Journal of Great Lakes Research 44 (2018) 1164–1182

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Lake Turkana, major Omo River developments, associated hydrological cycle change and consequent lake physical and ecological change

Sean T. Avery [a,b,c,*], Emma J. Tebbs [d]

[a] Kenya Wetlands Biodiversity Research Team (KENWEB), National Museums of Kenya, Kenya
[b] Water Resource Associates, Wallingford, United Kingdom
[c] University of Leicester, Department of Geography, United Kingdom
[d] King's College London, Department of Geography, United Kingdom

ARTICLE INFO

Article history:
Received 5 October 2017
Accepted 24 August 2018
Available online 22 October 2018

Communicated by Robert E. Hecky

Keywords:
Turkana
Omo
Dams
Irrigation
Hydrology
Ecology
Fisheries
Lakes

ABSTRACT

This study aimed to explore Lake Turkana's ecological reliance on hydrology and to determine the hydrological changes and consequences arising from the major hydropower and irrigation developments in the lake's basin. The major developments on Ethiopia's Omo River are especially significant as this river provides over 80% of the lake's annual freshwater influx and associated nutrients. The cascade of hydropower dams permanently dampens the natural hydrological cycles and lake level variability. The driving force of the flood influx to the lake is curtailed and the pattern of lake currents will adjust. Ultimately 80% of the river inflow to the lake will be regulated. Large volumes of water are required to initially fill the hydropower dam reservoirs. During 2015–16 when the huge Gibe III reservoir was filled, Lake Turkana's water level declined 2 m.

The study has shown that large-scale irrigation schemes in the Lower Omo can potentially abstract 50% of the Omo River water, and that this would cause the lake level to shrink permanently to the detriment of the lake ecology. Possible lake level drops of over 15 m are demonstrated. The basin's natural capital is being replaced by large-scale plantation developments. The hydrological changes are drastic and the ecological consequences on Lake Turkana have not been fully understood. Without serious mitigation measures, Lake Turkana is a potential African Aral Sea disaster in the making, emulating what has happened to other great lakes such as Lake Chad.

Introduction

Formerly called the Samburu Sea by Emperor Menelik (Collins, 2005) and then named Lake Rudolf by European explorer Von Höhnel in 1888, the lake is today named Lake Turkana. It is popularly called the Jade Sea on account of the striking colour of its water. The lake is a fascinating example of climate and environmental change, having once been a mega freshwater lake 100 m higher. An area nearly five times the area of today's contemporary lake was once inundated (Ferguson and Harbott, 1982, p. 7). And, that mega-lake was spilling into the Nile basin (Hopson, 1982, vol. 6, figs. 1–6; Dunkley et al., 1993; Johnson and Malala, 2009; Garcin et al., 2012). The lakeshores host Kenya's only archaeological national park, Sibiloi. Early human remains have been found here. The lake area is often described as the "Cradle of Mankind" (Amin, 1981), and Sibiloi is part of the UNESCO listed Lake Turkana National Parks World Heritage Site. The World Heritage Committee is concerned that the Gibe III dam and Kuraz sugar plantation and factory developments in the Omo basin threaten the Site's outstanding values (UNESCO-ICOMOS, 2015). In June 2018, the Lake Turkana National Parks World Heritage Site was inscribed on the list of world heritage in danger (UNESCO Press Release No. 2018-55; Avery, 2018).

Lake Turkana was the last of the world's great lakes to be studied in detail, its biology and bathymetry being documented by the Lake Turkana Project 1972–75 (Hopson, 1982, vol. 1, pp. i–ii). The lake's closed basin is the largest such basin within the East African Rift system (Halfman, 1996). The basin is split in roughly equal drainage area proportions between Kenya and Ethiopia (Fig. 1 a). The lake today is still relatively pristine, but its unique semi-saline hydrobiology is at the upper limit of salinity for sustaining its fisheries (Yuretich and Cerling, 1983). And The lake depends on Ethiopia's Omo-Gibe Basin for most of its freshwater inflow (Ferguson and Harbott, 1982, p. 12; Johnson and Malala, 2009). This river terminates in Lake Turkana at its delta on the Ethiopian/Kenyan border. This delta has been in a constant state of change in response to natural hydrological cycles, including lake level change, and sediment deposition by the river on entering the lake.

The lake's SE winds induce a surface current from the lake's southern sector that prevails throughout the year (Ferguson and Harbott, 1982, p. 51; Yuretich and Cerling, 1983). Surface water tends to move northwest with a compensating reverse flow of deeper water to the southeast (Ferguson and Harbott, 1982, p. 51). Sediment plumes that enter the

* Corresponding author at: P.O. Box 24135-00502, Nairobi, Kenya.
E-mail address: sean@watres.com (S.T. Avery).

https://doi.org/10.1016/j.jglr.2018.08.014
0380-1330/

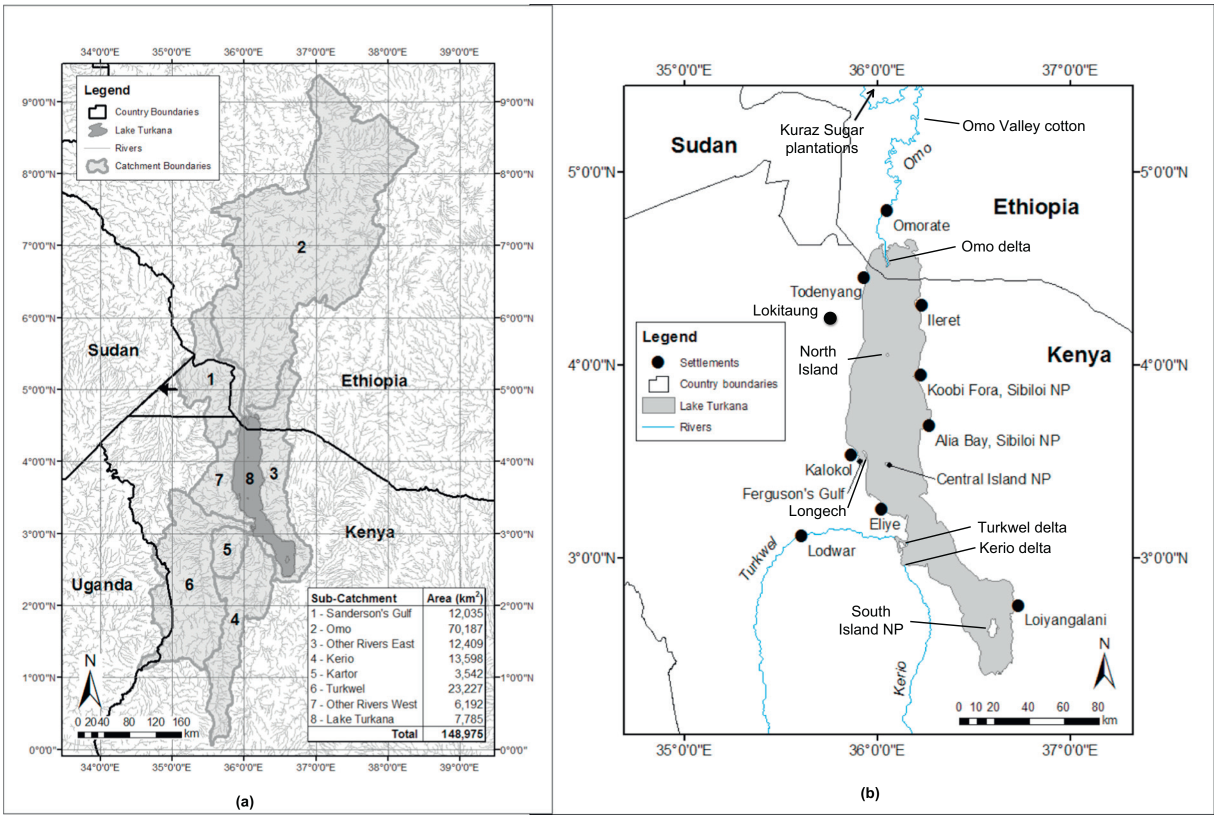

Fig. 1. (a) Sub-catchments of Lake Turkana Basin and the lake environs: Lake Turkana's sub-catchments have been delineated. The drainage areas are tabulated and the distribution between Kenya and Ethiopia is near equal. The former palaeo lake overflowed west from the Ilemi Triangle into the Nile Basin in Sudan in sub-catchment 1 (arrowed). (b) The three main river deltas are the Omo, Turkwel and Kerio. Kalokol centre and Longech Spit are located on Ferguson's Gulf, this being historically the lake's most productive fishing area. There are three island clusters named North, Central and South Islands. The latter two are national parks. Koobi Fora is the location of important fossil beds. Lodwar is the principal town. There are small centres with historic rainfall data at Todenyang, Ileret, Alia Bay, Loiyangalani in Kenya, and at Omorate in Ethiopia. The Kuraz sugar and Omo valley plantation locations are indicated north of the lake within Ethiopia's lower Omo valley.

lake from the Kerio and Turkwel rivers are transported north by these prevailing currents. In the lake's northern basin, the water circulation patterns do vary with the season. The currents are controlled by the SE winds confronting the Omo delta inflows from the north. During the flood season the driving force of Omo inflows predominates. The current is then anti-clockwise down the NW shore south before crossing the central sector to the east shore and then up north (Yuretich and Cerling, 1983). In the dry season when Omo flows are low, the SE winds predominate and the circulation pattern reverses to clockwise (ibid.). In both seasons, the circulation patterns cause water to upwell along the eastern shores of both the central and southern sectors. The southern sector's sediments also derive from the Omo basin, indicative of deep currents to the south (Ferguson and Harbott, 1982, p. 16; p. 42).

The Omo-Gibe's annual flood period has long been recognized as the critical driver for the lake ecology. The Omo's freshwater inflow is the "main agent of change" of the lake's limnology (Ferguson and Harbott, 1982, p. 51). The Omo is the dominant influence on the lake's nutrient balance (Kallqvist et al., 1988, p. 8; Kolding, 1992). The high dependence of the lake ecology on a single river from a neighbouring country is precarious. The Omo drains from highlands with plentiful rainfall, whereas the lake is within an arid and inhospitable environment. The lakeshore inhabitants are amongst the poorest in Kenya. Their traditional agro-pastoral livelihoods have long struggled to cope with the demands of a fast-increasing population. The lake's fishery resource is a vital alternative food supplement that is important to sustaining the riparian population.

In this study, we have identified major impacts on Lake Turkana arising from the cascade of hydropower and large-scale irrigation developments in Ethiopia's Omo-Gibe river basin (Fig. 2). The hydrological characteristics of the basin's river discharge into Lake Turkana have long been progressively changing with increasing human population pressure (e.g. Woodroofe et al., 1996). But since 2015, the lake inflow cycles have been permanently altered by the upstream developments on the Omo.

There have been repeated warnings that the Omo River and Lake Turkana's ecological diversity will in turn be critically affected (e.g., Nippon Koei/JICA, 1992; Woodroofe et al., 1996; Avery, 2010, 2012, 2013a; Muska et al., 2012). The challenges emulate those of Lake Chad in Central Africa. By 2001, Lake Chad had shrunk 20-times due to irrigation demands and climate change (NASA, 2001).

In 1990, Kenya's Kerio Valley Development Authority commissioned the Turkwel multi-purpose dam project nearly 200 km from the lake. This was the first major hydropower dam project within the Turkana Basin (Fig. 2). Ethiopia has long grappled with rising population and food security challenges, and as long ago as 1990, a staggering irrigation potential of 445,500 ha in the Omo-Gibe Basin was claimed (WAPCOS, 1990). In 1996, an integrated development master plan for the Omo-Gibe River Basin was presented (Woodroofe et al., 1996). This was the first plan of its kind for any basin in Ethiopia. The Omo-Gibe basin provides 14% of Ethiopia's substantial runoff, and the basin master plan's primary focus was economic development of hydropower and irrigated agriculture. The basin's hydropower potential is derived from the main river's 1600 m altitude drop over a distance of about 1100 km. This energy resource was totally unexploited at that time, although the Gilgel-Gibe project (Gibe I and II) was then under development with World Bank funding. The pre-feasibility study of the Halele-Werebesa hydropower project was also in progress. Because of the seasonality of natural river flow, the master plan noted that dams would be required to create

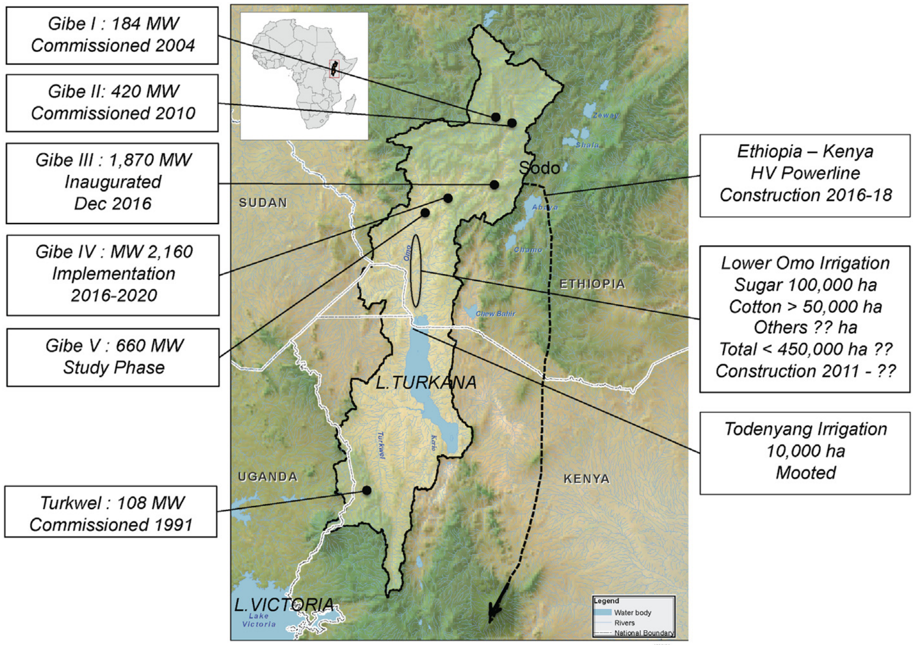

Fig. 2. Major developments along rivers that flow to Lake Turkana: A cascade of 5 hydropower stations is at an advanced stage of implementation along the Omo with only Gibe V to come. A high voltage powerline is under construction from Sodo in Ethiopia to Suswa in Kenya. Known irrigation developments are indicated, but the full scale of these is unclear.

storage reservoirs. Flow regulation by those reservoirs would enable and stabilize the downstream river use, particularly for irrigation. The master plan investigated the potential for 5864 MW of hydropower development. In addition the master plan established the potential for 31,780 ha of small-scale irrigation throughout the basin. The feasibility of 54,570 ha of large-scale irrigation development in the lower valley of the Omo was established on the plains approaching the lake.

Since the Omo-Gibe River Basin Integrated Development Master Plan was prepared, there has been pressure to develop water resources. In 2004, the World Bank linked Ethiopia's chronic and increasing poverty to dependence on rainfed subsistence farming coupled with inappropriate farming methods (World Bank, 2004). The World Bank described irrigation as a neglected sector and stated that "the Omo River Basin (irrigation potential 348,000 ha) could be an early candidate for development". Since that time, a cascade of five hydropower dam projects has been under progressive implementation along the length of the Omo-Gibe river. The latest to be commissioned is the 243 m high Gibe III dam. This is the tallest dam in Africa, and has been built 710 km upstream from Lake Turkana. Construction commenced in 2006 and the project was inaugurated in December 2016 (Avery, 2017). Meanwhile, contracts had already been signed earlier in 2016 to implement Gibe IV (Koysha) hydropower dam. This project is downstream of Gibe III on the Omo River and 580 km from the lake. Land clearance for large-scale sugar and cotton plantations downstream in the lower Omo valley had already begun in 2012, up to 200 km from the lake. The developments are part of a hasty process of socio-economic transformation that has been clouded by accusations of human rights abuses (Human Rights Watch, 2012). There were neither prior trans-boundary consultations nor agreements with directly affected parties (Avery, 2012, vol. I, pp. 28–46). Trans-boundary consultations have since been initiated, but with such slow progress (UNESCO-ICOMOS, 2015) that it will be a challenge to incorporate effective mitigation measures. Meanwhile Kenya had mooted 10,000 ha of irrigation development at Todenyang southwest of the Omo delta (Fig. 2) also using irrigation water from the Omo. In this paper we aim to update information from the literature with available satellite and ground-based observations to improve the water balance modeling for Lake Turkana, and predict the impacts of the dam and irrigation developments.

