001. *Lecture notes on the major soils of the world*. Food and Agriculture Organization of the United Nations, Rome.

Ebinger, C. 2005. Continental break-up: The East African perspective. *Astronomy and Geophysics*, **46**, 2.16-2.21, (At: https://academic.oup.com/astrogeo/article-lookup/doi/10.1111/j.1468-4004.2005.46216.x. Accessed: 3/8/2020).

ENA. 2020. Ministry Exerts Effort to Complete Koysha Hydropower Project in Three Years. *Ethiopian News Agency*, (At: https://www.ena.et/en/?p=17847. Accessed: 25/3/2021).

ESA CCI-LC. 2017. S2 Prototype Land cover 20m map of Africa 2016. Land Cover project of the ESA Climate Change Initiative. (At: http://2016africalandcover20m.esrin.esa.int/. Accessed: 7/8/2020).

Ethiopian Sugar Corporation. 2019. Omo-Kuraz Sugar Development Project. (At: https://www.ethiopiansugar.com/omo-kuraz-sugar-development-project/. Accessed: 4/8/2020).

FAO. 1978. *Report on the agro-ecological zones project. Vol 1: Methodology and results for Africa.* FAO, Rome. (At: https://edepot.wur.nl/480484. Accessed: 10/2/2021).

Fazzini, M., Bisci, C. & Billi, P. 2015. The Climate of Ethiopia. In: *Landscapes and Landforms of Ethiopia* (ed. Billi, P.), pp. 65–87. Springer Netherlands, Dordrecht.

FDRE. 2016. *National smallholder irrigation and drainage strategy*. Federal Democratic Republic of Ethiopia, Agricultural Transformation Agency, Addis Ababa. (At: https://www.cmpethiopia.org/content/download/2946/12150/file/National%20Smallholder%20Irrigation%20and%20Drainage%20Strategy_DRAFT.pdf. Accessed: 7/8/2020).

FDRE. 2018. *Progress report on the state of conservation of the Lower Omo Valley heritage property. Report submitted to World Heritage Committee, UNESCO.* Federal Democratic Republic of Ethiopia, Ministry of Culture & Tourism, Addis Ababa. (At: https://whc.unesco.org/document/165531. Accessed: 18/1/2021).

Fick, S.E. & Hijmans, R.J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, **37**, 4302–4315, (At: https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.5086. Accessed: 1/8/2020).

Frankl, A., Poesen, J., Deckers, J., Haile, M. & Nyssen, J. 2012. Gully head retreat rates in the semi-arid highlands of Northern Ethiopia. *Geomorphology*, **173–174**, 185–195, (At: https://linkinghub.elsevier.com/retrieve/pii/S0169555X12002954. Accessed: 12/3/2019).

Getahun, K., Poesen, J. & Van Rompaey, A. 2017. Impacts of Resettlement Programs on Deforestation of Moist Evergreen Afromontane Forests in Southwest Ethiopia. *Mountain Research and Development*, **37**, 474–486, (At: http://www.bioone.org/doi/10.1659/MRD-JOURNAL-D-15-00034.1. Accessed: 8/8/2020).

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. & Moore, R. 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, **202**, 18–27, (At: https://linkinghub.elsevier.com/retrieve/pii/S0034425717302900. Accessed: 11/2/2021).

Government of Kenya. 2018. *Kenya Vision 2030: Third Medium Term Plan 2018-2022. Transforming Lives: Advancing socio-economic development through the "Big Four."* The National Treasury and Planning, Nairobi, Kenya. (At: www.planning.go.ke.).

Gownaris, N.J., Pikitch, E.K., Aller, J.Y., Kaufman, L.S., Kolding, J., Lwiza, K.M.M., Obiero, K.O., Ojwang, W.O., Malala, J.O. & Rountos, K.J. 2017. Fisheries and water level fluctuations in the world's largest desert lake. *Ecohydrology*, **10**, e1769, (At: https://onlinelibrary.wiley.com/doi/abs/10.1002/eco.1769. Accessed: 20/11/2020).

