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JOURNAL OF GREAT LAKES RESEARCH

Devoted to Research on Large Lakes of the World and their
Watersheds

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

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Abstract

This study aimed to further 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 are on Ethiopia's Omo River, and are especially significant to the lake because this river alone provides over 80% of the lake's annual freshwater influx and associated nutrients.

The cascade of hydropower dams is shown to permanently dampen the natural hydrological cycles in the river and lake. The ecologically important flood inputs to the lake will be curtailed. And ultimately 80% of the river inflow to the lake will be regulated according to electrical power demands on the hydropower stations. Large volumes of water are required to initially fill the hydropower dam reservoirs and during 2015-16 when the huge Gibe III reservoir was filled, Lake Turkana's water level declined 2 m as a result. And by model simulation, it was shown that the lake would otherwise have risen.

The study has shown that large-scale irrigation schemes in Lower Omo can potentially abstract 50% of the river water, and that this would cause the lake level to shrink permanently, and that this would be to the detriment of the lake ecology. The lake depth averages 30 m, and possible lake level drops of over 15 m are demonstrated.

The basin's natural capital is being replaced by large-scale developments, and the hydrological changes are drastic, and the ecological consequences on Lake Turkana have not been adequately addressed. Without serious mitigation measures, Lake Turkana is a potential African Aral Sea in the making, emulating what has happened to other great lakes such as Lake Chad.

Keywords

Turkana, Omo, dams, irrigation, hydrology, fisheries, lakes

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. At that time, an area nearly five times the area of today's contemporary lake was inundated. And, that mega lake was spilling into the Nile basin (Hopson et al., 1982, Vol.6, Fig.1-6; Dunkley et al., 1993; Johnson & Malala, 2009; Garcin et al., 2012). The lakeshores include Kenya's only archaeological national park, Sibiloi. This is an important part of the UNESCO listed Lake Turkana National Parks World Heritage Site (Figure 3bError! Reference source not found.). Early human remains have been found here, and the area is often described as "the cradle of mankind". The World Heritage Committee has published concerns that the Site's outstanding values are threatened by developments in the Omo basin (UNESCO-ICOMOS, 2015).

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 et al., 1982, Vol.1, p.i-ii). The lake's closed basin is the largest within the East African Rift system (Halfman, 1986). The basin is split in roughly equal drainage area proportions between Kenya and Ethiopia (Figure 3aError! Reference source not found.). The lake today is still relatively pristine, but its unique semi-saline hydrobiology has been on the salinity brink for fisheries (Yuretich & Cerling, 1983). And the lake depends on Ethiopia's Omo-Gibe Basin for most of its freshwater inflow (Ferguson & Harbott, 1982. Vol.1, p.12; Johnson and Malala, 1990). This river terminates in Lake Turkana at its delta on the Ethiopian / Kenyan border. This delta has been in a constant state of change. This is in response to natural hydrological cycles, lake level change, and sediment deposited by the river on entering the lake. The Omo-Gibe's annual flood period has long been recognized to be the critical driver for the lake ecology. The Omo's freshwater inflow is the "main agent of change" of the lake's limnology (Ferguson & Harbott, 1982, Vol.1, p.51). The Omo is the dominant influence on the lake's nutrient balance in the lake (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. That river drains from highlands with plentiful rainfall, whereas the lake is within an arid and inhospitable environment. And the lakeshore inhabitants are amongst the poorest in Kenya. Their predominant traditional agro-pastoral livelihoods have long struggled to cope with the food requirements of a fast increasing population. The lake's unusual fishery resource

is thus a vital alternative food supplement that is important to sustain.

We have identified major impacts on Lake Turkana arising from the cascade of hydropower and large-scale irrigation developments that are principally taking place in Ethiopia's Omo-Gibe river basin (Figure 1). The hydrological characteristics of the basin's river discharge into Lake Turkana have for many years been progressively changing with increasing human population pressure (Woodroffe et al. 1996). But since 2015, the lake inflow cycles have been permanently and drastically altered by the major engineered river developments.

There have been repeated warnings that the Omo River and Lake Turkana's ecological diversity will in turn be critically affected (e.g., Ministry of Water Development, 1992; Woodroffe et al., 1996; Avery, 2010; 2012; 2013; Muska et al., 2012). The challenges emulate those of Lake Chad in Central Africa. By 2001, this great lake had shrunk 20-times due to irrigation demands and climate change (NASA, 2001). Our study shows how those historic warnings about Lake Turkana are becoming a reality.

Figure 1: Major developments along rivers that flow to Lake Turkana

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 (Figure 1).

In 1996, an integrated development master plan for the Omo-Gibe River Basin was presented (Woodroffe 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 1,600 m altitude drop over a distance of about 1,100 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. And the pre-feasibility study of the Halele-Werebesa hydropower project was also in progress. And because of the seasonality of natural river flow, the master plan noted that dams would be required to create storage reservoirs. And those reservoirs would regulate the river flows for downstream uses, particularly for irrigation. The master plan investigated the potential for 5,864 MW of hydropower development. In addition the master plan established the potential for 31,780 hectares of small-scale irrigation throughout the basin. And the feasibility of 54,570 ha of large-scale irrigation development in the lower valley of the Omo was established. These irrigated areas were proposed on the plains approaching the lake. 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).

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 cited Ethiopia's chronic and increasing poverty, and linked this 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. And, 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). And there were no prior trans-boundary consultations and agreements with directly affected parties (Avery, 2012, Vol.I, p.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 (Figure 1) and using irrigation water from the Omo.

2. Material and methods

2.1 Methods of 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 to 1980. These are the only measured lake river inflow data available. And unfortunately coincident lake level data does not exist (Avery, 2012, Vol I, p.209).

We obtained a simulated monthly river discharge sequence from 1956 to 1994 from the Omo-Gibe Basin master plan's runoff modeling (Woodroffe et al., 1996; Avery, 2012, Vol I, p.139). Over the common period from 1977 to 1980, these simulated flows correlated well with the measured data (Avery, 2012, Vol.I, p.138 and p.209).

We have obtained the other principal recent Omo hydrological studies (e.g. Salini and Pietrangeli, 2006; 2010; 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, p.3-4). That simple model derived inflows into the lake direct 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., p.213). This standard analytical method compares cumulative hydrological sequences (World Meteorological Organisation, 1981, Vol.II, p.5.9).

2.2 Lake water balance model

The water balance model was first developed for this lake by the African Development Bank team to help 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, p.205-239).