Material and methods

Assessing Omo river discharges into the lake

The Ethiopian Water Resources Authority (EWRA) has provided monthly Omo river discharge measurements at Omorate near the lake for the period 1977–80. These are the only measured lake river inflow data available and unfortunately coincident lake level data do not exist (Avery, 2012, vol. I, p. 209).

We obtained a simulated monthly river discharge sequence for the period 1956–94 from the Omo-Gibe Basin master plan's runoff modeling (Woodroofe et al., 1996; Avery, 2012, vol. I, p. 139). We have obtained the other principal recent Omo hydrological studies (e.g. Salini and Pietrangeli, 2006; Salini and Pietrangeli, 2010; Salini and Pietrangeli, 2016; UNEP, 2012). These studies relied on rainfall-runoff modeling without any coincident river inflow measurements to the lake. The insufficiency of measured flow data into the lake has been a model calibration constraint affecting all studies. Reliance has been placed by other modeling studies on river flow data in the upper high rainfall reaches of the catchment where the flow regime is not representative of the entire basin.

In this study, we have pursued the water balance model of the lake that was proposed for Lake Turkana in 2009 (Avery, 2010, pp. 3–4). That simple model derived inflows into the lake directly from water level changes measured by satellite radar altimetry (Avery, 2012, vol. I, p. 208). The absence of actual coincident lake inflow data has constrained the calibration of our water balance model too. But we successfully applied double-mass curve analyses to test the sensitivity of the model assumptions (ibid., pp. 213–215). This is a standard analytical method that compares cumulative hydrological sequences for consistency (WMO, 1983, vol. II, p. 5.9).

Lake water balance modeling

The water balance model was first developed for this lake to help the African Development Bank evaluate the impacts of the Gibe III dam on Lake Turkana (Avery, 2009, 2010). The model was designed to determine the Omo River inflows to the lake in the absence of measured inflow data. The University of Oxford later updated this same model by addressing in more detail the critical gross lake evaporation rate assumptions (Avery, 2012, vol. I, pp. 210–215).

The lake water balance modeling is an exercise in arithmetically comparing the water inputs with the outputs (Fig. 9). When inputs exceed outputs, the lake level rises and water is stored within the lake; and, when inputs fall below outputs, the lake level falls and the lake storage volume declines. The above fundamentals are captured in the following water balance equation:

$$\delta Vol/dT = Q_{Omo} + Q_{Others} + Rain - Evap - Losses$$

where:

δVol = Lake volume change
δT = Time interval (monthly model time step adopted in this study)
Q_{Omo} = Inflowing discharge volume from the Omo River
Q_{Others} = Inflowing discharge volume from all other rivers
Rain = Precipitation volume on the lake surface
Evap = Volume evaporated from the lake surface area.
Losses = Volume of seepage through lake bed

(1) The individual component methodology is outlined in later sections of this paper. And the model's data logic is briefly summarized as follows, below. The lake water levels have been obtained at ten-day intervals from available satellite data.
(2) Lake Turkana is a closed basin, and hence there is no direct outflow from the lake. And, there are no direct abstractions from the lake itself as the water quality is unsuitable.
(3) The gross evaporation has been measured by standard methods. It was also measured indirectly from water level changes during periods when there is no rain and also minimal Omo inflow. The model assumes a constant daily loss rate throughout the year.
(4) The rainfall on the lake surface is not measured directly. It has been estimated by extrapolation from shore-based measurement stations. We have reviewed the over-lake rainfall measurements by satellite infrared and microwave sensors.
(5) The inflows from other rivers are seasonal and comprise a small component in the lake balance. They are not measured and we have estimated these from national hydrological studies.
(6) The monthly Omo inflow series is thus derived for the pre-Gibe III filling period 1993 to 2014:

$$Q_{Omo} = \delta Vol/dT - Q_{Others} - Rain + Evap$$

(7) And finally, the same model has been reversed to simulate the effect of changes to lake level as a direct consequence of the Gibe III reservoir filling. The model was also used to simulate the impact of irrigation abstractions from the Omo River. Thus:

$$\delta Vol/\delta T = [Q_{Omo} - Abstraction] + Q_{Others} + Rain - Evap$$

As the lake volume is large, a monthly time step was adopted.

Assessing other river discharges reaching the lake

Kenya's drainage to the lake comprises near 50% of the catchment area. But the flow contribution is small when compared to the Omo. The Kerio and Turkwel rivers are Kenya's two major influents to the lake, each discharging through individual deltas in close proximity on the western shore (Fig. 1 b). Both rivers are perennial in their highland upper reaches and ephemeral in the lower semi-arid plains approaching the lake. Some river discharge data are available in the upper perennial reaches, and some historic data exist in middle ephemeral reaches (Sogreah, 1982). There are also significant but unmeasured irrigation abstractions from both rivers. The lower reaches of the rivers are insecure areas, and hence national abstraction licensing requirements have not been enforced.

We have obtained hydrological data from regional and national studies commissioned by the Government of Kenya (e.g., Sogreah, 1982; Nippon Koei/JICA, 1992). Sogreah analysed the limited actual flow data and carried out supplementary flow measurements. The Nippon Koei/JICA study team analysed the national hydro-meteorological database and determined runoff characteristics throughout Kenya. They used a rainfall runoff model to derive flow sequences for key rivers, including Turkwel and Kerio. Nippon Koei/JICA updated their landmark studies twenty years later (Nippon Koei/JICA, 2013).

The Turkwel dam was commissioned in 1991, and since that time the river flows immediately downstream have been regulated according to the dam's hydropower turbine releases. The turbine flow releases depend on variable national electrical power requirements. The turbines typically run during daylight and early evening hours, shutting down thereafter till dawn. The Turkwel river at this point has thus become perennial, albeit diurnal. Some natural flow variability is restored 18 km downstream at the confluence with River Malmalte. This tributary contributes roughly 30% of onward annual downstream discharge (Avery, 2015) and due to high riverbed losses, in the lowest river reaches nearing the lake, visible surface flow ceases at times.

There are numerous other smaller ephemeral rivers reaching the lake. These typically flow only for a few hours in any year in response to storm rainfall. However, throughout Kenya's arid and semi-arid lands, there has been progressive land degradation (Ministry of Environment and Natural Resources, 2017). Consequently, increasingly more flood runoff occurring in response to storm rainfall would be expected. Less rainfall is recharging the underground aquifers and the proportion of storm rainfall reaching the lake as surface runoff is increasing. But there are no flow data that quantify these expected changes.

There are notable perennial artesian springs at Eliye and Lobolo on the western lakeshore (Avery, 2012, vol. I, pp. 177–188). And a borehole drilled in the Kerio delta area was initially artesian (Pers. Comm., Tullow Oil, 2016). Loiyangalani's warm springs on the southeastern shore are also notable. These springs serve as community water supply sources. Flows are small and the contribution to the lake water balance is negligible.

The Kerio, Turkwel and littoral river inflows may be significant, but there are no current data. We have modeled inflows expressed as a simple function of the catchment area (A), rainfall (P), and runoff coefficient (RO). The runoff coefficient is the proportion of the catchment rainfall that generates runoff reaching the lake through seasonal watercourses. The runoff coefficient is itself a function of many factors including topography, land use and soil type. We abstracted the broad average annual catchment runoff parameters from Kenya's national water master plan (Nippon Koei/JICA, 1992, in Sectoral Report (B)), as follows:

$$P = 532\ \text{mm for R.Turkwel and } 696\ \text{mm for R.Kerio}$$

$$RO = 4.1\%\ \text{for R.Turkwel and } 7.2\%\ \text{for R.Kerio}$$

Measuring lake water chemistry

Three field missions have been completed on the lake. During the first mission, in situ measurements were made using YSI's Professional Plus multi-parameter meter with pH, dissolved oxygen (DO), temperature and conductivity sensors (Avery, 2012). During the subsequent missions, YSI's EXO multi-parameter water quality

Sonde was substituted with 60 m cabling for profiling through the lake water column (Avery, 2016). The Sonde included additional sensors to measure depth, total suspended solids (TSS), total algae (dual channel chlorophyll and blue-green algae), and fluorescent dissolved organic matter (fDOM, surrogate for CDOM). Water samples were also collected with full chemical analyses undertaken by Crop Nutrition Laboratory Services (Avery, 2012) and SGS Laboratories (Avery, 2016).

Measuring lake water levels

We were unable to obtain any lake water level records from Ethiopia. Station 93,003 (Lake Rudolf @ Kelem) was listed long ago as "not operated" (Woodroofe et al., 1996). In Kenya, the national authority holds records that date from 1949, but these lack continuity and quality control (Avery, 2012, vol. I, p. 150).

We obtained lake level fluctuations for the period 1880 to 1970 from the International Omo Expedition (Butzer, 1971). The Lake Turkana Project extended this same sequence from 1971 to 1975 (Hopson, 1982, vol. 6, fig. 1.13). The Lake Turkana Limnological Study further extended the lake water level series to 1988 (Kallqvist et al., 1988, p. 17). We obtained data after 1988 from the Kenya Marine Fisheries Research Institute (KMFRI). They reported that logistical challenges hampered data collection on the lake, and we have previously documented the datum discrepancies (Avery, 2012, vol. I, pp. 150–152). Remotely sensed lake water level data became available from 1992, thereby providing an ongoing alternative data source to replace the unreliable lake gauge. We have downloaded the remotely sensed data regularly from the website of the Foreign Agricultural Service of the United States Department of Agriculture (USDA) (https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/, accessed monthly).

The USDA water level data is derived from satellite radar altimetry. The satellite crosses diagonally through the central portion of the lake at ten-day intervals. This interval is adequate for the monthly modeling time-step that we have adopted. We have ground-truthed the satellite lake level datum through geodetic survey of the existing national lake water level gauge located on the lake within Ferguson's Gulf near Kalokol (Pers. Comm., Tullow Oil Kenya BV, 2015). That survey was undertaken at our request. Two Leica GS15 dual frequency GPS units were deployed. The data were processed by Leica Geo-Office Version 8.2.0.0. Results were expressed at different datums, including the 2008 Earth Gravitational Model (EGM 2008) (Pavlis et al., 2012).

The USDA satellite radar altimeter measurements are the only reliable continuous lake water level data for our study. These are an excellent illustration of the vital contribution of satellite remote sensing in these areas of data scarcity. But the data are subject to high frequency noise and outliers. Force 8 winds (64 km/h) have been recorded on the lake, and wave heights up to 4.5 m have been measured from trough to crest (Ferguson and Harbott, 1982, p. 41). The strong SE winds will induce a seiche effect. Storms over the lake also cause dramatic lake level changes. During one such storm, water levels in Ferguson's Gulf rose 30 cm within 3 h. Without accurate ground-based data around the lake, the absolute accuracy of the radar altimetry estimates cannot be assessed. For calm waters, an accuracy 10–15 cm rms would be expected (Pers. Comm., Sharon Birkett, University of Maryland, 2018). As the satellite measurements are mid-lake, we have assumed minimal seiche effect.

Updating the lake bathymetry

We obtained the original lake physical dimensions and bathymetry from the Lake Turkana Project 1972–75 (Hopson, 1982, vol.6). The bathymetry was published in both tabular and map form. We have compared depth contours from later publications (Halfman, 1996; Johnson et al., 1986). During the Lake Turkana Limnological Study 1985–88, the lake level declined and they added one extra lower contour line from Landsat imagery (Kallqvist et al., 1988, p. 13).

During oil explorations on the lake in 2011 and 2012, geo-referenced bathymetric surveys were undertaken (Pers. Comm., Tullow Oil Kenya BV, 2015). We have inspected the results. We have also checked the original Lake Turkana Project data by superimposing lake surface areas we measured from Landsat imagery dated 2000–16.

Assessing catchment and lake rainfall

We have sourced traditional rainfall gauge data from publications (Norconsult, 1983; Sogreah, 1982; Nippon Koei/JICA, 1992) and the Kenya Meteorological Department. We have obtained satellite data from TRMM, the Tropical Rainfall Monitoring Mission (https://giovanni.gsfc.nasa.gov/giovanni/), and from CHIRPS, the Climate Hazards Group InfraRed Precipitation with Station database (http://chg.geog.ucsb.edu/data/chirps/). We accessed the following two main TRMM products and one CHIRPS product: (1) TRMM 3B42 v7 that applies the Multi-Satellite Precipitation Algorithm. This combines data from TRMM and other satellites including both microwave and infrared instruments, and ground-based data are also incorporated; (2) TRMM 3A12 v7 that uses data from the TRMM Microwave Imager and (3) CHIRPS that incorporate 0.05° resolution satellite imagery with ground data (Funk et al., 2015). TRMM and CHIRPS data are available from 1998 and 1981 respectively.

The lake is within an arid zone at 365 m above sea level. There is a national meteorological station at similar altitude at Lodwar 50 km southwest of the lake mid-point (Fig. 1 b) (Avery, 2012, vol. I, p. 132). Another long-term station at Lokitaung is less representative as it is to the north and at higher elevation. We thus adopted Lodwar as the baseline rainfall station for our water balance modeling. We have obtained Lodwar's annual ground-based rainfall totals dated 1921–2017, and daily data from 1940 (Kenya Meteorological Department). We have downloaded the TRMM 3B42 database from 1998 and have compared Lodwar's ground data and the CHIRPS database for the same period.

We also utilised historic monthly data at Kalokol and Longech on the lakeshore at Ferguson's Gulf not far from Lodwar (Fig. 1 b). These shore stations were only 8 km apart, and the Lake Turkana Project published useful records dated 1973–74 (Ferguson and Harbott, 1982, p. 30 and p. 89). We have compared these with Lodwar.

We have previously contrasted the Lodwar data with other rainfall gauges around the lake at Loiyangalani, Alia Bay, Ileret and Todenyang (Fig. 1 b) (Avery, 2012, vol. I, pp. 127–129). The data for these other stations exist for very much shorter data periods and records are much less reliable. But we have used these records to derive an arithmetic mean for annual rainfall for the lakeshore.

We also required rainfall data on the lake surface itself. Past studies have found that rainfall over a lake is higher than surrounding areas, but direct over-lake data usually do not exist. With modern satellite sensing technology, over-lake rainfall is now being derived directly, but significant differences have been reported. For instance, the increased estimates of Lake Victoria's annual lake rainfall relative to land-based rainfall varied according to the satellite products and regression equations used; for TRMM 3B42 the enhancement was in the range 33% to 28%. For PERSIANN the enhancement was in the range 76% to 85% (Kizza et al., 2012). We downloaded the TRMM and CHIRPS over-lake data for our own analysis.

We obtained rainfall data for the Omo Basin from publications (Woodroofe et al., 1996; Cheung et al., 2008; Salini Costruttori S.p.A and SP studio ing.g.pietangeli s.r.l., 2006), and also direct from the Ethiopian National Meteorological Agency in Addis Ababa (Avery, 2012, vol. I, pp. 115–120). We obtained design rainfall data for the lower Omo plantation areas from various Sugar Development Corporation and associated documents (WWDSE and CES, 2012b, p. 22; WWDSE, 2014, sec. 4.2, p. 14; Wolde and Adane, 2014). We have supplemented these with data provided by Ethiopian authorities to

UNESCO (UNESCO-ICOMOS, 2015). We derived our own rainfall gradient for the lower Omo from TRMM rainfall data.

Measuring lake air and water temperature

We obtained historic air and lake water temperature data from the Kenya Meteorological Department and Lake Turkana Project 1972–75. We contrasted the historic data with the more recent ARCLake satellite dataset provided by the School of Geosciences, University of Edinburgh (Avery, 2012, vol. I, pp. 123–125). We recently obtained historic lake water temperature data for 1990 (Halfman, 1996), this dataset being restricted to the northern half of the lake.

Assessing lake surface water evaporation

Evaporation rates are conventionally measured using instruments installed at meteorological stations (WMO, 1981, vol. I, sec. 2.3, p. 2.3.2). But because of the difficulties measuring evaporation from lakes and reservoirs, indirect methods are recommended, including the water budget approach that we have adopted (WMO, 1981, vol. I, sec. 2.3, p. 2.40).

We have obtained the lake evaporation measurements of the Lake Turkana Project 1972–75 (Ferguson and Harbott, 1982, pp. 31–32). They operated an evaporation pan and an evaporimeter on the western lakeshore at Longech Spit on Ferguson's Gulf. They also analysed lake water level recession rates. They had logically concluded that if rainfall and inflow into the lake are negligible during the driest periods, the lake recession rate provides a direct measure of this lake's evaporation. The same water level recession technique has successfully been applied in arid zones elsewhere (Costelloe et al., 2007). In that case, the water bodies studied were in the Lake Eyre Basin, an arid zone in central Australia. As most of those water bodies have a clay base, groundwater exchange was inhibited, and hence in the absence of inflow, the water level changes provided a direct measure of evaporation loss.