Gownaris, N.J., Pikitch, E.K., Ojwang, W.O., Michener, R. & Kaufman, L. 2015. Predicting Species' Vulnerability in a Massively Perturbed System: The Fishes of Lake Turkana, Kenya (S Ban, Ed.). *PLOS ONE*, **10**, e0127027, (At: https://dx.plos.org/10.1371/journal.pone.0127027. Accessed: 19/2/2021).

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, **342**, 850–853, (At: https://www.sciencemag.org/lookup/doi/10.1126/science.1244693. Accessed: 7/8/2020).

Hirpa, F.A., Dyer, E., Hope, R., Olago, D.O. & Dadson, S.J. 2018. Finding sustainable water futures in data-sparse regions under climate change: Insights from the Turkwel River basin, Kenya. *Journal of Hydrology: Regional Studies*, **19**, 124–135, (At: https://linkinghub.elsevier.com/retrieve/pii/S2214581818302155. Accessed: 7/8/2020).

Hodbod, J., Stevenson, E.G.J., Akall, G., Akuja, T., Angelei, I., Bedasso, E.A., Buffavand, L., Derbyshire, S., Eulenberger, I., Gownaris, N., Kamski, B., Kurewa, A., Lokuruka, M., Mulugeta, M.F., Okenwa, D., Rodgers, C. & Tebbs, E. 2019a. Social-ecological change in the Omo-Turkana basin: A synthesis of current developments. *Ambio*, **48**, 1099–1115, (At: http://link.springer.com/10.1007/s13280-018-1139-3. Accessed: 8/1/2021).

Hodbod, J., Tebbs, E., Chan, K. & Sharma, S. 2019b. Integrating Participatory Methods and Remote Sensing to Enhance Understanding of Ecosystem Service Dynamics Across Scales. *Land*, **8**, 132, (At: https://www.mdpi.com/2073-445X/8/9/132. Accessed: 8/1/2021).

HWRM-ETHZ. 2019. *Integrated model of the WEF Nexus, Deliverable D3.5*. ETH Zürich, Politecnico di Milano, ICRE8, KU Leuven, Univ. of Aberdeen, Univ. of Osnabrück, IWMI, ACCESS, Univ. Eduardo Mondlane, Addis Ababa Univ., VISTA, ATEC-3D, EIPCM, Zürich. (At: https://dafne.ethz.ch/results/deliverables/. Accessed: 10/2/2021).

IUSS Working Group WRB. 2007. *World reference base for soil resources 2006. First update 2007. A framework for international classification, correlation and communication.* FAO, Rome.

Jones, A., Breuning-Madsen, H., Brossard, M., Dampha, A., Deckers, J., Dewitte, O., Gallali, T., Hallett, S., Kilasara, M., Le Roux, P., Michéli, E., Montanarella, L., Spaargaren, O., Thiombiano, L., Van Ranst, E., Yemefack, M. & Zougmore, R. (Eds). 2013. *Soil atlas of Africa*. Publications Office of the European Union, Luxembourg, Luxembourg.

Kamski, B. 2016. The Kuraz Sugar Development Project (KSDP) in Ethiopia: between 'sweet visions' and mounting challenges. *Journal of Eastern African Studies*, **10**, 568–580, (At: https://www.tandfonline.com/doi/full/10.1080/17531055.2016.1267602. Accessed: 4/8/2020).

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A. & Nyssen, J. 2017a. Transition from Forest-based to Cereal-based Agricultural Systems: A Review of the Drivers of Land use Change and Degradation in Southwest Ethiopia: From Forest-based to Cereal-based Agricultural Systems in SW Ethiopia. *Land Degradation & Development*, **28**, 431–449, (At: http://doi.wiley.com/10.1002/ldr.2575. Accessed: 8/3/2019).

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A. & Nyssen, J. 2017b. Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. *Agriculture, Ecosystems & Environment*, **247**, 273–282, (At: https://linkinghub.elsevier.com/retrieve/pii/S0167880917302773. Accessed: 8/3/2019).

Kassa, H., Dondeyne, S., Poesen, J., Frankl, A. & Nyssen, J. 2018. Agro-ecological implications of forest and agroforestry systems conversion to cereal-based farming systems in the White Nile Basin, Ethiopia. *Agroecology and Sustainable Food Systems*, **42**, 149–168, (At: https://www.tandfonline.com/doi/full/10.1080/21683565.2017.1382425. Accessed: 8/3/2019).