The lake water balance modeling is an exercise of arithmetically comparing the water inputs with the outputs (Figure **9Error! Reference source not found.**). The obvious

underlying principle is that if inputs exceed outputs, the lake level rises and water is stored within the lake. On the other hand, if inputs fall below outputs, the lake level falls and the lake storage volume declines. The above principle is captured in the following water balance equation:

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

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	=	Gross volume evaporated from the lake surface area
Seepage	=	Volume of seepage losses through the lake bed
Abstraction	=	Volume of irrigation water taken from Omo River
Losses	=	Seepage losses + Abstraction

The individual component methodology is outlined in later sections of this paper. And the model's data logic is briefly outlined below. As the lake volume is large, a monthly time step was adopted. The same model was then reversed into a predictive tool with which to simulate the impact of water input reduction due to the filling of the Gibe III reservoir and irrigation abstractions.

- (1) The lake water levels have been obtained at ten-day intervals from reliable satellite data.
- (2) Lake Turkana is a closed basin, and hence there is no direct outflow from the lake. And, the water quality is moderately saline and unsuitable for crop agriculture, and hence there are no direct abstractions from the lake itself.
- (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. The over-lake rainfall has also been estimated from infrared and microwave sensors in satellites.
- (5) The inflows from other rivers are seasonal and comprise a small component in the lake balance. They are not measured and have been estimated from national hydrological studies.
- (6) The monthly Omo inflow series is thus derived for the pre-Gibe III filling period 1993 to 2014:

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

- (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:

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

2.3 Assessing other river discharges reaching the lake - methods

Kenya's catchments draining to the lake are significant in area, but their 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. Both rivers are perennial in their highland upper reaches and historically became 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 irrigation abstractions from both rivers, but these are not measured. The lower reaches of the rivers are insecure with frequent banditry, 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 flow gaugings themselves. The 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. The JICA team updated their landmark studies twenty years later (Nippon Koei / JICA, 2012).

The Turkwel dam was commissioned in 1991, and since that time the river flows downstream of the dam have been regulated according to the dam's hydropower turbine releases. The turbine flow releases depend on unpredictable national electrical power requirements. The turbines typically run during daylight and early evening hours, shutting down thereafter till dawn. This river has thus become perennial, albeit diurnal. And 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 (<http://www.environment.go.ke/wp-content/uploads/2017/10/LADA-Land-Degradation-Assessment-in-Kenya-March-2016.pdf>, accessed 13th January 2017). This means that there is increasingly more flood runoff occurring in response to storm rainfall. This in turn means that less rainfall is recharging the underground aquifers. And it means the proportion of storm

rainfall reaching the lake as surface runoff is increasing. But there are no flow data.

There are perennial artesian springs on the lakeshores, notably Eliye and Lobolo Springs on the western shore, and the cluster of warm springs at Loiyangalani on the southeastern shore (Avery, 2012, Vol.I, p.177-188). These springs serve as community water supply sources. The spring flows are tiny, and the water balance reaching the lake is negligible.

The Kerio, Turkwel and littoral river inflows are significant but there are no current data. We have simply modeled inflow as a function of the catchment area (A), rainfall (P), and runoff coefficient (RO). The runoff coefficient is the proportion of the catchment rainfall generating runoff that reaches the lake through the catchment's 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 (JICA / Nippon Koei, Sectoral Report (B), 1992), as follows:

P = 532 mm for Turkwel and 696 mm for Kerio (ibid., p.BT-5)

RO = 4.1% and 7.2% respectively for Turkwel and Kerio (ibid.)

2.4 Lake chemistry - methods

Three field missions have been undertaken on the lake (Avery, 2012; 2015; 2016). Some water samples were also collected, with full chemical analyses later undertaken in certified commercial laboratories according to standard methods.

2.5 Lake water levels - methods

We were unable to obtain any lake water level records from Ethiopia. Station 93003 (Lake Rudolf @ Kelem) was listed long ago as "not operated" (Woodroffe 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 et al., 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 (KMFRRI). They reported that logistical challenges hampered data collection on the lake. We have previously documented the datum discrepancies (Avery, 2012, Vol.I, p.150-152). Remote sensed lake water level data became available from 1992 onwards, thereby providing an ongoing alternative data source to supplement the problematical lake gauge (ibid., p.151). We have downloaded the remote 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 20 August 2017).

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 (Tullow Oil, 2015). That survey was undertaken at our request. Two Leica GS15 dual frequency GPS units were deployed. The data was processed by Leica Geo-Office Version 8.2.0.0. Data were expressed at different datums, including the 2008 Earth Gravitational Model (EGM 2008) (Pavlis et al., 2012).

The USDA satellite measurements are the only reliable continuous lake water level data source for our study. And these data 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 & Harbott, 1982, Ch.1, p.41). The strong SE winds will induce a seiche effect. Storms over the lake also cause lake dramatic level changes. During one such storm water levels rose 30 cm within three hours in Ferguson's Gulf (ibid., p.42). Without accurate ground-based data around the lake, the absolute accuracy cannot be assessed. If the waters were calm, an accuracy 10-15 cm rms might be expected (Pers.Comm, Sharon Birkett, 2018). As the satellite measurements are mid-lake, we have assumed the seiche effect to be minimal.

2.6 Lake bathymetry - methods

We obtained the original lake physical dimensions and bathymetry from the reports of the Lake Turkana Project (Hopson et al., 1982). These were published in both tabular and map form (ibid., Vol.1, p.75; ibid., Vol.6, Fig.1.14). We compared depth contours from other publications (Halfman, 1986; Johnson et al., 1986). Later, during the Lake Turkana Limnological Study 1985-88, the lake level was declining, and the original bathymetric map was therefore "reconstructed" (Kallqvist et al., 1988, p.13). An extra lower contour line was added. This was derived from a Landsat satellite image (ibid.).

And during oil exploration work on the lake in 2011 and 2012, a geo-referenced and very much tighter 1 m interval bathymetric survey was undertaken (Pers. Comm., Tullow Oil Kenya BV, 2016). Those data are not readily accessible. But our comparisons show that the original Lake Turkana Project survey data remains applicable. We therefore retained these for our

water balance modeling.

2.7 Rainfall - methods

We have sourced traditional rainfall data from publications and the Kenya Meteorological Department. And we have obtained satellite data from the Tropical Rainfall Monitoring Mission (TRMM) and from the Climate Hazards Group InfraRed Precipitation with Station database (CHIRPS). TRMM applies the Multi-Satellite Precipitation Algorithm that uses a combination of data from TRMM and other satellites including both microwave and infrared instruments as well as incorporating ground-based data. CHIRPS incorporate 0.05° resolution satellite imagery with ground data. 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 50 km west of the lake mid-point at Lodwar at similar altitude (Avery, 2012, Vol.I, p.132). We also considered another long-term station at Lokitaung, but this is not representative, being to the north and at higher altitude within hilly terrain. We adopted Lodwar as the baseline rainfall station for our water balance modeling. We have obtained annual ground-based rainfall totals dating from 1921 to 2017, and daily data from 1940 (Kenya Meteorological Department). We have downloaded the TRMM 3B42 database from 1998, and have compared this with Lodwar's ground data and the CHIRPS database.