The Lake Turkana Project subjected 20 separate years from 1945 to 1975 to regression analyses of water level recession rates. We tested this indirect method in our previous studies (Avery, 2012, vol. I, pp. 130–133). And we have updated this earlier analysis. We have computed the water level changes over each time interval in USDA's satellite lake water level database dated 1992–17. This series was then ranked in order of descending magnitude and a normal probability value was computed for each ranked value. Our analysis is based on standard hydrological flow duration methodology (WMO, 1983, vol. II, sec. 5.3.6.1, p. 5.75).

To supplement the above analyses, we applied standard double-mass hydrological analytical techniques to test different evaporation rates (WMO, 1983, vol. II, sec. 5.2.2.2, p.5.9). Cumulative flow sequences have been derived from our water balance model at different evaporation rates. These cumulative flows were plotted against other known cumulative data sequences (Avery, 2012, vol. I, pp. 213–215). Using this technique we ascertained which evaporation value provides the best fit to the known cumulative data series.

Assessing crop supplementary irrigation water requirements in the lower Omo valley

We have computed the supplementary irrigation crop water requirements of the Kuraz sugar plantation area using the CropWat decision support tool developed by the Land and Water Development Department of the Food and Agriculture Organization of the United Nations (FAO, 2017). We used FAO's CropWat tool in our earlier studies to estimate the irrigation water requirements in the lower Omo. We previously contrasted published data and a range of different crop water requirement scenarios (Avery, 2012, vol. I, pp. 61–64). We included schemes in semi-arid areas of Kenya that are comparable to the lower Omo (ibid.)

We have obtained the Kuraz project's design crop reference evapotranspiration computations from the project's hydrology and climatology report. The Ethiopian government's Water Works and Design Supervision Enterprise (WWDSE) undertook the studies for the Ethiopian Sugar Development Corporation (WWDSE, 2014, sec. 4.2.3, p. 15). The WWDSE report's computations were also based on FAO methodology. In the absence of measurement stations within the study area, WWDSE derived the mean climatic factors from "judicious combinations of various neighbouring stations" (WWDSE, 2014, sec. 4.2.0, p. 13) within the Omo basin and by applying the indirect approach of relating rainfall to altitude. The climatic factors included minimum and maximum air temperature, humidity, wind speed, and sunshine hours.

We later obtained more recent climate data from the Ethiopian Sugar Corporation (Wolde and Adane, 2014). Although dated 2014, this publication provides soil and air temperature and rainfall data collected between 2012 and 2015 at a meteorological station established within the project area itself. Wolde and Adane (2014) proposed a sugar planting cycle based on their new data, and we have adopted this cycle for our calculations.

The FAO CropWat tool was first developed 40 years ago. Standard updated procedures have since been published in which the Penman-Monteith combination method was adopted as the standard for reference evapotranspiration (Allen et al., 1998). This method uses standard readily available climatic data, and there are procedures for calculating the various parameters. Where site-specific data are not available, the FAO guidelines offer appropriate values from databases that FAO has compiled from all over the world.

Results and discussion

Lake water level sequence

As recently as 5500 years ago, Lake Turkana was 80–100 m higher than today and was overflowing into the Nile Basin (Ferguson and Harbott, 1982; Johnson and Malala, 2009; Garcin et al., 2012). In the late-1800s, the lake was still 20 m higher than its lowest contemporary levels of the mid-1940s, mid-1950s and the late-1980s (Fig. 3 a). Since the 1940s, the lake has been rising overall. A contributing factor will be the increasing human pressure and associated catchment degradation.

The Lake Turkana Project adopted the lake level on 10th September 1972 as their zero datum. They estimated this to be 365.4 m above mean sea level (masl), ±5 m (Ferguson and Harbott, 1982, p. 9). Through geodetic survey, we have established the zero datum to be exactly 365.4 masl EGM2008, and 365.07 masl EGM96 (Tullow Oil, 2015). The recent USDA satellite water level data includes a conversion factor to EGM2008 that is consistent with our survey.

Lake bathymetry and circulation patterns

The lake's original bathymetric survey derived lake contours (Fig. 3 b) and computed the lake surface area and storage at different elevations (Fig. 3 c, d). Our water balance model computes algorithms for the elevation/area/storage curves.

The lake has two interconnected basins, each reaching over 70 m deep (Fig. 3 b). The northern basin includes the Omo delta and northern and central sectors. The Turkwel sector is the narrowest part of the lake with depths not exceeding 30 m and is the link to the southern sector. The deepest point of the lake is over 100 m deep and is within the southern sector. Historically, Ferguson's Gulf has been the lake's most productive fishing zone. This gulf dries up when the lake elevation falls to 362.3 masl (Kallqvist et al., 1988, p. 17). The regulation of the natural cycles of Omo flows by the Gibe dams has dampened the effects of the Omo floods on the lake's currents. Nutrient influxes will have

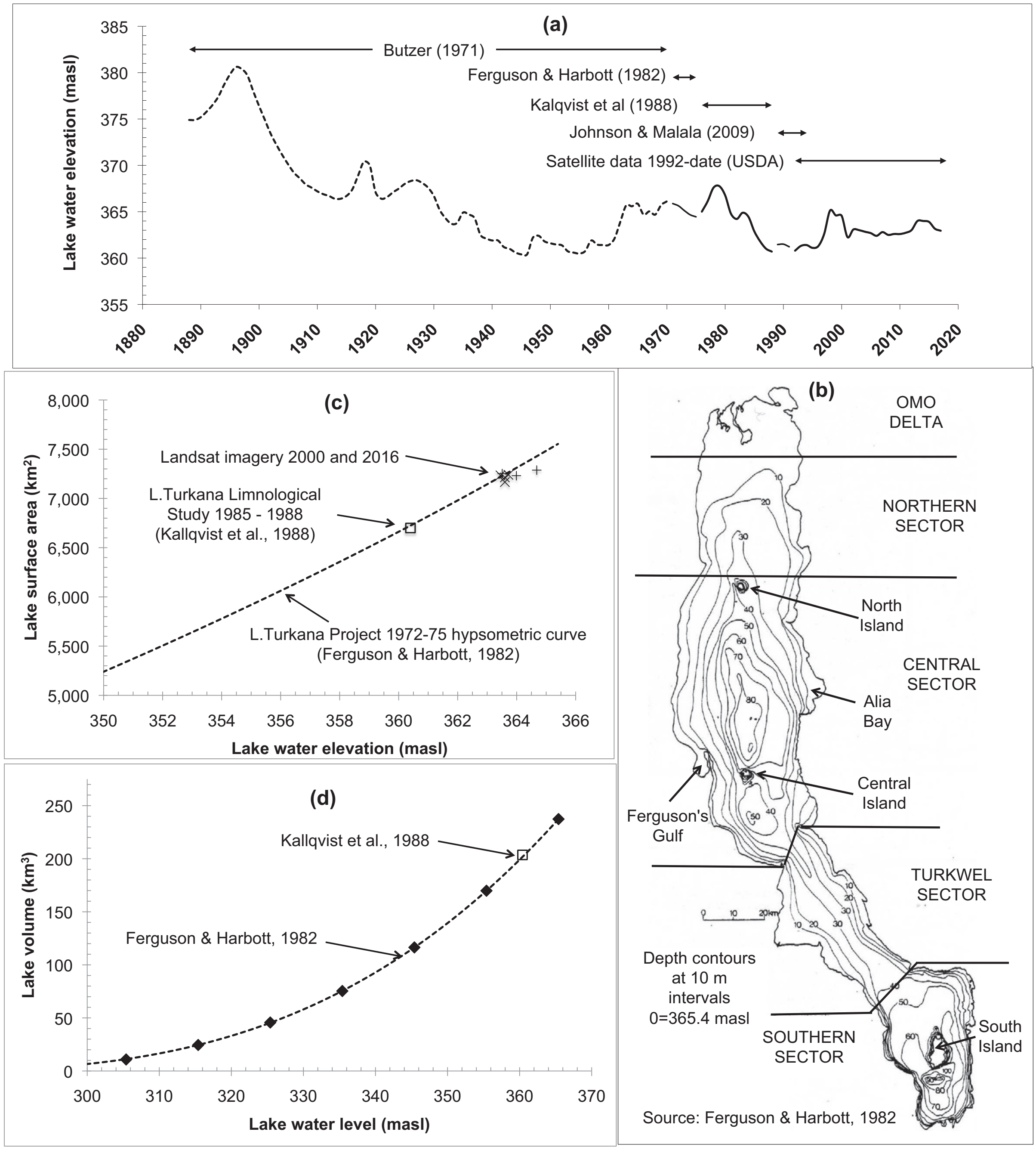

Fig. 3. Lake Turkana's contemporary water level and bathymetry characteristics: (a) Contemporary water levels from 1888 to 1949 pieced together from explorer's maps and colonial documents (Butzer, 1971). Water level gauge first installed on Ferguson's Gulf in 1949. Water levels since 1992 remotely sensed at ten-day intervals by satellite radar altimeters. (b) L. Turkana Project 1972–75 published lake bathymetry contours. The zero contour = 365.4 masl (Earth Gravitational Model 2008 at Kalokol location co-ordinates 3°33′18.49183″N, 35°54′56.57582″E). Ferguson's Gulf dries up at 362.3 masl. Kallqvist et al. "reconstructed" the bathymetric map by adding intermediate 5-m contours. One lower contour was also added and their zero datum was 5 m lower. (c) Lake surface area/elevation curve developed by the L.Turkana Project 1972–75. Verified by Kallqvist et al., 1988. We also verified upper curve with areas measured from Landsat imagery. (d) Lake volume/elevation developed by L.Turkana Project 1972–75 and verified by Kallqvist et al., 1988.

diminished and the past water circulation patterns in the northern and central sectors will have changed proportionally. This will have affected nutrient distribution by water currents, and affects fish feeding patterns.

The rivers draining into the lake and their catchment areas

We have delineated the Turkana Basin into sub-catchment areas based on data downloaded from HydroSHEDS (http://www.hydrosheds.org/; Fig. 1 a). This is a transboundary basin, and Ethiopia's perennial Omo-Gibe Basin comprises half the drainage area (sub-catchment 2). The Kerio River and the lake's surrounding littoral drainage are within Kenya (sub-catchments 4, 5, 3 and 7). And the Turkwel River is essentially within Kenya, but its western fringe rises in Uganda (sub-catchment 6). Sanderson's Gulf near Todenyang (sub-catchment 1) drains the area northwest of the lake. This includes the Ilemi Triangle whose borders are disputed by Sudan and Kenya (Collins, 2005). Sanderson's Gulf became isolated from the lake between 1908 and 1920 when the lake level receded (Ferguson and Harbott, 1982, p. 8). The Gulf has since been a closed basin periodically flooded by the Kibish River and by overland flood flow from the Omo (Butzer, 1971, p. 41; Avery, 2012, vol I, pp. 140–142). The water table beneath the isolated Gulf will be hydraulically connected underground to the main lake, as are crater lakes on Central Island (Avery, 2012, vol. I, p. 160).

The lake's water quality

The lake's strong winds ensure the water is well mixed with minimal thermal stratification. Consequently, the water is well oxygenated at all depths. However, despite this mixing the specific conductivity levels of the lake water increase along the length of the lake from north to south and are higher in sheltered areas like Ferguson's Gulf due to evaporation (Avery, 2012, vol. I, pp. 163–166). The salinity gradient reflects the significant dilution effects of the inflowing freshwater contributions of the vast Omo River (Yuretich and Cerling, 1983). This river's average annual inflow volume equates to near 10% of the entire lake volume.

The lake water is alkaline and moderately saline, the principal ions being Na^+, HCO_3^- and Cl^- (Fig. 4). When compared to incoming river water, the lake has been concentrated 100 times (Yuretich and Cerling, 1983). In addition, nitrogen concentrations are low (<100 μg/L) (Kallqvist et al., 1988). Nitrates are rapidly utilised and nitrogen is a potential limiting nutrient. Silicate levels are high and there are permanently high levels of phosphorus. Noteworthy from a health perspective are the fluoride concentrations in the main lake, which generally exceed 10 mg/L, with lower levels within the Omo delta dilution zone (Avery, 2012, vol. I, p. 174).

The contemporary Lake Turkana is the most saline lake in East Africa containing normal fish fauna. The lake's fish fauna is Nilotic and also includes endemic species (Hopson and Hopson, 1982, p. 284). Unlike so many African lakes, the lake has not yet been impacted by the introduction of alien species. But the salinity was said to be at a critical level to various fauna, and at the extinction limit for molluscs (Yuretich and Cerling, 1983). With increasing salinity levels, fish dwarfism may occur (Beadle, 1974; Yuretich and Cerling, 1983). The lake already lacks extensive marginal vegetation, and the salinity inhibits alien plant proliferation except within the fresher waters of the delta areas.

The salinity has been very slowly rising since the lake became a closed basin. At that time the water was fresh. Actual conductivity measurements are of course only recent (Fig. 4). Values since 1932 varied in the range 2860 to 3830 μS/cm, and up to 6900 μS/cm in Ferguson's Gulf (Avery, 2012, vol. I, pp. 162–164). Comparable values in the fresh water of the Omo river were 80 μS/cm (Hopson, 1982) and <200 μS/cm in the Omo delta (Avery, 2012, vol. I, table 39, p. 165). But upstream river developments that deplete the incoming Omo water volumes will accelerate the natural salinity increase rate, potentially reaching the catastrophic level for fisheries.

The lake water quality is generally not suitable for either human or livestock consumption (MALDM, 1994; Avery, 2012, vol. I, p. 172–173). It contains unacceptably high fluoride concentrations (ibid., pp. 170–171). At fluoride concentration > 10 mg/L crippling skeletal fluorosis may ensue in humans (WHO, 1984, vol. 1, p. 55). The symptoms of skeletal fluorosis are evident amongst lakeshore inhabitants (Avery, 2012, vol. I, p. 173). The lake salinity level is unsuitable for irrigation water use (Avery, 2012, vol. I, p. 175). In contrast, the quality of incoming river waters is generally chemically suitable for all uses.

Rainfall on the lakeshore and over the lake

The average annual rainfall declines along the lakeshore from north to south. At Todenyang, Ileret, Alia Bay, Lodwar and Loiyangalani (Fig. 1 b), the mean annual rainfall measurements are 324, 280, 240, 192, and 152 mm respectively (Avery, 2012, vol. I, pp. 127–128). The arithmetic mean of these lakeshore readings is 238 mm/y, and this is 1.3 times the Lodwar rainfall mean.

Lodwar's annual rainfall since 1921 has varied in the range 18.5 to 472.3 mm/y (Fig. 5 b). The high inter-annual variability is characteristic of arid areas, and droughts do occur. The TRMM 3B42 Lodwar results are for a much shorter period, but are consistent with the ground-based meteorological record except that there is a 24% positive bias (Fig. 5 c). But there are points of inflection on the graphs, and these indicate some change to the data. The TRMM 3A12 and CHIRPS data displayed a negative bias. Another study has similarly reported a positive bias with satellite rainfall data that requires the introduction of a bias correction in modeling (Velpuri et al., 2012). And a global study also showed

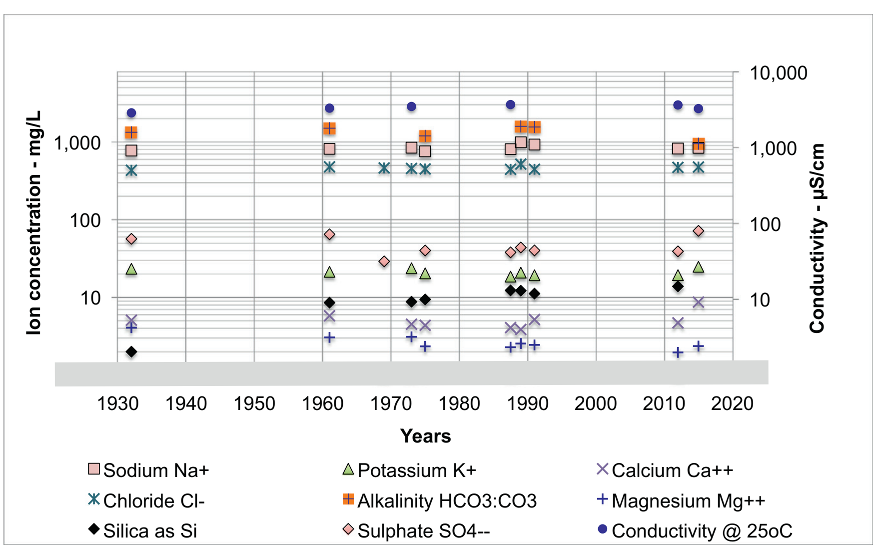

Fig. 4. Lake Turkana chemistry: Some baseline data are included from various sources: 1932 data (Beadle, 1932); 1961 data (Talling and Talling, 1965); 1969 data (Walsh and Dodson, 1969); 1973 data (Hopson, 1982); 1975 data (Yuretich and Cerling, 1983); 1987–88 data (Kallqvist et al., 1988); 1989 data (Dunkley et al., 1993); 2012 data (Avery, 2012, vol. I, pp. 163–176); 2015 data (Tullow Oil, 2015, sampling by S.T. Avery, analysis by SGS Laboratories, Kenya). No obvious trends are noted. Variability is likely attributable to differing sampling methodology and locations, dilution effects linked to lake level variations, and different laboratory procedures.