Kassa, H., Frankl, A., Dondeyne, S., Poesen, J. & Nyssen, J. 2019. Sediment yield at southwest Ethiopia's forest frontier. *Land Degradation & Development*, (At: http://doi.wiley.com/10.1002/ldr.3260. Accessed: 8/3/2019).

Kleinschroth, F., Mekuria, W., Schwatke, C. & McCartney, M. 2021. Ecosystem services in changing social-ecological systems. In: *The Omo-Turkana Basin: cooperation for sustainable water management* (eds. Lautze, J., McCartney, M. & Gibson, J.), pp. 78–101.

Kolding, J. 1992. A summary of Lake Turkana: An ever-changing mixed environment. *SIL Communications, 1953-1996*, **23**, 25–35, (At: https://www.tandfonline.com/doi/full/10.1080/05384680.1992.11904005. Accessed: 9/8/2021).

Koptev, A., Burov, E., Calais, E., Leroy, S., Gerya, T., Guillou-Frottier, L. & Cloetingh, S. 2016. Contrasted continental rifting via plume-craton interaction: Applications to Central East African Rift. *Geoscience Frontiers*, **7**, 221–236, (At: https://linkinghub.elsevier.com/retrieve/pii/S1674987115001280. Accessed: 21/1/2022).

Nicholson, S.E. 2017. Climate and climatic variability of rainfall over eastern Africa. *Reviews of Geophysics*, **55**, 590–635, (At: https://onlinelibrary.wiley.com/doi/10.1002/2016RG000544. Accessed: 18/1/2022).

Nicholson, S.E. 2018. The ITCZ and the Seasonal Cycle over Equatorial Africa. *Bulletin of the American Meteorological Society*, **99**, 337–348, (At: https://journals.ametsoc.org/doi/10.1175/BAMS-D-16-0287.1. Accessed: 18/1/2022).

Odada, E.O., Olago, D.O., Bugenyi, F., Kulindwa, K., Karimumuryango, J., West, K., Ntiba, M., Wandiga, S., Aloo-Obudho, P. & Achola, P. 2003. Environmental assessment of the East African Rift Valley lakes. *Aquatic Sciences*, **65**, 254–271, (At: http://link.springer.com/10.1007/s00027-003-0638-9. Accessed: 19/2/2021).

Ojwang, W.O., Obiero, K.O., Donde, O.O., Gownaris, N., Pikitch, E.K., Omondi, R., Agembe, S., Malala, J. & Avery, S.T. 2018. Lake Turkana: World's Largest Permanent Desert Lake (Kenya). In: *The Wetland Book* (eds. Finlayson, C.M., Milton, G.R., Prentice, R.C. & Davidson, N.C.), pp. 1–20. Springer Netherlands, Dordrecht.

Pekel, J.-F., Cottam, A., Gorelick, N. & Belward, A.S. 2016. High-resolution mapping of global surface water and its long-term changes. *Nature*, **540**, 418–422, (At: http://www.nature.com/articles/nature20584. Accessed: 18/2/2021).

Reid, R.S., Kruska, R.L., Muthui, N., Taye, A., Wotton, S., Wilson, C.J. & Mulatu, W. 2000. Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia. *Landscape Ecology*, **15**, 339–355.

Saiz, G., Wandera, F.M., Pelster, D.E., Ngetich, W., Okalebo, J.R., Rufino, M.C. & Butterbach-Bahl, K. 2016. Long-term assessment of soil and water conservation measures (Fanya-juu terraces) on soil organic matter in South Eastern Kenya. *Geoderma*, **274**, 1–9, (At: https://linkinghub.elsevier.com/retrieve/pii/S0016706116301409. Accessed: 21/1/2022).

Santos, M.J., Dekker, S.C., Daioglou, V., Braakhekke, M.C. & van Vuuren, D.P. 2017. Modeling the Effects of Future Growing Demand for Charcoal in the Tropics. *Frontiers in Environmental Science*, **5**, 28, (At: http://journal.frontiersin.org/article/10.3389/fenvs.2017.00028/full. Accessed: 8/8/2020).