We have also obtained historic monthly data at Kalokol and Longech on the lakeshore at Ferguson's Gulf not far from Lodwar. These shore stations were only 8 km apart, and the Lake Turkana Project published useful records from 1973 to 1974, which we have used to compare with Lodwar (Ferguson and Harbott, 1982, Vol.1, p.30 and p.89).

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

We also needed rainfall data on the lake surface itself. Past studies have established that rainfall over a lake is higher than surrounding areas, but over-lake data usually do not exist. And estimating an appropriate "enhancement" factor to apply to available lakeshore data is a challenge. With modern satellite sensing technology, over-lake rainfall can now be derived directly. But significant differences have been reported. For instance, the enhancement of Lake Victoria's annual lake rainfall relative land 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 have downloaded the TRMM and CHIRPS over-lake data. Two main TRMM products were accessed, namely TRMM 3B42 v7 and TRMM 3A12 v7.

We obtained rainfall data for the Omo Basin from publications (Woodroffe et al., 1996; Cheung et al., 2008; Salini & SP, 2006), and also direct from the Ethiopian National Meteorological Agency in Addis Ababa (Avery, 2012, Vol.I, p.115-120).

We obtained design rainfall data for the lower Omo plantation areas from various Sugar Development Corporation documents (WWDSE, 2012; WWDSE, 2014; 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 satellite-based TRMM rainfall estimates.

2.8 Air and water temperature data - methods

We obtained historic air and lake water temperature data from the Kenya Meteorological Department and Lake Turkana Project 1972-75 (Hopson et al., 1982). We contrasted the historic data with recent satellite data provided by the School of Geosciences, University of Edinburgh (Avery, 2012, Vol.I, p.123-125). We recently obtained historic lake water temperature data for 1990 (Halfman, 1986), this dataset being restricted to the northern half of the lake.

2.9 Lake surface evaporation depth - methods

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

We have obtained the lake evaporation measurements of the Lake Turkana Project 1972-75 (Ferguson and Harbott, 1982, Vol.1, Ch.1, p.31-32). The Project operated an evaporation pan and an evaporimeter on the western lakeshore at Ferguson's Gulf. In addition the Project analysed lake water level recession rates. The Project 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, p.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 from 1992 to 2017. 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, Section 5.3.6.1, p.5.75).

To supplement the above analyses, we have applied standard double-mass hydrological analytical techniques to test different evaporation rates (World Meteorological Organisation, 1981, Vol.II, p.5.9). Cumulative flow sequences have been derived from our water balance model at various evaporation rates. These cumulative flows have then been plotted against other known cumulative data sequences (Avery, 2012, p.213-215). This double-mass technique is very useful for ascertaining hydrological data inconsistencies, and we used this technique to ascertain which evaporation value provides the best fit to the cumulative data series.

2.10 Crop supplementary irrigation water requirements - method

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). The FAO CropWat model was used 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, p.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 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, Part A, Section 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" within the Omo basin and by applying the indirect approach of relating rainfall to altitude (ibid., p.13). 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. Interestingly, Wolde and Adane do not cite the 2014 WWDSE report. Wolde and Adane have proposed a sugar planting cycle based on their new data, which we have adopted for our calculations.

The FAO CropWat model 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. And where site-specific data are not available, the FAO guidelines offer appropriate values from databases that FAO has compiled from all over the world.

3.0 Results and discussion

3.1 Lake water levels – results and discussion

Perhaps less than 10,000 years ago, Lake Turkana was 80-100 m higher than today, and was overflowing into the Nile Basin (Johnson and Malala, 2009; Garcin et al., 2012). In the late 1800s, the lake was still 20 m higher than its lowest contemporary levels in the mid 1940s, mid 1950s and the late 1980s (**Figure 2a**). Since the 1940s, the lake has been rising overall, perhaps a consequence of basin deforestation.

The Lake Turkana Project adopted the lake level the lake level on 10th September 1972 as the zero datum. And they estimated this zero datum to be 365.4 m above sea level (masl), plus or minus 5 m (Ferguson & Harbott, 1982, Ch.1, p.9). Through geodetic survey, we have established the zero datum to be exactly 365.4 masl EGM2008, and 365.07 EGM96 (Tullow Oil, 2015). The recent USDA satellite water level data includes a conversion factor to EGM2008 that is consistent with our survey.

3.2 Bathymetry and circulation patterns – results and discussion

The lake's original bathymetric survey derived lake contours and computed the lake surface area and storage at different elevations (**Figure 2d,b,c**). Our water balance model computed algorithms for the elevation / area / storage curves.

The lake has two interconnected basins, each reaching over 70 m deep (**Figure 2d**). The

northern basin comprises the Omo delta, 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 over 100 m deep is within the southern sector.

The lake's SE winds induce a surface current from the lake's southern sector that prevails throughout the year (Ferguson and Harbott, 1982; Yuretich & Cerling, 1983). Sediment plumes that enter the lake from the Kerio and Turkwel rivers are transported north by these prevailing currents.

In the lake's northern basin, the water circulation patterns vary with the season. The currents are generated by the SE winds confronting the Omo delta inflows from the north (ibid.) During the flood season, the Omo flows predominate, and the current follows the NW shore south. The current flows anti-clockwise and after flowing south crosses the central sector to the east shore and then north. In the dry season when Omo flows are low, the SE winds predominate and the circulation pattern reverses (ibid.).

In both seasons, the circulation patterns cause water to upwell along the eastern shores of both the central and southern sectors (ibid.). And the southern sector's sediments derive from the Omo basin, also indicative of deep reverse currents to the south (Hopson et al., 1982, Ch.1, p.16, citing Yuretich, 1976).

The regulation of the natural cycles of Omo flows by the Gibe dams will dampen the driving force of the Omo floods. The water circulation patterns in the northern and central sectors will change proportionally. This will affect nutrient distribution by water currents, and will affect fish feeding patterns.

Figure 2: Lake Turkana's water level and bathymetry characteristics

(a) Lake Turkana's contemporary water levels from 1888 to 1949 pieced together from explorer's maps and colonial documents (Butzer, 1971). A water level gauge was first installed on Ferguson's Gulf in 1949, and since 1992 water level changes have been remote sensed at ten-day intervals by satellite radar altimetry. (b) Lake Turkana Project from 1972-75, the lake's bathymetry was presented at 10 m contour intervals (Ferguson & Harbott, 1982). (c) Elevation / area / storage volume curves were derived from bathymetric contours (Zero contour = 365.4 masl, Earth Gravitational Model 2008 at Kalokol location co-ordinates 3°33'18.49183"N, 35°54'56.57582"E).