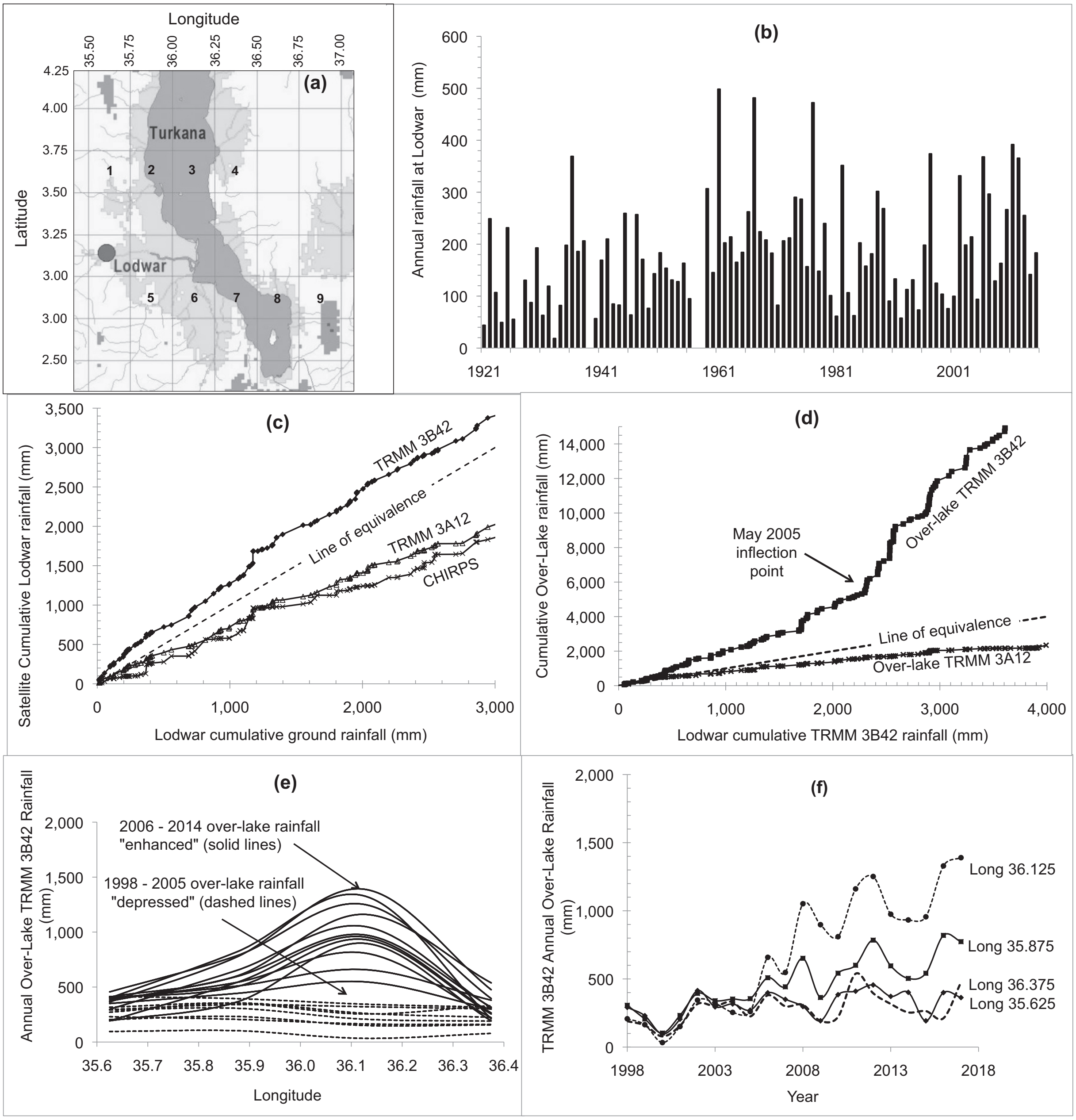

Fig. 5. Lodwar and over-lake rainfall: (a) Map shows location of Latitude 3.625 Transect 1–4 (from the western shore across the lake to the eastern shore). (b) Lodwar's inter-annual rainfall variation 1921–2015. The increasing volume trend of middle and later years is visibly apparent. (c) TRMM 3B42, TRMM 3A12 and CHIRPS cumulative satellite rainfall for Lodwar compared with Lodwar Met. Station's ground data. Note the positive bias of TRMM 3B42 and negative bias of TRMM 3A12 and CHIRPS. (d) TRMM 3B42 and TRMM 3A12 cumulative satellite over-lake rainfall at arbitrary points on the lake compared with Lodwar's TRMM 3B42 satellite data for 1998–2015. Note the significant TRMM 3B42 over-lake enhancement compared to Lodwar. Note the TRMM 3B42 over-lake change of slope in May 2005. Note TRMM 3A12 negative bias compared to Lodwar TRMM 3B42 and note change of slope. (e) Note Transect 1–4's TRMM 3B42 "depressed" over-lake rainfall from 1998 to 2005 (dashed lines) contrasted with TRMM 3B42's "enhanced" over-lake rainfall from 2006 to 2014 (solid lines). This scenario is improbable. (f) Transect 1–4's TRMM 3B42 over-lake 1998–2018 rainfall trend in each pixel of Transect 1–4. Note dramatic over-lake increase from 2005 consistent with the change of slope noted in (d). These satellite over-lake data are unreliable.

the negative bias of the CHIRPS data west of Lake Turkana (Funk et al., 2015).

In arid areas, annual rainfall volumes can vary considerably over short distances. This is well illustrated by the historic data for Longech and Kalokol located close together on Ferguson's Gulf and with Lodwar some distance southwest (Fig. 1 b). In 1973, the annual totals were 227.1, 129.4 and 212.0 mm respectively (Kenya Meteorological Department; Ferguson and Harbott, 1982, p. 89). In 1974, the annual totals were 214.7, 201.0 and 290.3 mm respectively. Although only 8 km apart, Longech's annual total in 1973 was nearly double the annual rainfall at nearby Kalokol over the same period. In the following year, they were nearly identical.

For our updated modeling, we have continued to adopt Lodwar's ground-based rainfall as our lake baseline. We have factored the Lodwar data 1.3 times in order to reflect the arithmetic mean shoreline rainfall for the entire lake. The factored Lodwar data is then subjected to enhancement in the water balance model to derive the over-lake rainfall input. We investigated the over-lake enhancement as follows:

The early assessments for direct rainfall on Lake Turkana include 250 mm/y (Kallqvist et al., 1988) and <200 mm/y (Halfman and Johnson, 1988). These were estimates, not measurements. In our earlier work, we estimated rainfall over the lake by assuming 20% enhancement of the Lodwar monthly rainfall series (Avery, 2012, vol. I, sec. 18.5, p. 210). That computation was $1.2 \times 184.1 = 221$ mm/y, comparable to the published estimates cited above. However, water-balancing studies on Lake Victoria found the over-lake rainfall to be 25 to 30% enhanced when compared to rainfall over the surrounding land area (Piper et al., 1986; Nicholson and Yin, 2001). Satellite-based over-lake measurements on Lake Victoria have yielded rainfall enhancement of between 33% and 85% over the basin rainfall (Kizza et al., 2012). The 33% enhancement was determined using the same TRMM 3B42 satellite product that we have used. The much higher 85% enhancement came from the PERSIANN satellite product.

UNEP reported satellite measurements of over-lake rainfall for Turkana averaging 65 to 40 mm/month from 1998 to 2009 (UNEP, 2012; Velpuri et al., 2012). These are equivalent to 780 to 480 mm/y. When compared to our estimated lakeshore rainfall average of 238 mm/y, these equate to over-lake rainfall enhancement of 327% to 200%. Our own TRMM over-lake rainfall data download from 1998 to 2004 averaged 24.9 mm/month (298 mm/y), and from 2005 to 2014 they averaged 67.6 mm/month (811 mm/y). On average, the TRMM results are of similar order to the UNEP results. But, the averages of the two TRMM time periods differ by almost 300%, which is questionable. Inconsistencies are also revealed by our sample transect of TRMM data across the lake at Latitude 3.625 (Fig. 5 e). This transect suggests depressed over-lake rainfall from 1998 to 2005 and enhanced values from 2066 to 2014; and between 1998 and 2017, the over-lake rainfall increased 7-fold (Fig. 5 f). In direct contrast, the UNEP study reported a decline. An obvious inconsistency in the TRMM over-lake data over time is also revealed by the cumulative rainfall comparison with the Lodwar TRMM data (Fig. 5 d). The change of slope in May 2005 is a clear indication of a major change at that point.

We have presumed that the inconsistencies within the satellite data have arisen from differing measurement sensors at different times. UNEP used measurements by passive microwave instruments. TRMM used both microwave and infrared measurements supplemented by ground data when available. As no over-lake measurements exist, there is no "ground"-truthing yet with which to explore inconsistencies. To derive the over-lake rainfall for our lake water balancing, we instead adopted an enhancement of 30% over the shore rainfall.

Rainfall over the lower Omo's Kuraz sugar plantations

The Omo-Gibe Basin Master Plan developed a map of annual isohyets for the basin draining to the lake from Ethiopia (Woodroofe et al., 1996, vol. XI, F1, p. 14). That same map was reproduced in hydrological studies for the Gibe III dam design (Salini Costruttori S.p.A and SP studio ing.g.pietangeli s.r.l., 2006, p. 12). The lake area was not studied. In the highlands, the average annual rainfall reaches 1900 mm and diminishes on descending south to the lake. Rainfall seasonality changes from unimodal peaking in July/August to the bimodal peaking in April and November (Fig. 6 a) that is characteristic of the lower Omo and lake area (Avery, 2012). The master plan isohyetal map shows the average annual rainfall declining from 750 mm at the Kuraz intake to 300 mm at the lake's Omo delta. Our TRMM rainfall studies have shown the rainfall declining from 1200 mm to 400 mm over this section (Fig. 6 b). These TRMM results suggest higher rainfall than the master plan, but have not been ground-truthed.

The Kuraz sugar plantation's supplementary irrigation design abstractions from the Omo River were originally based on an annual average expectation of 482 mm rainfall (WWDSE and CES (India), 2012b, p. 22). This was the arithmetic mean of rainfall measured at ten climate stations (Jinka, Kako, Key Afer, Omoratte, Turmi, Weito, Konso, Burji in Ethiopia; and Lokitaung and Banya in Kenya). In 2014, the Kuraz design rainfall was revised upwards to 661 mm (WWDSE, 2014, sec. 4.2.0, table 4.1, p. 14). This higher figure was derived from a slightly different set of climate stations, all within Ethiopia, in both highlands and lowlands (Jinka, Kako, Key Afer, Omoratte, Turmi, Weito, Hana, Dimeka and Erbore). In 2015, the Ethiopian authorities provided Kuraz rainfall data to UNESCO for the period 2011–14. That annual rainfall data totaled

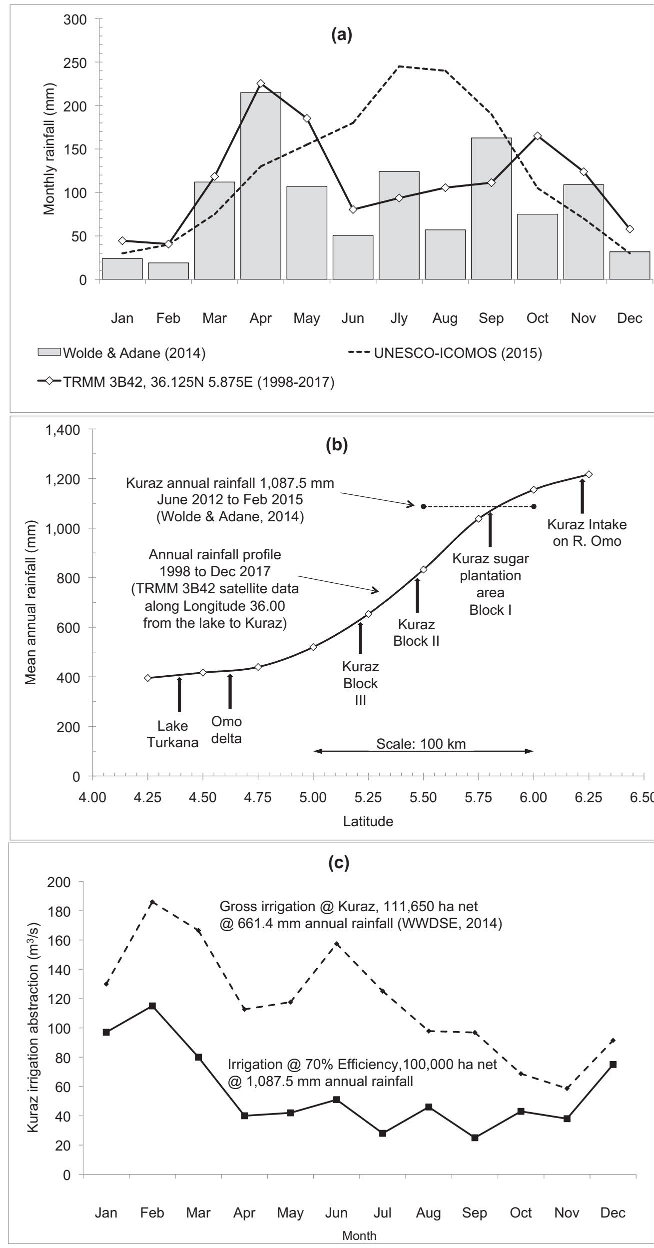

Fig. 6. Rainfall patterns and sugar irrigation requirements in lower Omo: (a) Mean monthly rainfall distribution at Kuraz from TRMM 3B42 (our study), Wolde and Adane (2014), and UNESCO-ICOMOS (2015). Note the incompatible unimodal pattern of data provided to UNESCO-ICOMOS. (b) Longitudinal mean annual rainfall profile along Longitude 36.00 from Kuraz intake to L.Turkana. Wolde and Adane (2014) did not derive a longitudinal profile and their data is shown by a horizontal dotted line. (c) Monthly irrigation requirements at Kuraz computed by FAO's Cropwat. The upper curve (dashed line) is from Kuraz project design documents. The lower curve (solid line) is our computation based on the revised rainfall and irrigation areas.

1490 mm (UNESCO-ICOMOS, 2015, p. 15 and p. 20). This is near treble the original design assumption. There are no details about the data source. But the rainfall profile is shown as unimodal and peaking in July (Fig. 6 a), which is not representative of this location. At much the same time, data have been reported from a meteorological station within the Kuraz project area itself (Wolde and Adane, 2014). These useful measurements from June 2012 to February 2015 averaged 1087.5 mm per annum and are more expectedly seasonally bimodal (Fig. 6 a). They are compatible with our TRMM results, but the rainfall gradient through the project area was not assessed (Fig. 6 b). This gradient is an important consideration as the supplementary irrigation abstraction needs increase with declining rainfall. Our TRMM results show the rainfall declining with falling altitude to 600 mm/y in the planned Kuraz plantation Block III (Fig. 6 b). With potential bias correction, that figure could be near identical to the original design figure of 482 mm/y.