Schad, P. & Dondeyne, S. 2016. World Reference Base for Soil Resources (R Lal, Ed.). *Encyclopedia of Soil Science, Third Edition*, (At: http://www.crcnetbase.com/doi/book/10.1081/E-ESS3. Accessed: 27/8/2019).

Stave, J., Oba, G., Stenseth, N.Chr. & Nordal, I. 2005. Environmental gradients in the Turkwel riverine forest, Kenya: Hypotheses on dam-induced vegetation change. *Forest Ecology and Management*, **212**, 184–198, (At: https://linkinghub.elsevier.com/retrieve/pii/S0378112705001982. Accessed: 27/9/2021).

Tebbs, E.J., Avery, S.T. & Chadwick, M.A. 2019. Satellite remote sensing reveals impacts from dam-associated hydrological changes on chlorophyll- *a* in the world's largest desert lake. *River Research and Applications*, rra.3574, (At: https://onlinelibrary.wiley.com/doi/abs/10.1002/rra.3574. Accessed: 1/8/2020).

Teffera, F.E., Lemmens, P., Deriemaecker, A., Brendonck, L., Dondeyne, S., Deckers, J., Bauer, H., Gamo, F.W. & De Meester, L. 2017. A call to action: strong long-term limnological changes in the two largest Ethiopian Rift Valley lakes, Abaya and Chamo. *Inland Waters*, **7**, 129–137, (At:

https://www.tandfonline.com/doi/full/10.1080/20442041.2017.1301309. Accessed: 6/3/2019).

Teffera, F.E., Lemmens, P., Deriemaecker, A., Deckers, J., Bauer, H., Gamo, F.W., Brendonck, L. & De Meester, L. 2019. Why are Lake Abaya and Lake Chamo so different? A limnological comparison of two neighboring major Ethiopian Rift Valley lakes. *Hydrobiologia*, **829**, 113–124.

Trabucco, A. & Zomer, R. 2019. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. (At: https://figshare.com/articles/Global_Aridity_Index_and_Potential_Evapotranspiration_ET0_Climate_Database_v2/7504448/3 Accessed: 3/8/2020).

UNEP. 1992. *Status of desertification and implementation of the United Nations Plan of action to combat desertification.* UNEP, Nairobi, Kenya. (At: https://pdfs.semanticscholar.org/a6ee/81d5c2f45a0bcd287d33ac7b1be036f90e31.pdf Accessed: 1/8/2020).

Van Orshoven, J. & Rosier, I. 2019. Agriculture, livestock and fisheries development. In: *Future drivers and scenarios. Report of the DAFNE project: A Decision-Analytic Framework to explore the water-energy-food Nexus in complex and transboundary water resources systems of fast-growing developing countries.* (eds. Sinclair, S., Peleg, N. & Burlando, P.), p. xvi + 220. ETH Zürich. (At: https://dafne.ethz.ch/wp-content/uploads/2020/10/DAFNE_D22.pdf Accessed 21/1/2022)

Wolka, K., Sterk, G., Birhanu Biazin & Mesele Negash. 2018. Benefits, limitations and sustainability of soil and water conservation structures in Omo-Gibe basin, Southwest Ethiopia. *Land Use Policy*, **73**, 1–10.

Yang, W., Seager, R., Cane, M.A. & Lyon, B. 2015. The annual cycle of East African precipitation. *Journal of Climate*, **28**, 2385–2404, (At: http://journals.ametsoc.org/doi/10.1175/JCLI-D-14-00484.1. Accessed: 21/1/2022).

Yuretich, R.F. & Cerling, T.E. 1983. Hydrogeochemistry of Lake Turkana, Kenya: Mass balance and mineral reactions in an alkaline lake. *Geochimica et Cosmochimica Acta*, **47**, 1099–1109, (At: https://linkinghub.elsevier.com/retrieve/pii/0016703783902405. Accessed: 11/2/2021).

Zaniolo, M., Giuliani, M., Bantider, A. & Castelletti, A. 2021. Hydropower Development: Economic and Environmental Benefits and Risks. In: *The Omo-Turkana Basin: cooperation for sustainable water management* (eds. Lautze, J., McCartney, M. & Gibson, J.), p. 26. Routledge, Taylor & Francis Group, London.