3.3 The rivers draining into the lake and their catchment areas – results and discussion

We have delineated the Turkana Basin into sub-catchment areas (Figure 3). This is a transboundary basin with the perennial Omo-Gibe Basin in Ethiopia comprising 50% of 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 fell (Ferguson and Harbott, Ch.1, p.8, 1982). The Gulf has since been a closed basin periodically flooded by the Kibish River and overland flood flow from the Omo (Butzer, 191, p.41; Avery, 2012, Vol I, p140-142). The water table beneath the isolated Gulf will be hydraulically connected underground to the main lake, as are crater lakes on Central Island (Avery, Vol.I, 2012).

Figure 3: Sub-catchments of Lake Turkana Basin and the lake environs

(a) Lake Turkana's sub-catchments. The former lake overflow west into the Nile Basin in Sudan is arrowed from sub-catchment 1. (b) Key locations around the lake are marked. These include the three main river deltas, Ferguson's Gulf, the three main islands, three national parks, Lodwar town and various centres around the lake for which rainfall data was obtained. In Ethiopia, the locations of Omorate and the Kuraz sugar plantations are shown.

3.4 The lake's water quality – results and discussion

The lake's strong winds ensure the water is well mixed with minimal thermal stratification. And, the water is well oxygenated at depth. But, the specific conductivity levels of the lake water increase along the length of the lake from north to south (Avery, 2012, Vol.I, p.163-166). And specific conductivity levels are higher in sheltered areas like Ferguson's Gulf due to evaporation. The salinity gradient reflects the significant dilution effects of the inflowing freshwater contributions of the vast Omo River (Yuretich and Cerling, 1983). The Omo 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^- (**Figure 4**). And when compared to incoming river water, the lake has been concentrated 100 times (Yuretich and Cerling, 1983). In addition, nitrogen concentrations are low ($< 100 \mu\text{g/L}$) (Kallqvist et al., 1988). Nitrates are rapidly utilized and nitrogen is a potential limiting nutrient (ibid.). Silicate levels are high and there are permanently high levels of phosphorus (ibid.). In addition, fluoride concentrations in the main lake 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. 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). And, with increasing salinity levels, fish dwarfism is reported to occur (ibid., citing Beadle, 1974). The lake's fish fauna is Nilotic and includes endemic species (Hopson & Hopson, 1982, p.5). And unlike so many African lakes, the lake has not yet been impacted by the introduction of alien species. Its salinity level 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 10,000

years ago. At that time the water was fresh. Actual conductivity measurements are of course only recent (**Figure 4**). Values since 1932 varied in the range 2,860 to 3,830 $\mu\text{S}/\text{cm}$, and up to 6,900 $\mu\text{S}/\text{cm}$ in Ferguson's Gulf (Avery, 2012, Vol.I, p.162-164). Comparable values in the fresh water of the Omo river were 80 $\mu\text{S}/\text{cm}$ (Hopson et al., 1982) and less than 200 $\mu\text{S}/\text{cm}$ in the Omo delta (Avery, 2012, Vol.I p.165). But upstream river developments that deplete the incoming Omo waters will accelerate the natural salinity increase rate and potentially reach catastrophic levels for fisheries.

The lake water is generally not suitable for either human or livestock consumption (MALDM, 1994; Avery, 2012, Vol.I p.172). And the water chemistry is unsuitable for irrigation (ibid., p.175). The Kenya water quality standards limit fluoride concentration to 3 mg/L for human consumption and 6 mg/L for livestock (Nippon Koei, JICA, 1992). And skeletal fluorosis can occur in humans at fluoride concentration > 10 mg/L (World Health Organisation, 1984). The symptoms of skeletal fluorosis are evident amongst lakeshore inhabitants (Avery, 2012, Vol.I, p.172). In contrast, the quality of incoming river waters is generally chemically suitable for all uses (ibid., p.175).

Figure 4: Lake Turkana chemistry

1932 data (Beadle, 1932); 1961 data (Talling & Talling, 1965); 1969 data (Walsh & Dodson, 1969); 1973 data (Hopson et al., 1982); 1975 data (Yuretich et al., 1983); 1987-88 data (Kallqvist et al., 1988); 1989 data (Dunkley et al., 1992); 2012 data (Avery, 2012, Vol.I, p.163-176); 2015 data (Tullow Oil, 2015), sampling by S.T.Avery, analysis SGS Laboratories, Kenya.

3.5 Rainfall over Lake Turkana – results and discussion

The average annual lakeshore rainfall declines along the lake from north to south. At Todenyang, Ileret, Alia Bay, Lodwar and Loiyangalani (Figure 3b), the mean annual rainfall measurements are 324, 280, 240, 192, and 152 mm respectively (Avery, 2012, Vol.I, p.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 (Figure 5b). The high inter-annual variability is characteristic of these arid areas, and droughts occur. But overall this long record displays an annual increasing trend. The TRMM 3B42 results for Lodwar are for a much shorter period, but are consistent with Lodwar's meteorological record (Figure 5c). But there are points of inflection, and these are indicative of some change to the data. Overall, the TRMM 3B42 data has a 24% positive bias (Figure 5c). In contrast, the TRMM 3A12 and CHIRPS data displayed a marked 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 & Senay, 2012, p.2). And a global study showed the same negative bias of the CHIRPS data to the west of the lake (Funk et al., 2015).

In arid areas such as the lake, 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 some distance from Lodwar (Figure 3b). In 1973, the annual totals were 212.0, 227.1, and 129.4 mm respectively (Kenya Meteorological Department; Ferguson and Harbott, 1982, Vol.1, p.89). In 1974, the annual totals were 290.3, 214.7, and 201.0 mm respectively (ibid.). Although only 8 km apart, Longech's annual total in 1973 was nearly half the annual fall at Kalokol over the same period. In the following year, they were near identical.

For our updated modeling, we have continued to adopt Lodwar's ground rainfall as our lake baseline. And we have factored the Lodwar data 1.3 times in order to reflect the lake arithmetic mean shoreline rainfall for the entire lake. The factored Lodwar data is then subjected to enhancement to derive the over-lake rainfall input to the water balance model. 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 less than 200 mm/y (Halfman & Johnson, 1988). These were estimates, not measurements. In our earlier work, we estimated rainfall over the lake through an assumed 20% enhancement of the Lodwar monthly rainfall series (Avery, 2012, Vol.I, p.210). That computation was $1.2 \times 184.1 = 221$ mm/y. This value was comparable to the early published estimates cited above. Water balancing studies on Lake Victoria have 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 (ibid.)

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 (ibid.). And 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 it averaged 67.6 mm/month (811 mm/y). On average, the TRMM results are a 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 a sample transect of TRMM data across the lake at Latitude 3.625 (Figure 5e). This transect suggests depressed over-lake rainfall from 1998 to 2015 and enhanced values from 2016 to

2015. And between 1998 and 2017 the over-lake rainfall increased 7-fold (Figure 5f). 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 (Figure 5d). The change of slope in May 2005 is a clear indication of inconsistencies.