Evaporation loss from the lake surface and lake warming

The evaporated water depth is the crucial element of the lake water balance (Avery, 2012, vol. I, pp. 129–131). We have updated our previous work and compared data from other arid zones (Table 1). The Lake Turkana Project observed relatively high evaporation rates persisting on the lake throughout the year (Hopson, 1982, vol. 6, fig. 1.43). Their evaporation pan measured 5800 mm/y (15.9 mm/d) (Ferguson and Harbott, 1982, p. 32). But they noted that wave action had precluded installing floating evaporation pans in the lake. Instead their evaporation pan was placed on the shore. As a result the water temperature in the evaporation pan was 3 °C higher than the adjacent lake water. They thus concluded that their shore-based evaporation pan measurements of 5800 mm/y over-estimated actual lake surface evaporation. Their lakeshore evaporimeter recorded 3200 mm (8.8 mm/d). This result was much lower, but they suggested it should be reduced further by a factor. They were uncertain what factor to apply to the evaporimeter data. They also estimated the annual lake surface evaporation from lake recession rates to be 2335 mm/y (6.4 mm/d). However they had no Omo lake inflow measurements and they assumed these to be "minimal" during the dry periods. We have checked this assumption using EWRA's later flow measurements at Omorate from 1977 to 1980. Even during the Omo River's lowest flow periods, the Omo inflow at that time could not be assumed minimal in terms of lake level change. Thus the Lake Turkana Project's evaporation rate derivation from lake water level recession data needs to be adjusted upwards (Avery, 2012). As an example of this adjustment, the lowest monthly discharges in the 1977–80 EWRA database were 20, 240, 247 and 137 m^3/s. These low flow inflow values equated to between 0.2 and 2.7 mm/d water depth on the lake surface. Similarly the Omo basin master plan's lowest monthly flow in each of the years 1956 to 1994 varied from 55 to 313 m^3/s and averaged 124 m^3/s. The original recession data were not published; so we have been unable to complete the adjustments.

We have analysed water level changes from 1993 to 2017 (Fig. 7). The database time interval is ten-days (the satellite overpass interval).

Table 1
Lake evaporation loss.

Evaporation (mm/y)	Method	Data source
Lodwar Met Station		
3488	Pan Type A, Lodwar Met. Stn. 1961–80	KMD, 1984
2625	Penman Eq. Et, Lodwar Met. Stn.	Kalders, 1988, p. D42
Lake Turkana		
5800	Lakeshore Pan	Ferguson and Harbott, 1982, p. 31
3200	Piche evaporimeter	Ferguson and Harbott, 1982, p. 32
2335	Lake recession, zero lake inflow assumed	Ferguson and Harbott, 1982, p. 32
2482–3029	Lake recession with Omo inflow added	Avery, 2009, 2010, 2012
2900	Simulated (Gibe III study)	Salini Costruttori and Studio Pietrangeli, 2010, p.28
2160–2640	Veg Et modeling	UNEP, 2012, fig. 17
2810	Simulated (Gibe IV study)	Salini Impregilo and Studio Pietrangeli, 2016, p. 42
3029	Lake recession, value-duration and double-mass analyses	This study
Other lakes		
1500–2500	Modified Penman Eq. (Australia)	Costelloe et al., 2007
2070–2270	Lysimeters (Lake Chad)	Bouchez et al., 2016

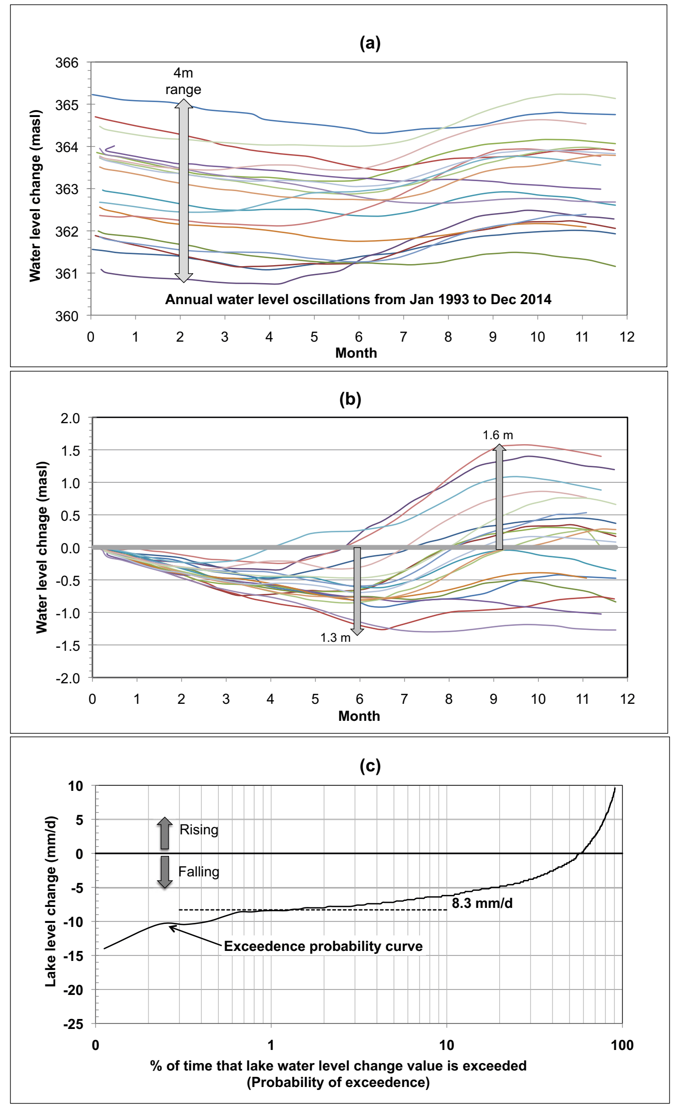

Fig. 7. Lake level changes: (a) The lake's monthly water level cycle relative to mean sea level plotted for each calendar year to demonstrate the lake's diverse range of water levels. (b) The same series of annual water level cycles anchored to a zero datum at the beginning of each year to demonstrate the diverse range of the lake's natural rise and fall cycles. (c) The probability curve of lake level change rates in mm/d using standard value-duration analysis methodology. The evaporation loss rate of 8.3 mm/d was adopted for our lake water balance model.

The water level can rise and fall over any ten-day period up to 10 mm/d on average. The highest 10-day lake recession was 14 mm/d (Fig. 7 c). The highest 10-day rise was 65 mm/d. But these are outliers, being two extremes in a database of 893 values. The outliers are acceptable as the satellite water level measurements are noisy, and the data we have used have been smoothed at source.

The Gibe III dam design team adopted our double-mass curve methodology to similarly derive the annual lake evaporation loss (Salini Costruttori and Studio Pietrangeli, 2010; Salini Impregilo and Studio Pietrangeli, 2016). They proposed 2900 mm annual lake evaporation loss (7.9 mm/d) (Table 2). But their analysis disregarded other river inflows. UNEP's study used satellite-based evapotranspiration methodology. They determined that in the period 1998–2009 the annual lake evaporation increased from 2160 to 2640 mm/y (5.9 to 7.2 mm/d) (Velpuri et al., 2012; UNEP, 2012) (Table 2). These satellite-derived values have not been ground-truthed on the lake. Our early studies tested a range of values, and the cumulative runoff comparison between the lake model and the master plan simulations correlated closely at the

Table 2
Omo annual lake inflows.

Inflow m^3/s	Inflow km^3/y	Derivation method	Source
526	16.6	1956–1994 rainfall runoff simulated	Woodroofe et al., 1996
560	17.7	1993–2008, Lake model @ 7.2 mm/d loss	Avery, 2010, p. 3–6
502	15.8	1956–1994, Lake model @ 6.8 mm/d loss	Avery, 2010, table 26, p. 3–7
535	16.9	1956–1994, Lake model @ 7.2 mm/d loss	Avery, 2010, table 26, p. 3–7
627	19.8	1956–1994, Lake model @ 8.3 mm/d loss	Avery, 2010, table 26, p. 3–7
650	20.5	Simulated flow	Salini Costruttori and Studio Pietrangeli, 2010; Salini Impregilo and Studio Pietrangeli, 2016
555	17.5	1993–2011, Lake model @ 7.2 mm/d loss	Avery, 2012, vol. I, p. 213
729	23.0	Simulated flow	WWDSE and CES, 2012b, p. 1
750	23.6	Simulated flow	Studio Galli Ingegneria and Sembenelli Consulting, 2013, p. 14
650	20.5	Simulated flow	Velpuri et al., 2012
517	16.3	Simulated flow	WWDSE, 2014, sec. 9.4, p. 66
826	26.0	Simulated flow	IGAD - INWRM, 2015a, Arba Minch, p. 5
526	16.6	Flow cited from Woodroofe et al., 1996	IGAD - INWRM, 2015b, Mekelle, p. 21
570	18.0	Aquastat database	FAO, 2016
632	20.0	1993–2014 Lake Model @ 8.3 mm/d loss	This study

uppermost evaporation value of 3029 mm/y (8.3 mm/d) (Avery, 2012; Table 2).

We have re-modeled lake inflows from lake levels at an evaporation loss rate of 8.3 mm/d. These inflows replicate the annual rise and fall cycles until the Gibe III filling commenced (Fig. 8 a). They also correlate with the cumulative lake inflow simulations of the Omo-Gibe Master Plan (Woodroofe et al., 1996) and the Kuraz sugar plantation feasibility study (WWDSE, 2014) (Fig. 8 b).

The lake's exceptionally strong prevailing southeasterly winds are notable, and these enhance the surface evaporation process. The daily wind run measured at Lodwar 50 km west of the lake averaged 203 km/24 h (KMD, 1984). On the lake itself, winds are fiercest in the south (760 mean and up to 1100km/24 h), diminishing in force to the north (163 km/24 h mean) (Hopson, 1982, vol.6, fig. 1.34; Ferguson and Harbott, 1982, p. 28). Long-term wind trends have not been studied on the lake. And the lake mean air and water temperatures have increased about 1 °C since records began in 1972 (Avery, 2012, fig. 39). Assuming no reduction in wind force and patterns, evaporation losses will thus be rising gradually with warming over time.

Water abstraction and seepage from the lake

There is no water abstraction from the lake. Chemical balance studies of the lake ruled out the possibility of any major sub-surface seepage outflow from the lake to the south and west (Dunkley et al., 1993; op. cit. Yuretich and Cerling, 1983). We have thus assumed zero outflow from the lake.

There are small perennial artesian springs at points above the lake's shoreline. And apart from minor recharging of the immediate lakeshore storage during periods of lake level rises, the net groundwater flow is towards the lake (Pers. Comm., Tullow Oil, Kenya, 2018). The groundwater contribution to the lake from the Kenyan catchments is believed to be small, perhaps as little as 2.7 m^3/s (ibid).

River inflows into the lake

Through the lake water balance model we generated the monthly Omo River inflows from the satellite water level series (Fig. 8 a). Over this period the Omo's lake inflow averaged 20.0 km^3/y (Fig. 9). The

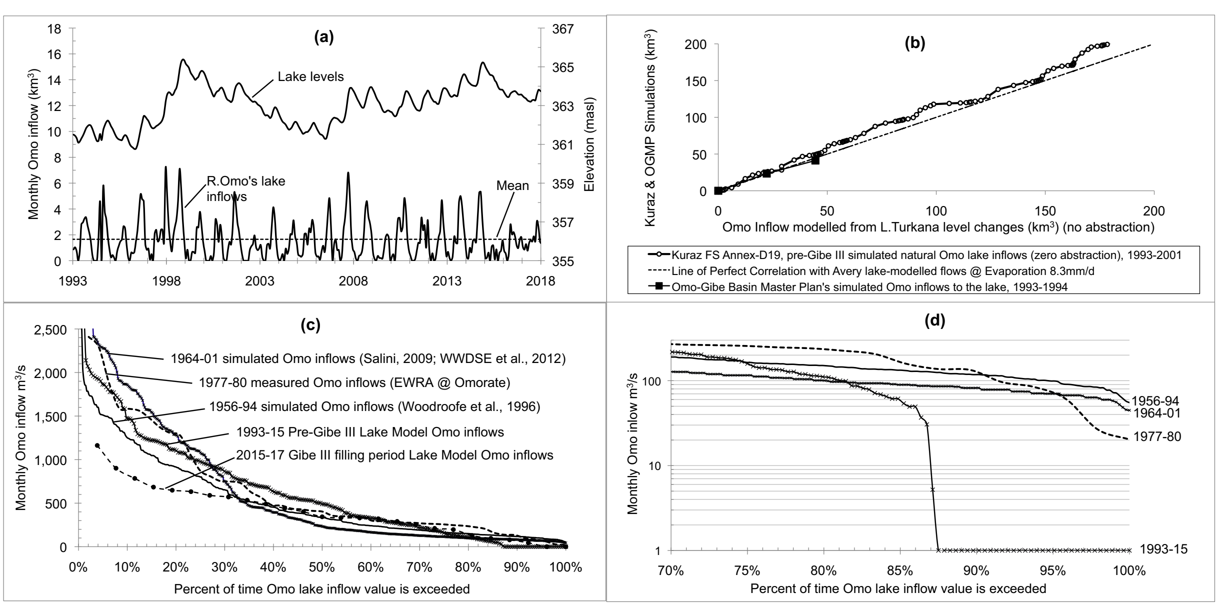

Fig. 8. Omo lake inflow analyses: (a) Satellite lake levels 1993–2018 (top graph). Omo River lake inflow hydrographs generated from lake water balance modeling (bottom graph with mean inflow shown dashed). Note the annual rise and fall cycle up to the time that Gibe III was commissioned. (b) Double-mass analysis to check the degree of correlation between our modeled Omo River inflows and lake inflow sequences from the Omo-Gibe basin master and from the Kuraz design hydrology simulations. (c) R.Omo lake inflow exceedance probability curves from our modeling compared with other studies. The lack of high flows during the Gibe III filling is illustrated. (d) Omo River lake inflow exceedance curves enlarged to better detail the low-flow periods.

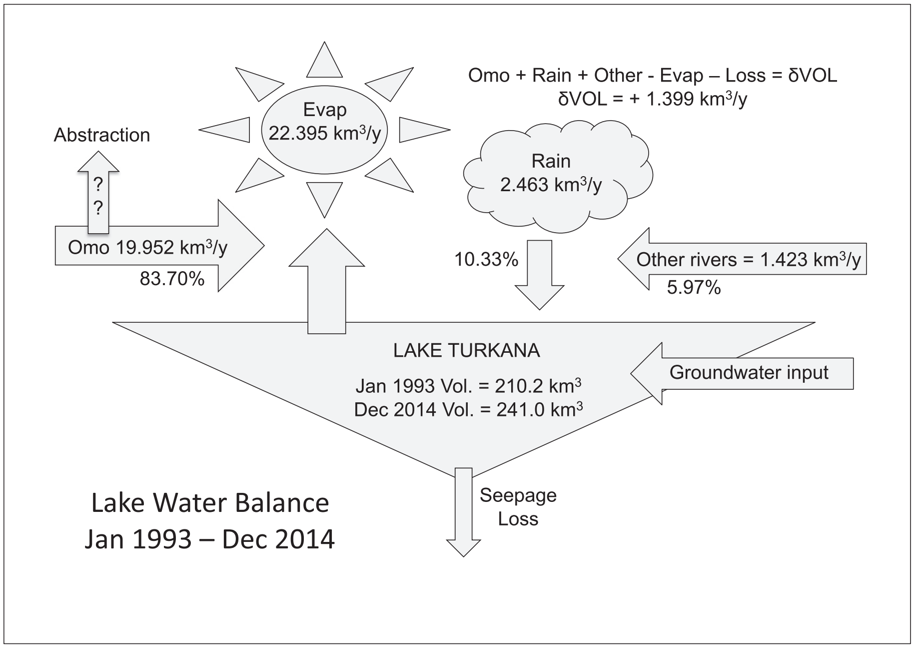

Fig. 9. Water balance model summary for Lake Turkana: Other river inflows: 0.426 km^3/y R.Turkwel (Sub-catchment 6), 0.746 km^3/y R.Kerio and Kartor (Sub-catchments 4 and 5), 0.251 km^3/y littoral (Sub-catchments 3 and 7). Abstractions and seepage assumed zero (negligible). During the modeling period, there was a rise in lake water elevation, hence water was taken into storage.

Omo-Gibe basin master plan 1956–94 simulations averaged 16.6 km^3/y (Woodroofe et al., 1996) (Table 2). Other recent study results varied up to 19.8 km^3/y depending on the lake evaporative loss (Avery, 2010, 2012), and 20.5 km^3/y (Salini Costruttori and Studio Pietrangeli, 2010; Salini Impregilo and Studio Pietrangeli, 2016), and in the case of one Ethiopian study, 26.0 km^3/y was proposed (IGAD-INWRM, 2015a) (Table 2).

Our modeled pre-Gibe III flow-duration pattern is directly comparable to other simulations (Fig. 8 c). And it is comparable to the only existing flow measurements by EWRA dated 1977–80 (Fig. 8 c). In the recent years low flows have tended to persist longer (1993–15 in Fig. 8 d). This is to be expected with catchment degradation and the increasing small-scale irrigation abstractions from the river in recent years.

Our modeled inflow hydrograph replicated the important pronounced natural flood period between July and November that would recharge the lake (Fig. 10 a). Flows would recede in the early part of the year and increase significantly from April to August/September. The flows then receded until the following year's annual cycle repeated. The floods and associated lake level changes are vital drivers of the lake's ecology. They stimulate the lake's ecological diversity with level oscillations acting as a nutrient pump.