We have presumed the inconsistencies within the satellite data have arisen from differing measurement sensors. UNEP used measurements by passive microwave instruments, whereas 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 adopted an enhancement of 30% over the shore rainfall.

Figure 5: Lodwar and over-lake rainfall

Satellite rainfall data downloaded from <https://giovanni.gsfc.nasa.gov/giovanni/#service=DiArAvTs&starttime=&endtime=&variableFacets=dataFieldMeasurement%3APrecipitation%3B> (b) Lodwar met station ground data. (c) Cumulative rainfall curves for Lodwar comparing satellite rainfall products with ground data (d) Cumulative rainfall curves comparing satellite over-lake rainfall products with Lodwar ground data. (e)(f) West-East Transect 1-4 over the lake in Map (a)]

3.5 Rainfall over the Lower Omo's Kuraz Sugar Plantations – results and discussion

The Omo Basin Master Plan developed a map of annual isohyets for the basin draining to the lake from Ethiopia (Woodroffe et al., 1996, Vol.XI, F1, p.14). That same map was reproduced in hydrological studies for Gibe III dam (Salini & SP, 2006, p.12). The lake area was not included. In the highlands the average annual rainfall reaches 1,900 mm and diminishes as one descends south to the lake. And rainfall seasonality changes from unimodal peaking in July/August to the bimodal peaking in April and November that is characteristic of the lower Omo and lake area (Avery, 2012, Vol.I, p.120-128, and Figure 6a). 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 1,200 mm to 400 mm over this section (Figure 6b). 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, 2012, 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) (ibid., p.20). In 2014, the Kuraz design rainfall was revised upwards to 661 mm

(WWDSE, 2014, 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) (ibid., Section 2.1.1, p.5). In 2015, the Ethiopian authorities provided Kuraz rainfall data to UNESCO for the period 2011 to 2014. That annual rainfall data totaled 1,350 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 (Figure 6a), 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 1,087.5 mm per annum and are more correctly bimodal (Figure 6b). They are compatible with our results, but the rainfall gradient through the project area was not assessed (Figure 6b). This is an important consideration as the supplementary irrigation abstraction needs will increase with declining rainfall. Our TRMM results show the rainfall declining with falling altitude to 847 mm/y in the Kuraz plantation Block III (Figure 6b). With potential bias correction that figure could be 650 mm/y. This is still higher than the original design figure 482 mm/y, but comparable.

Figure 6: Rainfall profile north of the lake

3.6 Evaporation loss from the lake surface and temperature change – results and discussion

The evaporated water depth is the crucial element of the lake water balance (Avery, 2012, Vol.I, p.129-131). We updated our previous work and compared data from other arid zones (Table 1).

Table 1: Lake evaporation loss

The Lake Turkana Project observed relatively high evaporation rates persisting on the lake throughout the year (Hopson et al. 1982, Vol.6, Fig.1.43). Their evaporation pan measured 5,800 mm (15.9 mm/d) (Ferguson and Harbott, 1982, Vol.1, Ch.1, p.32). But they noted that wave action had precluded installing floating evaporation pans in the lake water body. And, instead the evaporation pan was placed on the shore. And as a result the water temperature in the evaporation pan was 3°C higher than the adjacent lake water. They concluded from this that their shore-based evaporation pan measurements of 5,800 mm/y over-estimated actual lake surface evaporation. Their lakeshore evaporimeter recorded 3,200 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. The equivalent annual lake surface evaporation they derived from lake recession rates was 2,335 mm (6.4 mm/d). However the Lake Turkana Project lacked any gauged Omo lake inflow data and they had assumed

“minimal” inflow during the dry periods. We have checked this assumption using later flow measurements by EWRA 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. And the actual evaporation rate derived from lake water level recession data needs to be adjusted upwards (Avery, 2012, p.130). As an example of this adjustment, the lowest monthly discharges in the EWRA database from 1977 to 1980 were 20, 240, 247 and 137 m³/s. These low flow inflow values equated to between 0.2 and 2.7 mm water depth on the lake surface. The equivalent addition to the lake surface was 1.5 mm on average. Similarly the Omo basin master plan’s lowest monthly flow in each of the years 1956 to 1994 varied from 55 to 313 m³/s and averaged 124 m³/s (Avery, 2012, Vol.I, p.139). Thus the Lake Turkana Project recession evaporation would increase on average to $6.4 + 1.5 = 7.9$ mm/d, and potentially higher.

We have analysed water level changes from 1992 to 2017 (**Figure 7**). The database time interval is ten-days (the satellite overpass interval). 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 (**Figure 7c**). The highest 10-day rise was 65 mm/d. But these are outliers, being two extremes in a database of 893 values. The Lake Turkana Project’s recession value of 6.4 mm/d was exceeded 8.4% of the time during the period 1993 to 2017. The above data outliers are acceptable as the satellite measurements are noisy, and the data we have used have been smoothed at source. The readings are also subject to unknown seiche and wave effects.

Figure 7: Lake level changes

(a) The water level cycle in each year is plotted. From 1993-2017 the lake level varied over a range of 4 m. (b) The water level departure from the beginning of each year is plotted. The lake level falls in the early part of the year and then rises with the Omo flood season. (c) Water level changes have been ranked and an exceedence probability has been computed.

The Gibe III dam design team adopted our double-mass curve methodology to similarly derive the annual lake evaporation loss (Salini and Studio Pietrangeli, 2010; 2016). They proposed 2,900 mm annual lake evaporation loss (7.9 mm/d) (ibid.). But their analysis disregarded other river inflows. UNEP’s study used satellite-based evapotranspiration methodology. UNEP determined that in the period 1998 to 2009 the annual lake evaporation increased from 2,160 to 2,640 mm (5.9 to 7.2 mm/d, Velpuri et al., 2011; UNEP, 2012). These satellite-derived values have not been ground-truthed on the lake. Our early studies tested a range of values, the uppermost value being 3,029 mm (8.3 mm/d). The cumulative runoff comparison between the lake model and the master plan simulations correlated closely at this upper evaporation value (Avery, 2009; 2010; 2012, Vol.I, Fig. 86-88, p.214-215).

We have re-modeled lake inflows at 8.3 mm/d evaporation (**Figure 8c**). These correlate

with the cumulative Omo-Gibe Master Plan simulations (Figure 8c). They also correlate with the cumulative lake inflow simulation by the Kuraz sugar plantation feasibility study from 1993 to 2001 (Figure 8c). The lake model's cumulative Omo flows are consistent with other studies.

The lake's exceptionally strong prevailing southeasterly winds are notable, and these will enhance the surface evaporation process. The daily wind run measured at Lodwar 50 km west of the lake averaged 202 km/24 h (Kenya Met. Dept.). On the lake itself, winds are fiercest in the south (760 km/24 h), diminishing in force to the north (160 km/24 h) (Hopson et al., 1982, Vol.6, Fig.1.34). Long-term wind trends have not been studied on the lake. But the lake mean water temperature has increased about 1°C since records began in 1972 (Avery, 2012, Vol.I, p.125). Assuming no reduction in wind force and patterns, evaporation losses will thus be rising gradually over time with warming.

3.7 Water abstraction from the lake, seepage underground, groundwater exchange – results and discussion

There is no water abstraction from the lake. And 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 output flow 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 rise, the net groundwater flow is towards the lake (Pers. Comm., Tullow Oil, Kenya, 2017). The groundwater contribution to the lake from the Kenyan catchments flow is believed to be small, perhaps as little as 2.7 m³/s (ibid.) This is the subject of ongoing work.

3.8 River inflows into Lake Turkana – results and discussion

Through the lake water balance model we have generated the monthly Omo River inflows from the satellite water level series (Figure 8a). This Omo's lake inflow averaged 19.952 km³/y (Figure 9). The Omo's average annual inflow has been variously estimated with the Omo-Gibe basin master plan estimating 16.9 km³/y (Woodroffe, et al., 1996) (Table 2). Later study results vary, for instance with up to 19.8 km³/y depending on the lake evaporative loss (Avery, 2010; 2012), and 20.6 km³/y (Salini et al., 2010; 2016). And in the case of one Ethiopian study, as much as 26 km³/y was derived (IGAD-INWRM, 2015). Our modeled pre-Gibe III flow duration pattern is directly comparable to other simulations (Figure 8b). And it is comparable to the only actual flow measurements of EWRA, albeit dated (Figure 8b). And our lake-modeled inflow hydrograph confirms the important pronounced flood period between July and

November when huge volumes of water recharge the lake (**Figure 10a**). After falling in the early part of the year, the lake levels rise with the flood before falling until the next year's flood influx (**Figure 7a**). The floods and lake level changes are vital parts of the lake's ecological diversity pump.

Table 2: Omo annual flows

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. And being at the lowest point of the basin, the lake's level and water quality are the ultimate indicators of hydrological 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 (Woodroffe et al., Vol. VI, AI, p.C8). This is reflected in the rising lake level trend (**Figure 2a**). The Gibe III documents also reported hydrological extremes arising from heavy deforestation in the upper watershed (Agriconsulting et al., 2009, p.2). And global climatic events are increasingly more extreme. With changing catchment characteristics, there is an ongoing increasing runoff response to rainfall. 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).

But the Turkana basin has a history of climate-induced hydrological change dating back long before contemporary times (Johnson & Malala, 2009; Garcin et al., 2012). In contemporary times, the lake receded dramatically and was lowest in the 1940s (**Figure 2a**). The lake then rose over the period 1940s to early 1980s (**Figure 2a**). That period included several global climatic El Niño and Southern Oscillation events (ENSO). There were "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 that follows is associated with drought. This drought phase is La Niña, the counterpart of El Niño.

Since the 1950s, there have been twelve "weak", six "moderate", three "strong" and three "very strong" events (ibid.). ENSO events are not always linked to extreme climatic events. They 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.

Figure 8: Omo lake inflow series

(a) Satellite lake levels from 1993 to 2017 and Omo River lake inflow generated from lake water balance modeling. (b) Omo River flow duration curves. The Gibe III reservoir's filling period significantly dampened lake inflows

Figure 9: Water balance model summary for Lake Turkana

Other river inflows: 0.426 km³/y R.Turkwel (sub-catchment 6), 0.746 km³/y R.Kerio & Kartor (sub-catchments 4 and 5), 0.251 km³/y littoral sub-catchments 3 and 7.

3.9 The regulation of the Omo river hydrograph by the Gibe dams – results and discussion

We have abstracted the natural lake level oscillations for each calendar year from 1993 to December 2014. The lake level invariably fell in the early months of the year, and then rose in later months (**Figure 7a**). The lake level varied over a 4 m range (**Figure 7a**). From the beginning of each year, the lake fell up to 1.3 m and rose up to 1.6 m (**Figure 7b**). With regulation by the Gibe dams, the annual water level oscillations will instead be confined within a 300 mm band (Salini et al., 2016, p.61).

Since Gibe III dam was inaugurated in December 2016, the downstream Omo river discharge has been regulated according to 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 achieved by Gibe III. Almost total flow regulation is planned (**Figure 10b**). The natural low flow periods from December to May have been uplifted and are sustained eight months of the year. There will be a small flow peak in September arising from the unregulated residual catchment portion between the dams and the lake. But, the flood duration and volume is negligible.

The Gibe III project proponents claim that the stabilization of lake water levels by flow regulation is "sensible" and positive for the lake (Salini et al., 2010, p.2). They have stated that "...in dry years, the flow regulation will contain the lake decline avoiding catastrophic shrinkage of the shores (Salini et al., 2016)". And they have 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 (ibid.)".

The Omo floods were stated to be "destructive to human and animal life, private assets and infrastructure" (Agriconsulting et al., 2009, p.2). The floods were attributed to deforestation (ibid.) There is little doubt that catchment degradation has affected the natural Omo hydrology. Increased inter-annual flow variation in recent years has been noted (Avery, 2012, Vol.I, p.135-140). And, the low flow duration regime had altered (Avery, 2012, Vol.I, Fig.94, p.219). The recent low flow periods were more pronounced (**Figure 8d**). But some observers disagree with the flood "destruction" claims (personal communication, David Turton,

African Studies Centre, 2012). And whereas flood peaks will have increased in recent years, the EWRA measured monthly highest flow duration regime from 1977-80 appears to be directly comparable to the monthly high flow simulations by the project proponents (Figure 8c).

The indigenous inhabitants of lower Omo traditionally practice flood recession agriculture and floods are highly valued (ibid.). And the areas that inundate with floods are depressions near the Omo delta that naturally fill with water (Avery, 2012, Vol.I, p.142). And the floods fill oxbows and thereby enable 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, Vol.I, p.140-142). On the other hand, uncontrolled tillage practices within riparian zones along riverbanks can be destructive. They disturb these zones, and the runoff increases, and erosion and sediment runoff processes accelerate.

The project proponents claim that stabilizing Lake Turkana's water levels is "sensible". This claim is diametrically opposite to the reality that the lake's ecological diversity is a consequence of the natural hydrological diversity of the Omo River. With the uniformity arising from flow regulation, the diversity of the lake's ecology will be adversely affected instead (Omo case study, Kratli, 2015, p.67).