In the absence of a flow gauging station on the Omo at the lake, the lake model very usefully monitors surface water influx, and does so remotely. Being at the lowest point of the basin, the lake's level and water quality are the ultimate indicators of hydrological and other changes in the basin. The master plan reported an increase in the runoff in the Omo Basin as a consequence of deforestation since the 1980s (Woodroofe et al., 1996). This is reflected in the rising lake level trend (Fig. 3 a). The Gibe III documents also reported hydrological extremes arising from heavy deforestation in the upper watershed (Agriconsulting S.p. A and Mid-Day International Consulting Engineers, 2009, p. 2). Global climatic events are increasingly more extreme. In Kenya's Rift Valley basin, the annual renewable surface water resource has been forecast increasing 1.5 times from 2010 to 2050 (Nippon Koei/JICA, 2013).

The Turkana basin has a history of climate-induced hydrological change dating back long ago (Johnson and Malala, 2009; Garcin et al., 2012). In contemporary times, the lake receded dramatically and was lowest in the 1940s (Fig. 3 a). The lake then rose over the period 1940s to early-1980s (Fig. 3 a). That period included several global climatic El Niño and Southern Oscillation (ENSO) events. There were

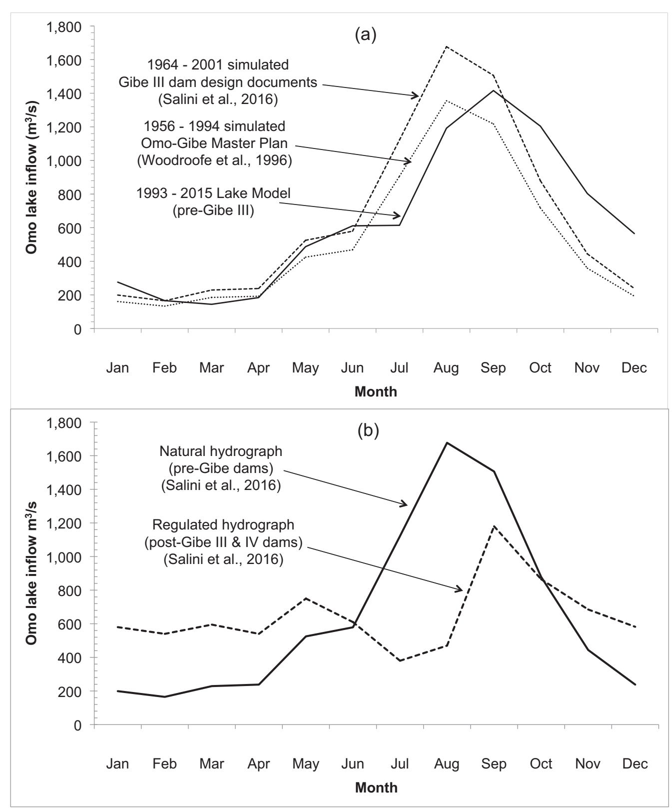

Fig. 10. Omo River's average lake inflow hydrographs: (a) Our modeled Omo lake inflow hydrograph compared with the basin master plan and Gibe III hydrological studies. These are the "natural" hydrographs that preceded the Gibe dams. (b) The pre-Gibe III natural hydrograph contrasted with the planned regulated post-Gibe III and IV hydrograph (both hydrographs abstracted from the Gibe dam design documents).

“strong” events dated 1957/58, 1965/66, and 1972/73, and a “very strong” event dated 1982/83.

The ENSO events are categorized by strength according to the Oceanic Niño Index (ONI) (National Oceanic and Administration National Weather Service, USA, website accessed May 2017). El Niño is associated with extreme rainfall, whereas the other extreme of the ENSO cycle, La Niña, is associated with drought. Since the 1950s, there have been twelve “weak”, six “moderate”, three “strong” and three “very strong” ENSO events. Whereas ENSO events are not always linked to extreme climatic events, they do account for up to 50% of the inter-annual rainfall variance in eastern and southern Africa (Ogallo, 1994). In East Africa, periods of well above average rainfall and river flows followed by drought are linked with the “very strong” ENSO events.

The regulation of the Omo river hydrograph by the Gibe dams

We analysed the natural lake level oscillations for each calendar year from 1993 to December 2014. The lake level invariably followed an annual rise and fall cycle, and over the years fluctuated over a 4 m range (Fig. 7 a). From the beginning of each year, the lake fell up to 1.3 m and later rose up to 1.6 m (Fig. 7 b). With river flow regulation by the Gibe dams, the lake's annual water level oscillations will instead be confined within a 300 mm band (Salini Impregilo and Studio Pietrangeli, 2016, p. 61).

The regulated flow regime commenced following Gibe III's inauguration in December 2016. The downstream Omo River discharge has since depended on the electrical generating requirements of Ethiopia's national electricity grid. Gibe IV is planned to come online in 2020 and will emulate the flow regulation created by Gibe III. Almost total flow regulation is planned (Fig. 10 b). The natural low flow periods from December to May have been uplifted and will be sustained most of the year. There will be a small natural flow peak in September. The only natural inflow cycle driving force will arise from rainfall on the unregulated residual catchment portion between the dams and the lake.

The Gibe III project proponents claim that the stabilization of lake water levels by flow regulation is “sensible” and positive for the lake (Salini Costruttori and Studio Pietrangeli, 2010, p. 2). They stated that “…in dry years, the flow regulation will contain the lake decline avoiding catastrophic shrinkage of the shores” (Salini Impregilo and Studio Pietrangeli, 2016, p. 59). No supporting data is provided on the catastrophes. And they stated that “…in wet years the flow regulation will contain the disastrous consequences (of large floods) for the downstream exploited areas and for the lake environment”. The Omo floods were stated to be “destructive to human and animal life, private assets and infrastructure” (Agriconsulting S.p.A and Mid-Day International Consulting Engineers, 2009, p. 2). The increasing floods were attributed to deforestation. We do agree that catchment degradation has likely affected the natural Omo hydrology. We have noted increased inter-annual flow variation in recent years in the flow record generated since 1956 (Avery, 2012), and the low flow duration regime had been altered (Avery, 2012). Our analysis confirms more pronounced low flow periods in recent years (Fig. 8 d). But some observers question the flood “destruction” claims (Pers. Comm., David Turton, African Studies Centre, 2012). The indigenous inhabitants of lower Omo traditionally practice flood recession agriculture and floods are highly valued. Depressions near the Omo delta naturally fill with water (Avery, 2012). The floods inundate oxbows and thereby stimulate cultivation (Sogreah, 2010, p. 36). The flood inundations and resultant groundwater recharge are of direct benefit to the rangelands (ARWG, 2009; Avery, 2009; Avery, 2012). Whereas floods are viewed with trepidation in the crowded modern world, in the lower Omo and the lake, they are a boon that boosts production. On the other hand, tillage practices along riverbanks need to be carefully managed (Avery, 2012). If riparian zones are disturbed, the runoff into the river increases, and erosion and sediment runoff processes are accelerated. In Kenya, tillage within riparian zones is forbidden but not generally enforced.

The project proponents claim that stabilizing Lake Turkana's water levels is “sensible”. Their claim is contrary to the findings of numerous scientific studies cited below. With the uniformity arising from flow regulation, the diversity of the lake's ecology will instead be adversely affected (Kratli and de Jode, 2015). Tropical fisheries studies long ago demonstrated that aquatic productivity increases with instability (Welcomme, 1979; Junk et al., 1989; both cited by Kolding, 1993). Lake Turkana is an “erratic ecological system” and its natural erratic behaviour stimulated the lake's natural resilience (Kolding, 1992). Tropical flood-plain fisheries are the most productive (Kolding, 1993). The lake's water level changes promote interaction between aquatic and terrestrial systems (Kolding, 1993). Lake level changes distribute nutrients from the shoreline into a lake's main body (Gaudet and Muthuri, 1981). Annual fluctuations in lake level are very much more significant than absolute level (Karenge and Kolding, 1995). And Lake Turkana's peak production rates have been associated with peak rises in lake level (Kolding, 1993).

The dampening of the inflow hydrograph and associated lake cycles must thus inevitably adversely affect the lake's aquatic productivity (Avery, 2009; Muska et al., 2012; Avery, 2012, 2013a). It has been predicted that complete loss of seasonal oscillations will decrease the lake fishery yield by over two thirds (Gownaris et al., 2015).

Ecological flows to the lake

The Gibe III dam is committed to maintain a minimum of 25 m^3/s in the river at all times (Agriconsulting S.p.A and Mid-Day International Consulting Engineers, 2009; Salini Impregilo and Studio Pietrangeli, 2016, p. 19). This corresponds to the lowest monthly average dry season flow in the river at the dam site. It is very little, amounting to <6% of the river's average daily flow. In addition, the dam has the hydraulic capacity to release a controlled flood of 1000–1200 m^3/s for 10 days in September each year to meet environmental and human needs. It had been assumed this flood would swell to 1600 m^3/s before reaching the lake (Agriconsulting S.p.A and Mid-Day International Consulting Engineers, 2009). The peak flood of 10-year recurrence interval has been estimated to be 4800 m^3/s (Agriconsulting S.p.A and Mid-Day International Consulting Engineers, 2009, p. 42). The controlled flood magnitude is less than the mean annual flood. Furthermore, the annual release of a controlled flood was later reported by the Ethiopian Power Corporation to be a temporary measure only (Pers. Comm., David Turton, 2012). This temporary flood release would allow flood recession agriculture only until the local people were socio-economically transformed away from their traditional livelihoods. The project proponents have harshly described the land use and livelihood practices of the indigenous population as “primitive” and “backward” (Agriconsulting S.p.A and Mid-Day International Consulting Engineers, 2009, p. 2). There is thus no onward commitment to release floods solely to sustain the lake ecology. And in spite of the scale of the Gibe projects and their potential ecological effects, no scientific studies have been done to quantify the ecological flow needs of the lake (Avery, 2009; Avery, 2012).

The effect of the filling of the Gibe III and Gibe IV reservoirs on the lake's water levels

The Gibe III reservoir required 15 km^3 of water to fill to full supply level (Salini Impregilo and Studio Pietrangeli, 2016). This volume equated to 75% of the basin's average annual discharge to the lake. The reservoir filling commenced in January 2015, and the dam was inaugurated in December 2016 (and presumed full). Lake Turkana's water levels plummeted 2 m during the filling period (Fig. 11 a and b). This had been predicted (Avery, 2012, vol. I, p. 220). By simulation, we have shown that the lake level would otherwise have risen (Fig. 11 b) during this period.

The Gibe III filling period coincided with one of the three strongest global climatic El Niño and Southern Oscillation (ENSO) events since

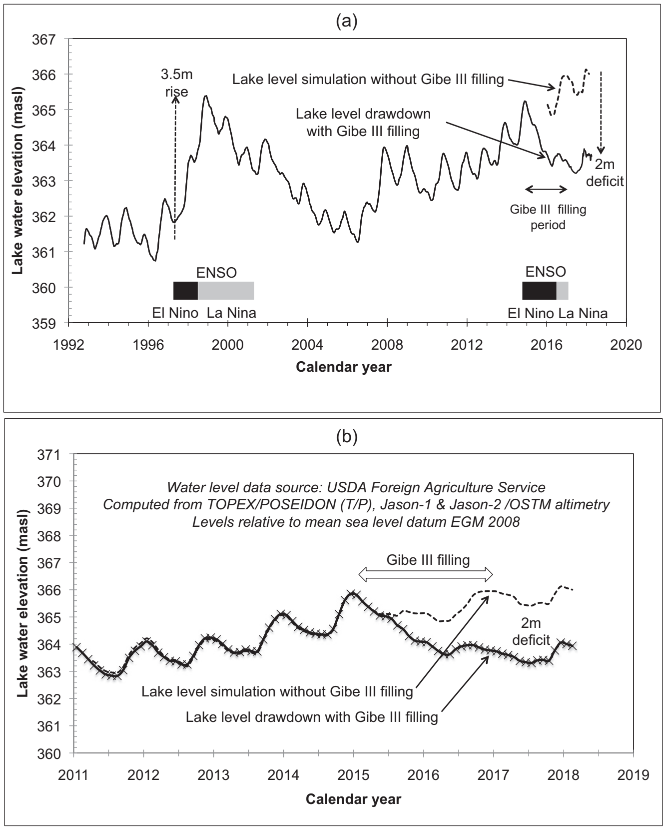

Fig. 11. Impact of the filling of Gibe III on Lake Turkana's water level: (a) Lake Turkana's lake level fluctuation is graphed. Two major ENSO event periods occurred (El Niño in black followed by La Niña in grey). The water level drawdown during the Gibe III reservoir filling is shown. (b) Lake Turkana's lake level drawdown during the Gibe III filling is contrasted with the simulation "without Gibe III" (upper dashed line). The filling resulted in a 2 m deficit.

the 1950s (National Oceanic and Administration National Weather Service, USA, website accessed May 2017). There have been two "very strong" ENSO events during the period for which satellite lake level data is available for Turkana. These events do not always affect East Africa (Ogallo, 1994), but during the 1997/98 El Niño the lake level rose 3.5 m (Fig. 11 a). And whereas Gibe III's reservoir was envisaged filling in three years (Salini Costruttori and Studio Pietrangeli, 2010, p. 3), the reservoir filled in only two years during 2015/16. This period coincided with a very strong El Niño, (Fig. 11 a).

There are no official fisheries statistics yet available for the Gibe III filling period (Pers. Comm., KMFRI, 2018). But our field observations and media reports confirmed a decline in fisheries catch during the Gibe III filling period (IRIN News, May 2017; The East African's article "A way of life under threat as lake shrinks", May 27–June 2, 2017). This is as would be expected as fisheries always decline with lake recession.

The Gibe IV dam will require 6.5 km^3 of water to fill its reservoir (Mid-Day, 2016, p. 196), with impounding planned to start in June 2020. The project proponents have stated that the resultant 0.9 m fall in lake level will "not be rapid, rather slow and gradual decline, favouring the adaptation of biological species to the change" (Salini Impregilo and Studio Pietrangeli, 2016, p. 52). No supporting scientific study citations were provided for this forecast.

Irrigation plans in the lower Omo valley and abstraction impacts on the lake

In 1996, the Omo-Gibe River Basin Integrated Development Master Plan forecast utilizing 5.34 km^3/y of water to meet the total basin water demand by the year 2024, with 94% of that demand being for irrigation water (Woodroofe et al., 1996, vol. XI, F1, p. 77). That water requirement forecast amounted to 32% of the entire average annual river discharge estimate at that time. It would amount to 26% of the updated current water resource estimate.

In 2011, Ethiopia's Sugar Development Corporation started clearing 245,000 ha of land for the Kuraz sugar cane plantations along both banks of the Omo. Much of that land has been excised from two national parks and a wildlife reserve (Cherie et al., 2011). Other significant known irrigation schemes include 10,000 ha of cotton development downstream from Kuraz (Omo Valley Cooperation, 2012). This cotton scheme's development area has since reportedly been increased to 50,000 ha (Kamski, 2016, p. 578). The full extent of irrigated development in the lower Omo valley is very unclear, as are the expected water abstractions. Ethiopian government documents have noted that the Omo's water resource could theoretically irrigate well over 1000,000 ha based on an estimated average annual water resource of 23 km^3/y (729 m^3/s) (WWDSE and CES, 2012b, p.19).

The Kuraz sugar project intake was designed to abstract 340 m^3/s (Studio Galli and Sembenelli, 2013, p. 39). When annualized to 10.575 km^3, this amounted to 50% of the Omo River flow. In 2014, the average Kuraz water requirement was computed to be 117 m^3/s for a net irrigated area 113,750 ha (Fig. 6 c upper curve). This amounted to 19.7% of the Omo flow at the scheme intake headworks (WWDSE, 2014, table 5.10, p. 34). In 2015, it was reported that rainfall had been under-estimated and that supplementary irrigation requirements are less than expected (UNESCO-ICOMOS, 2015, p. 22). The Ethiopian government advised that Kuraz would abstract only 4–6% of the Omo River. This amounts to an order of magnitude reduction in planned abstraction by the Kuraz project. The irrigated area was further reduced to 100,000 ha according to the website of the Sugar Development Corporation (Kamski, 2016, p. 574).

For the Kuraz plantation area, we reviewed the average monthly rainfall distribution data (Fig. 6 a). We also revised the longitudinal rainfall profile from the Kuraz intake to the lake (Fig. 6 b). And, we have applied FAO's Cropwat model to compute the average monthly infield irrigation requirements based on the revised higher rainfall value and reduced plantation area (Fig. 6 c, lower curve). The irrigation requirement varies from month to month and averaged 56.6 m^3/s. This amounts to 16% of the scheme's intake design capacity, and is higher than the 4–6% figure reported to UNESCO-ICOMOS. Also, the Cropwat model by default assumes 70% "field application efficiency", which is optimistic. In addition, water conveyance losses are not included. Hence the gross water requirement might be higher.