Figure 10: Omo River lake inflow hydrographs

Tropical fisheries studies long ago demonstrated that aquatic productivity increases with instability (Welcomme, 1979; Junk et al, 1989; both cited by Kolding, 1994). And tropical flood-plain fisheries are the most productive (ibid.). The lake water level changes promote interaction between aquatic and terrestrial systems (Kolding, 1994). This process distributes nutrients from the shoreline into the main lake body (Gaudet and Muthuri, 1983). Annual fluctuations in lake level are very much more significant than absolute level (Karengue and Kolding, 1993). 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 by the Gibe hydropower dams must thus inevitably adversely affect the lake's aquatic productivity (Avery, 2009; Muska et al., 2012; Avery 2012; 2013). The lake is an "erratic ecological system" and its natural erratic behaviour stimulates the lake's natural resilience (Kolding, 1992). It has been predicted that complete loss of seasonal oscillations will decrease the lake fishery yield by over two thirds (Gownaris et al., 2016).

3.10 Ecological flows – results and discussion

The Gibe III dam is committed to maintain a minimum of 25 m³/s in the river at all times (Agriconsulting et al., 2009; Salini et al., 2016, p.19). This corresponds to the lowest monthly average dry season flow in the river at the dam site from 1964 to 2001. It is very little, being less than 6% of the river's average daily flow. In addition, the dam has the hydraulic capacity to release a controlled flood of 1,000 – 1,200 m³/s. This was to have been for 10 days in September each year for the purpose of meeting environmental and human needs. It had been assumed this flood would swell to 1,600 m³/s before reaching the lake (Agriconsulting et al., 2009). This flood magnitude is less than the mean annual flood. The peak flood of 10-year recurrence interval has been estimated to be 4,800 m³/s (Agriconsulting et al., 2009, p.42). However, 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 was to allow flood recession agriculture until the local people are 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 et al., 2009, p.2). Hence there is no onward commitment to release floods 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 determine the ecological flow needs of the lake (Avery, 2009).

3.11 The effect of the filling of the Gibe III & Gibe IV reservoirs on Lake Turkana's water levels – results and discussion

The Gibe III reservoir required 15 km³ of water to fill to full supply level (Salini et al., 2016, p.1). This volume equates 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 (Figure 11a and b). This had been predicted (Avery 2012, Vol.I, p.220). And by simulation, we have shown that the lake level would otherwise have risen (Figure 11b).

The Gibe III filling period coincided with one of the three strongest global climatic El Niño and Southern Oscillation (ENSO) events since the 1950s (National Oceanic and Administration National Weather Service, USA, website accessed May 2017). And, 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 (Figure 11a). And during the 2015/16 El

Niño, Gibe III's reservoir was filled in two instead of three years (Figure 11b).

There are no official fisheries statistics yet available, but anecdotal reports confirm 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).

The Gibe IV dam will require 6.5 km³ of water to fill its reservoir, 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 et al., 2016, p.52).

Figure 11: Impact of the filling of Gibe III on Lake Turkana's water level

(a) Natural lake level fluctuations 1993-date. ENSO events comprise El Niño (in black) followed by La Niña (in grey). (b) Without Gibe III filling, the lake level would have continued to rise (dashed line)

3.12 Irrigation plans in the lower Omo valley and abstraction impacts – results

In 1996, the Omo-Gibe River Basin Integrated Development Master Plan forecast utilizing 5.34 km³/y of water to meet the total basin water demand by the year 2024, with 94% of that demand being for irrigation water (Woodroffe et al., 1996, Vol.XI, F1, p.77). That water requirement 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 Table 2.

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 scheme's development area has since been increased to 50,000 ha (Kamski, 2016). 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 irrigate well over 1,000,000 ha based on an estimated average annual water resource of 23 km³/y (WWDSE (b) et al., 2012, p.1). The Kuraz sugar project intake was designed to abstract 340 m³/s (Studio Galli and Sembenelli, 2013, p.39). When annualized to 10.575 km³, this amounted to 50% of the Omo River flow. In 2014, the Kuraz water requirement was computed to be 117 m³/s on average, which was 19.7% of the Omo flow at the scheme intake headworks (WWDSE, 2014, p.34). In 2015, it was reported that rainfall had been under estimated and supplementary irrigation requirements are less than expected (UNESCO-ICOMOS, 2015, p.22). And the Kuraz scheme project area was also scaled down to a net area 111,650 ha (ibid., p.5). The

Ethiopian government advised that only 4-6% of the Omo River would be abstracted by Kuraz (ibid., p.23). This amounts to an order of magnitude reduction in planned abstraction by the Kuraz project.

We have derived the rainfall profile through the Kuraz plantation area (Figure 6a and b). And, we have applied FAO's Cropwat model to compute the average monthly infield irrigation requirements for the revised plantation area (Figure 6c). The irrigation requirement varies from month to month and averaged 56.6 m³/s. This amounts to 16% of the scheme's intake design capacity, and is higher than the 4-6% figure reported by UNESCO-ICOMOS. And note that the Cropwat model by default assumes 70% "field application efficiency". This efficiency level is optimistic. And in addition, water conveyance losses are not included.

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 (b), 2012, p.33). The total potential scheme losses are appreciable. FAO methodology allows conveyance losses through application of a "conveyance efficiency" factor. And the "overall scheme efficiency" is 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 more than 20% of the river would be abstracted by this scheme alone. Added to that will be the water abstraction of the 50,000 ha of the Omo Valley cotton plantation. The available environmental impact assessment for that cotton project did not quantify how much water would be abstracted (Omo Valley Farm, 2012). And there are other plantations planned downstream for which there are no details. Some of the lost canal water from the schemes will of course percolate towards the river. But that "returnable" water will not be useful as it will potentially contain crop chemicals.

We have assessed the irrigation limits that can theoretically be achieved with the river flow regime regulated by the Gibe dams (Figure 12c). Abstraction rates that exceed 50% of the annual average inflow to the lake will empty the Omo River at times. And at this high level of abstraction the lake recession would be catastrophic (Figure 12b). The lake could potentially drop over 15 m below the historic lowest ever level. The lake shoreline shrinkage would also be dramatic (Figure 13).

Figure 12: Impact of different abstraction rates on the Omo River

(a) At an evaporation rate of 8.3 mm/d, the lake tends to stabilize at 364 masl. (b) The lake level at zero abstraction is the measured lake level series since 1993. The effects of removing 27%

and 54% of the Omo River are demonstrated. In the case of the 54% level, the lake is still receding. (c) The lake inflow reduces with abstractions.

Figure 13: Lake Turkana's potential shoreline recession map
Reproduced from Avery, 2013a

4. Conclusions

Lake Turkana is an oasis annually evaporating 22.4 km³ of water into an arid environment. The lake is a focal point of the local microclimate. And the Omo River is the lake's umbilical cord. The lake water is semi saline and hence is not potable, nor suitable for agriculture. But its fishery is an important resource. And this resource is utilised by local people who are amongst the poorest in the region.