Conveyance losses comprise the water lost from the canals through percolation underground and through surface evaporation. The original Kuraz project design envisaged 254 km of main canals, 762 km secondary/tertiary canals, and 508 km drainage canals (WWDSE and CES, 2012a, p. 33). Hence, the total potential scheme conveyance losses were appreciable. FAO methodology allows conveyance losses through application of a "conveyance efficiency" factor. The "overall scheme efficiency" is then calculated as the product of "field application efficiency" and "conveyance efficiency". FAO criteria classify a "reasonable" overall scheme irrigation efficiency achievement to be 40%. But, it can be as low as 20% for schemes in the "poor" overall scheme efficiency category. Thus, the irrigation abstraction at Kuraz could potentially be 3.5-times what was reported to ICOMOS-UNESCO, and potentially >20% of the river might be abstracted by this scheme alone. The water abstraction of the 50,000 ha Omo Valley cotton plantation also needs to be considered. The available environmental impact assessment for that project (Omo Valley Farm, 2012) did not specify how much water would be abstracted. In addition, there are other plantations planned downstream for which there are no details. Hence the total potential irrigation water requirements from the river are more than the known figures for Kuraz.

We have modeled the lake's equilibrium level to be 364 masl at our selected evaporation loss rate and with zero abstractions (Fig. 12 c). The lake's lowest contemporary level was 360.4 masl (Fig. 3 a). And once the level falls below 362.3 masl, Ferguson's Gulf dries up totally (Kallqvist et al., 1988). When this happens, the lake's most productive fisheries zone is lost. With sedimentation, the Gulf's storage will already be diminishing. This important commercial fishing area is very vulnerable.

We have assessed the irrigation limits that can theoretically be achieved with the regulated river flow regime generated by the Gibe dams. Abstraction rates that exceed 50% of the annual average inflow to the lake would empty the Omo River at times (Fig. 12 c); and, at this high level of abstraction, the lake recession would be drastic (Fig. 12 b). The lake water elevation could potentially drop over 15 m below the historic lowest level. The associated lake shoreline shrinkage would especially affect the lake's northern and Omo delta zone (Fig. 13).

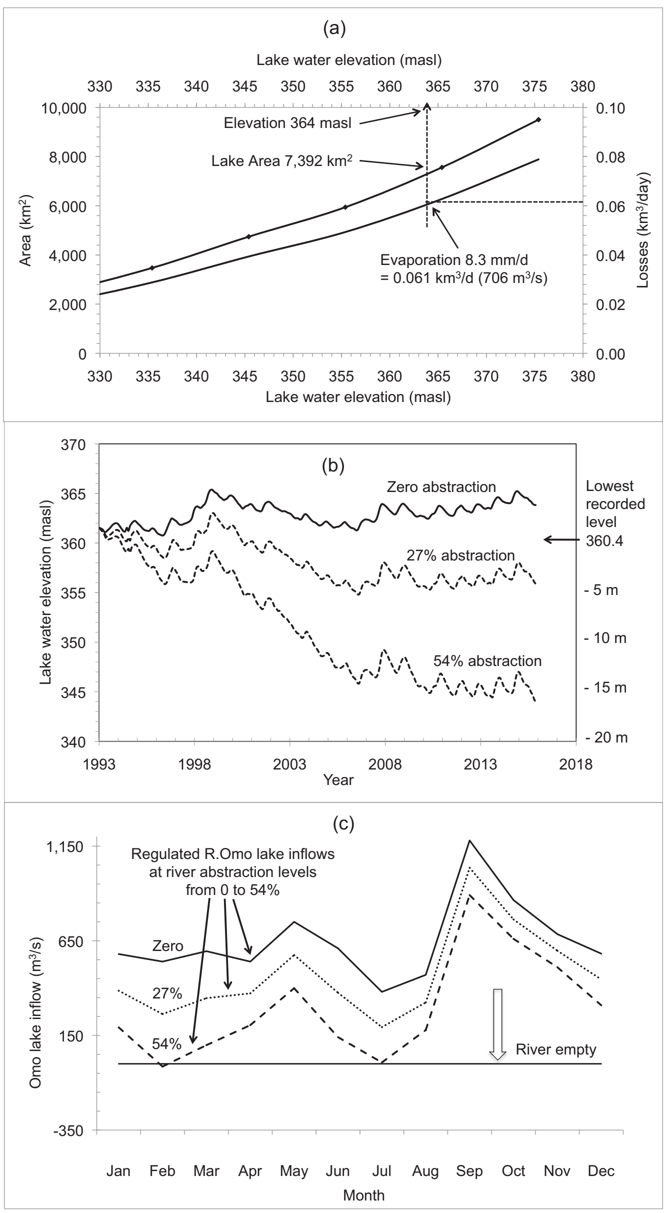

Fig. 12. Impact of different Omo River abstraction rates: (a) The lake's equilibrium level is plotted over a range of theoretical evaporation loss rates. At the loss rate 8.3 mm/d adopted in our modeling, the lake level will tend towards 364 masl (under a theoretical total regulated inflow regime without abstractions). (b) The lake recession is simulated at two different water abstraction levels (with the natural lake level series since 1993 as the simulation baseline at zero abstraction). The Kuraz monthly irrigation schedule in Fig. 6 c has been adopted in the modeling. In the case of the 54% abstraction rate, the lake is still receding. (c) The reduction in the average regulated annual monthly lake inflows has been simulated for two different rates of irrigation water abstraction.

Conclusions

Lake Turkana is on average evaporating 22.4 km^3/y of water into an arid environment. The lake is a focal point of the local microclimate. The lake's winds are a source of energy. The lake's semi-saline water is neither potable nor suitable for agriculture, but its fisheries are an important resource utilised by the poorest people in the region. The Omo River is the lake's umbilical cord (Avery, 2010, p. 4).

The Omo River developments will affect both the water quality and influx volume to the lake. Abstractions from the Omo River that diminish lake inflows will tend to concentrate chemical constituents and increase the lake's salinity. These changes affect an ecological balance already near its salinity threshold. Crop chemical pollution reaching the river via plantation drainage canals and via potential seepage underground will be detrimental to aquatic ecosystems. Uncontrolled irrigation abstractions from the Omo River could feasibly remove half the river's annual discharge. The lake water level could fall over 15 m as a result. The Omo River developments could thus emulate disastrous environmental precedents like the Aral Sea in Europe and Lake Chad in Africa (Avery, 2013a).

With both the Gibe III and IV dams commissioned, 80% of the Omo River discharge destined for the lake will be processed through

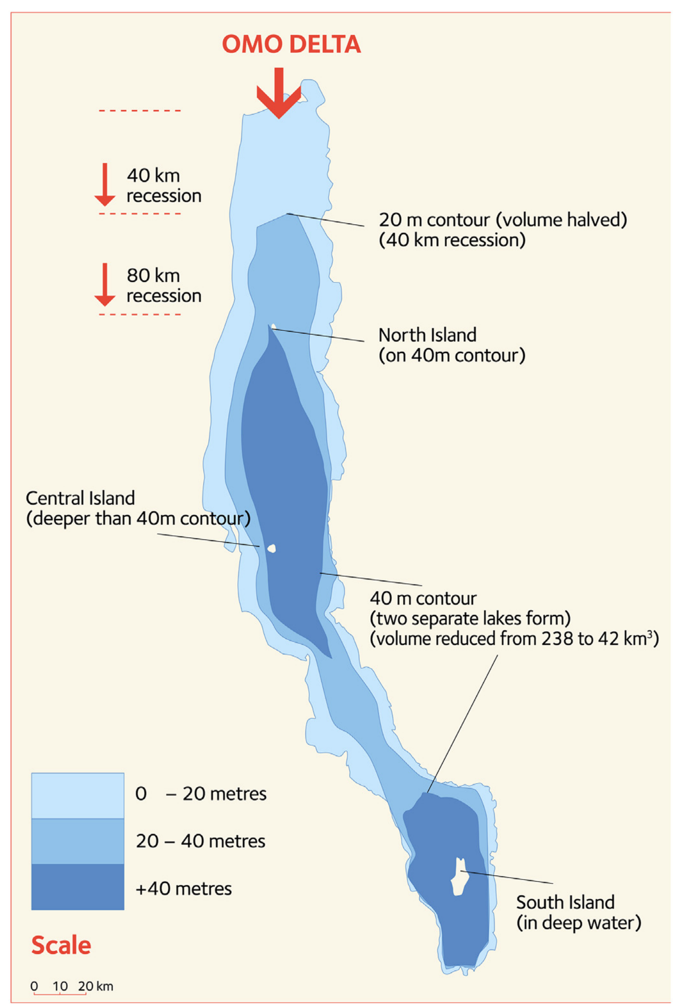

Fig. 13. Lake Turkana's shoreline recession and volume reduction scenarios: These are illustrated for water level declines of 20m and 40m below zero datum. Map reproduced from Avery (2013a).

reservoirs created by the dams. Nutrient flows and the passage of fish along the river will be arrested. The water is being released back into the river downstream, but the releases are now engineered according to power generation needs. The natural flow diversity of the Omo River has been altered forever. As this river is the key hydrological driver of Lake Turkana's ecological health and diversity, these changes will inevitably affect the lake ecology. This is contrary to claims by project proponents. They have further claimed that the hydropower dams will create a positive water balance for the lake by reducing riverbank flooding and associated evaporation losses. Yet seasonal inundation of the lower Omo rangelands was an ecologically beneficial groundwater recharge mechanism. These inundations also collected and distributed sediments and nutrients, to the benefit of both the rangelands and the lake. And the force of natural flood influxes to the lake provided seasonality and diversity to the lake currents that distributed nutrients within the northern Omo delta zone of the lake.

Irrigation expansion has been widely promoted as a solution to poverty and food security challenges (e.g., World Bank, 2004). But traditional irrigation projects consume vast quantities of water, especially in the drier lowlands. The regional experience with dryland irrigation projects is persistently disappointing (Avery, 2013b, 2014,). Countries like Kenya are already water stressed and cannot afford projects that squander their natural capital and scarce water resources. Ethiopia has the added consideration that 70% of its surface water resources flows onwards into other countries dependent on the same water. The reduction in river discharges through abstractions has direct adverse riparian consequences downstream. The consequences include rivers drying up and conflict. Ironically, through anthropogenic-induced catchment change, the surface water runoff in the Omo-Gibe Basin has been increasing. And in Kenya's Rift Valley basin, runoff is forecast to increase significantly by 2050 (Nippon Koei/JICA, 2013). Whereas this runoff increase tends to offset the water balance impact of abstractions, the faster runoff response to rainfall is invariably harder to control and enhances soil erosion risks. The economic life of reservoirs like Gibe III will reduce as a consequence.

Ethiopia has invested hugely to develop the hydropower potential of the Omo Basin, and there is no turning back. But, there is time to re-evaluate the feasibility of the thirsty irrigated and mono-cultural agriculture development models being implemented in the lower Omo. And re-instatement of the necessary ecological flood regime can then be re-considered. Gibe III has been designed with capacity to do this, and Gibe IV is yet to be built. There is time to review the haste with which the socio-economic transformation plans are being implemented. Ethiopia's heritage of unique natural capital in the lower Omo is being destroyed in the process. It is invariably the prime riparian zones along riverbanks that are developed, and blockage of wildlife access to the river is one result. The natural capital of Kenya's Lake Turkana is threatened too, notably its unique indigenous fisheries resource. The development architects seemingly attach neither significance nor economic value to these natural biodiversity assets. Traditional livelihood resilience is also disparaged yet the economic viability of substituting thirsty irrigated agriculture has been questioned elsewhere in Ethiopia (Behnke and Kervan, 2013). The greatest emerging challenge is unsustainable human population growth. In northern Kenya's arid lands, population growth rates are double the national average. Perhaps the UNEP-brokered trans-boundary project consultations will be addressing the multitude of concerns arising, but time has long been of essence (Avery, 2017).

We have monitored and modeled the impacts of the Omo dams on Lake Turkana's levels using remotely sensed data. We are also testing remotely sensed lake water quality indicators (Tebbs et al., 2015). We have identified shortcomings requiring further study. As Lake Turkana's water level and quality are the final integrated indicators of the impacts of development activities within the basin, continued monitoring is vital.

Acknowledgements

The Authors are grateful to the numerous contributions during nine years of work on Lake Turkana, either through their own work, or from consultations, or through data sharing, or through funding support or otherwise: African Development Bank for motivating ground breaking hydrological studies on the lake, with information accessed from the US Department of Agriculture, NASA, European Space Agency, Salini Impregilo, Ethiopian National Meteorological Services Agency, Kenya Meteorological Department, Kenya Ministry of Water Development and Irrigation, Friends of Lake Turkana, Turkana Basin Institute, John Malala and William Ojwang of Kenya's Marine Fisheries Research Institute (KMFRI); and special thanks to my two sons Patrick and Kieran Avery, Peter Ekale from Kalokol, Joyce Chianda at Jade Sea Journeys for vital fieldwork assistance; and thanks to the African Studies Centre and Dr. David Turton at the University of Oxford and their anonymous donor; University of Leicester and their John D and Catherine T. MacArthur Foundation Grant 103989 supporting momentum studies; Lori Pottinger of International Rivers, Thure Cerling, the late Frank Brown, Rolf and Eliye Springs Resort, Vanessa Tilstone of Drylands Learning and Capacity Building Initiative (DLCI) Nairobi with funding support from European Union and Ford Foundation; Jeppe Kolding; Barrie Harbott and Alastair Ferguson (Lake Turkana Project); Yannick Garcin, Narissa Alibhai, Lepalo Gideon from Loiyangalani, Benedikt Kamski; professional colleagues at Tullow Oil, and an anonymous friend in Ethiopia.

References

Africa Resources Working Group (ARWG), 2009. Commentary on the Environmental, Socio-economic and Human Rights Impacts of the Proposed Gibe III Dam in the Lower Omo River Basin of Ethiopia (28 pp.).

Agriconsulting S.p.A, Mid-Day International Consulting Engineers, 2009. Gibe III Hydroelectric Project, Environmental and Social Impact Assessment: Additional Study on Downstream Impact. Ethiopian Electric Power Corporation, Addis Ababa, pp. 1–289.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage Paper 56.

Amin, M., 1981. Cradle of Mankind. Chatto and Windus, London (ISBN-0-7011-2587-X).

Avery, S.T., 2009. Assessment of hydrological impacts of Ethiopia's Omo Basin on Kenya's Lake Turkana water levels. Draft Report for Mediating the Complaint Lodged by Friends of Lake Turkana. African Development Bank (1 to 6-10).

Avery, S.T., 2010. Assessment of hydrological impacts of Ethiopia's Omo Basin on Kenya's Lake Turkana water levels. Final Report. African Development Bank, Tunis (1 to 6-17).

Avery, S.T., 2012. Lake Turkana and the Lower Omo: Hydrological Impacts of Gibe III and Lower Omo Irrigation Development. vol. I. African Studies Centre, University of Oxford, England, pp. 1–239. http://www.africanstudies.ox.ac.uk/sites/sias/files/documents/Volume%20I%20Report.pdf.

Avery, S., 2013a. The Impact of Hydropower and Irrigation Development on the World's Largest Desert Lake: What Future Lake Turkana? African Studies Centre, University of Oxford, England, pp. 1–56. http://www.africanstudies.ox.ac.uk/what-future-lake-turkana

Avery, S., 2013b. Irrigating Kenya's Drylands – Food for Thought. Regional Learning and Advocacy Programme for Vulnerable Dryland Communities, Nairobi, Kenya, pp. 1–4.

Avery, S., 2014. Turkana County's aquifers and irrigated crop development prospects – some reasons to be cautious. Resilience in the drylands of the Horn of Africa – edition 5. Experiences and Lessons Learnt for Improved Policy and Practice. DLCI, Nairobi , pp. 16–20 available at. http://www.dlci-hoa.org/download/journal-5-resilience-in-the-horn-of-africa-experiences-and-lessons-learned-for-improved-policy-and-practice/?wpdmdl=2567.

Avery, S.T., 2015. Strategic water supply for development - preliminary hydrological review of Turkwel dam. Technical Report No. 1.1. Tullow Oil Kenya BV, pp. 1–18 September 2015.

Avery, S., 2016. Strategic water supply for development – Lake Turkana hydrology and water quality monitoring. Technical Report No. 2.1. Tullow Oil Kenya BV, pp. 1–32 January 2016.

Avery, S., 2017. Fears over Ethiopian dams' costly impact on environment, people. The Conversation https://theconversation.com/fears-over-ethiopian-dams-costly-impact-on-environment-people-80757.

Avery, S., 2018. How Ethiopia and Kenya have put a World Heritage site in danger. The Conversation https://theconversation.com/how-ethiopia-and-kenya-have-put-a-world-heritage-site-in-danger-99458.

Beadle, L., 1932. Scientific results of the Cambridge expedition to the East African Lakes. The waters of some east African Lakes. J. Linn. Soc. Zool. 38 (258), 157–211.

Beadle, L.C., 1974. The Inland Waters of Tropical Africa — An Introduction to Tropical Limnology. Longman, London, pp. 1–365.

Behnke, R., Kervan, C., 2013. Counting the costs: replacing pastoralism with irrigated agriculture in the Awash Valley, north-eastern Ethiopia. IIED Climate Change Working Paper No.4 , pp. 1–48. http://pubs.iied.org/10035IIED.html.

Bouchez, C., Goncalves, J., Deschamps, P., Vallet-Coulomb, C., Hamelin, B., Doumnang, J.-C., Sylvestre, F., 2016. Hydrological, chemical, and isotropic budgets of Lake Chad: a quantitative assessment of evaporation, transpiration and infiltration fluxes. Hydrol. Earth Sust. Sci. 20, 1599–1619.

Butzer, K.W., 1971. Recent history of an Ethiopian delta. Res. Paper No. 136. Department of Geography, University of Chicago, pp. 1–184.

Cherie, E., Derbe, D., Girma, T., 2011. Existing Challenges: Plantation Development Versus Wildlife. Ethiopian Wildlife Conservation Authority, Addis Ababa, pp. 1–15.

Cheung, Wing H., Senay, Gabriel B., Singh, Ashbindu, 2008. Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. Int. J. Climatol. https://doi.org/10.1002/joc.

Collins, R.O., 2005. The Ilemi Triangle. Annales d'Ethiopie vol. XX pp. 5–12.

Costelloe, J.F., Shields, A., Grayson, R.B., McMahon, T.A., 2007. Determining loss characteristics of arid zone river waterbodies. River Res. Appl. 23, 715–731 John Wiley and Sons.

Dunkley, P.N., Smith, M., Allen, D.J., Darling, W.G., 1993. The geothermal activity and geology of the northern sector of the Kenya Rift Valley. British Geological Survey, pp. 1–185 Research Report SC/93/1, prepared on behalf of the Overseas Development Administration, UK, for Kenya's Ministry of Energy.

FAO, 2016. Irrigation Water Management Irrigation scheduling. Annex 1: Irrigation Efficiencies. FAO Corporate Document Repository, Rome http://www.fao.org/docrep/t7202e/t7202e08.htm#TopOfPage.

FAO, 2017. Cropwat Version 8.0. http://www.fao.org/land-water/databases-and-software/cropwat/en/.

Ferguson, A.J.D., Harbott, B.J., 1982. Geographical, physical and chemical aspects of Lake Turkana. In: Hopson, A.J. (Ed.), Lake Turkana: A Report on the Findings of the Lake Turkana Project, 1972–75. vol. 1. Institute of Aquaculture, University of Stirling, UK, pp. 1–107 ch. 1. (ISBN 0-901636-41-X).

Funk, Peterson, Landsfeld, Pedreros, Verdin, Shukla, Husak, Rowland, Harrison, Hoell, Michaelsen, 2015. The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. Sci. Data 2, 150066. https://doi.org/10.1038/sdata.2015.66.

Garcin, Y., et al., 2012. East African mid-Holocene wet–dry transition recorded in palaeo-shorelines of Lake Turkana, northern Kenya Rift. Earth Planet. Sci. Lett., 1–13 https://doi.org/10.1016/j.epsl.2012.03.016.

Gaudet, J.J., Muthuri, F.M., 1981. Nutrient relationships in shallow water in an African Lake, Lake Naivasha. Oecologia (Berl.) 49, 109–118 (Springer-Verlag).

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. PLoS One 10 (5), 1–24. https://doi.org/10.1371/journal.pone.0127027 e0127027.

Halfman, J.D., 1996. CTD-transmissometer profiles from lakes Malawi and Turkana. In: Johnson, T.C., Odada, E.O. (Eds.), The Limnology, Climatology and Paleoclimatology of the East African Lakes. Gordon and Breach Publ., pp. 169–182.

Halfman, J.D., Johnson, T.C., 1988. High resolution record of cyclic climate change during the past 4 ka from Lake Turkana, Kenya. Geology 16, 496–500.

Hopson, A.J. (Ed.), 1982. Lake Turkana, a Report on the Findings of the Lake Turkana Project, 1972–75. vols 1–6. Institute of Aquaculture, University of Stirling, UK, pp. 1–1614 (ISBN 0-901636-41-X).

Hopson, A.J., Hopson, J., 1982. Lake Turkana, a report on the findings of the Lake Turkana project, 1972–75. The Fishes of Lake Turkana. vol. 1. Institute of Aquaculture, University of Stirling, UK, pp. 281–347 ch.5. (ISBN 0-901636-41-X).

Human Rights Watch, 2012. "What Will Happen if Hunger Comes?": Abuses Against the Indigenous Peoples of Ethiopia's Lower Omo Valley. (ISBN-56432-902-X). pp. 1–85.

IGAD - INWRM, 2015a. Intergovernmental Authority on Development (IGAD), Inland Water Resources Management Programme (INWRM). Assessment of Existing and Future Challenges of Multipurpose Water Resources Development and Reservoir Managements: Case Study Omo-Gibe Basin, Ethiopia. Arba Minch Institute of Technology, Arba Minch University, Arba Minch, Ethiopia, pp. 1–220.

IGAD - INWRM, 2015b. Intergovernmental Authority on Development (IGAD), Inland Water Resources Management Programme (INWRM). Multi Reservoir Operation and Challenges of the Omo River Basin: Part II: Potential Assessment of Flood Based Farming on Lower Omo-Ghibe Basin. Mekelle University, Mekelle, Ethiopia, pp. 1–37.

Johnson, T.C., Halfman, J.D., Rosendahl, B.R., Lister, G.S., 1986. Climatic and tectonic effects on sedimentation in a rift valley lake: evidence from high-resolution seismic profiles, Lake Turkana, Kenya. Geol. Soc. Am. Bull. 98, 439–447 12 figs, April 1987.

Johnson, T.C., Malala, J.O., 2009. Lake Turkana and its link to the Nile. In: Dumont, H.J. (Ed.), The Nile: Origin, Environments, Limnology and Human Use. Springer Science + Business Media B.V. (Ch. 15).

Junk, W., Bayley, P.B., Sparks, R.E., 1989. The flood pulse in river-floodplain systems. In: Dodge, D.P. (Ed.), Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106, pp. 110–127.

Kalders, J., 1988. Evapotranspiration in Kenya. Ministry of Water Development, Nairobi, Republic of Kenya.

Kallqvist, T., Lien, L., Liti, D., 1988. Lake Turkana Limnological Study 1985–1988. Norwegian Institute for Water Research (NIVA), Norway, pp. 1–98 (ISBN-82-577-1510-7).

Kamski, B., 2016. The Kuraz Sugar Development Project (KSDP) in Ethiopia: between 'sweet visions' and mounting challenges. J. East Afr. Stud. 10 (3), 568–580.

Karenge, L., Kolding, J., 1995. On the relationship between hydrology and fisheries in man-made Lake Kariba, Central Africa. Fish. Res. 22, 205–226.

Kizza, Michael, Westerberg, Ida, Rodhe, Allan, Ntale, Henry K., 2012. Estimating areal rainfall over Lake Victoria and its basin using ground-based and satellite data. J. Hydrol. 464–465 (2012), 401–411.

KMD, 1984. Kenya Meteorological Department, Climatological Statistics of Kenya.

Kolding, J., 1992. A summary of Lake Turkana: an ever changing mixed environment. Mit. Inrnat. Verein. Limnol. 23, 25–35.

Kolding, J., 1993. Population dynamics and life history styles of Nile tilapia, *Oreochromis niloticus*, in Ferguson's Gulf, Lake Turkana, Kenya. Environ. Biol. Fish 37, 25–46.

Kratli, S., de Jode, H. (Eds.), 2015. Case study by Sean Avery: consequences of sectoral development: Ethiopia's Omo Basin and Lake Turkana. Valuing Variability: New Perspectives on Climate Resilient Drylands Development. Available from: http://pubs.iied.org/10128IIED.html.

Mid-Day International, 2016. Koysha Hydroelectric Project, Environmental and Social Impact Assessment, Main Report. Ethiopian Electric Power, Federal Democratic Republic of Ethiopia, Addis Ababa, pp. 1–326.

Ministry of Agriculture, Livestock Development and Marketing (MALDM), 1994. Range Management Handbook of Kenya. vol. II pp. 1–189 9, Turkana District, Republic of Kenya.

Ministry of Environment and Natural Resources, 2017. Kenya Agricultural Productivity and Land Management Project (KASLMP). Report of the Land Degradation Assessment in Kenya. pp. 1–132 (Nairobi, Kenya).

Muska, M., Vasek, M., Modry, D., Jirku, M., Ojwang, W., Malala, J., Kubecka, J., 2012. The last snapshot of natural pelagic fish assemblage in Lake Turkana, Kenya: a hydroacoustic study. J. Great Lakes Res. 38 (2012), 98–106.

NASA, 2001. NASA/Goddard Space Flight Center—EOS Project Science Office. "Africa's Lake Chad Shrinks by 20 Times due to Irrigation Demands, Climate Change". ScienceDaily www.sciencedaily.com/releases/2001/02/010228080245.htm.

Nicholson, Sharone E., Yin, Xungang, 2001. Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. Climate Change. 48. Kluwer Academic Publishers, Netherlands, pp. 387–398.

Nippon Koei/JICA Team, 1992. The Study on the National Water Master Plan, Vols. 1, 2 and 3, Sectoral Reports A-S, Databooks DB1-DB6. Ministry of Water Development, Republic of Kenya.

Nippon Koei/JICA Team, 2013. The Study on the National Water Master Plan. Ministry of Water Development, Republic of Kenya.

Norconsult, 1983. Assessment of Water Resources in Turkana District. pp. 1–113, prepared by consultants Norconsult A.S. (Kenya) for the Ministry of Water Development, Republic of Kenya.

Ogallo, L.A., 1994. Validity of the ENSO-related impacts in Eastern and Southern Africa. In: Glantz, M. (Ed.), Usable Science: Food Security, Early Warning, and El Niño. Proceedings of the Workshop on ENSO/FEWS, Budapest, Hungary, October 1993. UNEP, Nairobi and NCAR, Boulder, Colorado, pp. 179–184.

Omo Valley Farm Cooperation PLC, 2012. Environmental Impact Assessment Study Feasibility Study (Final) Undertaken by Training and Research Centre Plc, Bole Sub-city, for Federal Democratic Republic of Ethiopia. pp. 1–112.

Pavlis, Nicholas K., Holmes, Simon A., Kenyon, Steve C., Factor, John K., 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). Journal of Geophysical Research: Solid Earth (1978–2012) 117 (B4) (April 2012).

Piper, B.S., Plinston, D.T., Sutcliffe, J.V., 1986. The water balance of Lake Victoria. Hydrol. Sci. J. Sci. Hydrol. 31 (1), 25–37 3/1986.

Salini Costruttori S.p.A, SP studio ing.g.pietangeli s.r.l., 2006. Basic design. Hydrological Report. vol. I. Ethiopian Electric Power Corporation, Addis Ababa, pp. 1–99.

Salini Costruttori, Studio Pietrangeli, 2010. Level 2 Design, Gibe III Impact on Lake Turkana Levels, Report No. 500 HYD RSP002A. Ethiopian Electric Power Corporation, Addis Ababa, pp. 1–42.

Salini Impregilo, Studio Pietrangeli, 2016. Koysha Hydroelectric Project, Basic Design, Koysha Impact on Lake Turkana Water Levels, Report No. 104 HYD RSP002A. Ethiopian Electric Power, Addis Ababa, pp. 1–65.

Sogreah, 1982. Regional Development Plan for the Kerio Valley, Water Resources Study. Kerio Valley Development Authority, Republic of Kenya, pp. 1–276.

Sogreah, March 2010. Independent review and studies regarding the Environmental & Social Impact assessment for the Gibe III Hydropower Project. Draft Final Report prepared for European Investment Bank.

Studio Galli Ingegneria, Sembenelli Consulting, 2013. Kuraz Headworks and Appurtenant Structures Detailed Design. Sugar Corporation, Federal Democratic Republic of Ethiopia, Addis Ababa, pp. 1–53.

Talling, J.F., Talling, I.B., 1965. The chemical composition of African lake waters. Int. Rev. Hydrobiol. 50 (3), 421–463.

Tebbs, E., Avery, S., Odermatt, D., 2015. Lake Turkana – monitoring the 'Jade Sea' from space. ESA Diversity II Biodiversity Story http://www.diversity2.info/products/documents/DEL8/D2Story-Turkana.pdf.

Tullow Oil, 2015. Kalokol, Lokwii and Turkana East Survey Verification. Ramani Land Services.

Turton, D., 2012. How Did It Come to this? Understanding River Development in Ethiopia's Omo Valley, Paper Prepared for the Panel on "Land Policies and Their Consequences for Vulnerable Populations in East Africa" at the Annual Meeting of the American Anthropological Association, San Francisco, 14–18 November, 2012.

UNEP, 2012. Ethiopia's Gibe III Dam: Its Potential Impact on Lake Turkana Water Levels. pp. 1–39.

UNESCO - ICOMOS, 2015. Report on Joint UNESCO-ICOMOS Reactive Monitoring Mission to Lower Omo Valley of the Omo World Heritage Property. pp. 1–35.

Velpuri, N.M., Senay, G.B., Asante, K.O., 2012. A multi-source satellite data approach for modeling Lake Turkana water level: calibration and validation using satellite altimetry data. Hydrol. Earth Syst. Sci. 16, 1–18.

Walsh, J., Dodson, R.G., 1969. Geological Survey of Kenya, Geology of Northern Turkana, Report No.82. pp. 1–42.

Water and Power Consultancy Services (India) Ltd., (WAPCOS), 1990. Preliminary Master Water Resources Development Plan. Ethiopian Valleys Development Studies Authority, Addis Ababa.

Welcomme, R.L., 1979. The Fisheries Ecology of Flood Plains. Longman, London (317 pp.).
WHO, 1984. Guidelines for Drinking Water Quality. vol. 1. World Health Organisation, Geneva, pp. 1–130.
WMO, 1981. WMO-No.168, Guide to Hydrological Practices. vol. I. World Meteorological Organisation, Geneva, pp. 1.1–4.41.
WMO, 1983. WMO-No.168, Guide to Hydrological Practices. vol. II. World Meteorological Organisation, Geneva, pp. 5.7–7.74.
Wolde, Z., Adane, A., 2014. Determination of planting season of sugarcane at Kuraz Sugar Development project, southern Ethiopia. Int. J. Sci. Basic Appl. Res. 7 (1), 44–49.
Woodroofe, Richard, Associates, Mascott Ltd., 1996. Omo-Gibe River Basin Integrated Development Master Plan Study. vol. II. Ministry of Water Resources, Federal Democratic Republic of Ethiopia, Addis Ababa parts 1 and 2.
World Bank, 2004. Building the Case for Water Infrastructure (Background Note for FY CEM). Available at. http://siteresources.worldbank.org/INTETHIOPIA/Resources/PREM/CP-WaterMila02.pdf, Accessed date: 21 August 2017.
WWDSE, 2014. Kuraz Sugar Development Project, Vol. III, Part A - Hydrology and Water Balance Study Main Report. Water Works Design and Supervision Enterprise, Federal Democratic Republic of Ethiopia, Addis Ababa, pp. 1–69.
WWDSE and CES (India), 2012a. Waterworks Design Supervision Enterprise (WWDSE) in Association with Southern Nations Nationalities and Peoples Regional State Design and Construction Enterprise and CES (India), Environmental Impact Assessment Draft Feasibility Report. Federal Democratic Republic of Ethiopia Sugar Corporation, Addis Ababa, pp. 1–169 (April 2012).
WWDSE and CES (India), 2012b. Kuraz Omo Sugar Development Project, Irrigation and Drainage Report (Draft). Sugar Development Corporation, Federal Democratic Republic of Ethiopia, pp. 1–119.
Yuretich, R.F., Cerling, T.E., 1983. Hydrochemistry of Lake Turkana, Kenya: mass balance and mineral equilibria in an alkaline lake. Geochim. Cosmochim. Acta 47, 1099–1109.