The Omo River developments will affect both water quality and quantity influx to the lake. Abstractions from the Omo River will tend to concentrate chemical constituents in the lake and increase salinity. These changes will impact an ecological balance that is already near its salinity threshold. This impact will be compounded by crop chemical pollution reaching the river via plantation drainage canals and seepage underground. In the case of Lake Turkana, irrigation abstractions from the Omo River are the major threat. They have the potential to remove up to 50% of the river's annual discharge. The lake water level could fall over 15 m as a result. This is potentially catastrophic as the lake's average depth is 30 m. The Omo River developments could 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 pass through the dams. The water will be stored in the reservoirs created by the dams. Nutrients will be captured 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 engineered, not natural. They are being controlled according to power generation needs. The river's annual hydrograph has thereby been smoothed. The river's low flows have been increased. And the annual flood has been dampened significantly in magnitude and duration. These changes have altered forever the flow diversity of the Omo River. As this river is the key hydrological driver of the lake's ecological health and diversity, these will inevitably be to the lake ecology's detriment.

The project proponents have claimed that the hydropower dams will create a positive water balance for the lake. This will be achieved by reducing riverbank flooding and associated evaporation losses. But on the other hand, the dams create large lakes from which water will evaporate. And water that formerly inundated the lower Omo rangelands was an

ecologically beneficial groundwater recharge mechanism. And these flood inundations distributed beneficial sediments and nutrients.

Irrigation expansion has been widely promoted as a solution to poverty and food security challenges (e.g., World Bank, 2004). But traditional irrigation projects require vast quantities of water, especially in the drier lowlands. And the regional experience with dryland irrigation projects is disappointing (Avery, 2013b). And countries like Kenya are already in a water stress situation that cannot afford projects that squander this scarce resource. Ethiopia has the added consideration that 70% of its surface water resource otherwise flows into other countries that are dependent on the same water. This is the case with Ethiopia's Omo feeding Kenya's Lake Turkana. Any reduction in river discharges through abstractions has direct adverse riparian consequences downstream. And these consequences create conflict. Ironically, through anthropogenic induced catchment change, the surface water runoff in the Omo Basin has been increasing. And in Kenya's Rift Valley basin, runoff is forecast to increase significantly by 2050 (JICA / Nippon Koei, 2013). This runoff increase would tend to offset the water balance impact of abstractions. But, those hydrological runoff increases will in turn bring challenges, notably erosion and floods that transport sediments that fill reservoirs beyond economic use.

Ethiopia has invested hugely to develop the hydropower potential of the Omo Basin, and there is no turning back. But, there is time to evaluate the feasibility of the thirsty irrigated agriculture development models being implemented in the lower Omo. And there is time to evaluate the haste with which the socio-economic transformation of the indigenous populace is being implemented. Ethiopia's heritage of unique natural capital in the lower Omo is being destroyed in the process. And it is invariably the prime riparian zones that are cherry-picked first. And wildlife access to the river is being blocked. The natural capital of Kenya's Lake Turkana is threatened too. The tragedy is that development architects diminish and attach neither significance nor economic value to these biodiversity losses. The sustainable role of pastoralism in semi-arid landscapes is not supported. And yet experience elsewhere in Ethiopia has questioned the economic viability of replacing pastoralism with irrigated agriculture (Behnke and Kervan, 2013). And the greatest challenge testing traditional livelihoods is unsustainable human population growth. In northern Kenya, these growths are double the national average.

Pristine riverine forest is being sacrificed in the lower Omo, and there is no economic valuation, nor proper understanding of Lake Turkana's ecosystem service provision. This notably includes its vulnerable fishery. Perhaps the UNEP-brokered trans-boundary project consultations will be addressing the multitude of concerns arising, but time has long been of

essence.

Our lake water balance modeling would not have possible without the continuity of remote sensed lake water level data since 1993. The lake level and water quality are the final indicators of the effect development activities within the basin. We have been able to monitor and model the impacts of the dams on the lake levels. And we have also used remote sensing to monitor baseline lake water quality indicators (Tebbs, Avery & Odermatt, 2015).

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Table 1: Lake evaporation loss

Evaporation (mm/yr)	Method	Data source
<u>Lodwar Met Station</u>		
3,488	Pan Type A, Lodwar Met, Stn. 1961-80	Kenya Met. Dept.
2,625	Penman Eq. Et, Lodwar Met. Stn.	Kalders, 1988
<u>Lake Turkana</u>		
5,800	Lakeshore Pan	Hopson et al., 1982
3,200	Piche evaporimeter	Hopson et al., 1982
2,335	Lake recession, no flood	Hopson et al., 1982
2,482 - 3,029	Lake recession, inflow added	Avery, 2009; 2010; 2012
2,900	Simulated (Gibe III study)	Salini & Pietrangeli, 2010
2,160 - 2,640	Veg ET modelling	Velpuri et al., 2011
2,700	Simulated (Gibe IV study)	Salini & Pietrangeli, 2016
<u>Other lakes</u>		
1,500 - 2,500	Modified Penman Eq. (Australia)	Costelloe et al., 2007
2,070 - 2,270	Lysimeters (Lake Chad)	Bouchez et al., 2015

Table 2: Omo annual flows

Inflow m ³ /s	Inflow km ³ /y	Derivation Method	Source
526	16.6	1956-1994 rainfall runoff simulated	Woodrooffe et al., 1996
560	17.7	1993-2008, Lake model @ 7.2mm/d loss	Avery, 2009; 2010
502	15.8	1956-1994, Lake model @6.8mm/d loss	Avery, 2009; 2010
535	16.9	1956-1994, Lake model @7.2mm/d loss	Avery, 2009; 2010
627	19.8	1956-1994, Lake model @8.3 mm/d loss	Avery, 2009; 2010
650	20.5	Simulated flow	Studio Pietrangeli et al., 2010; 2016
555	17.5	1993-2011, Lake model @ 7.2mm/d loss	Avery, 2012
646	23.0	Simulated flow	WWDSE & CES, 2012
750	23.7	Simulated flow	Studio Galli et al., 2013
650	20.5	Simulated flow	Velpuri & Senay, 2012
517	16.3	Simulated flow	WWDSE, 2014
826	26.0	Simulated flow	IGAD – INWRM, Arba Minch, 2015
526	16.6	Flow cited from Woodrooffe at al., 1996	IGAD-INWRM, Mekelle, 2015
570	18.0	Aquastat database	FAO, 2016
645	19.9	1993-2014 Lake Model @8.3 mm/d loss	This study

Figure 1: Major developments along rivers that flow to Lake Turkana

Figure 2: Lake Turkana's water level and bathymetry characteristics

Figure 3: Sub-catchments of Lake Turkana Basin

Figure 4: Lake Turkana chemistry

Figure 5: Lodwar and over-lake rainfall

Figure 6: Rainfall profile north of the lake

Figure 7: Lake level changesError! Reference source not found.

Figure 8: Omo lake inflow series

Figure 9: Water balance model summary for Lake Turkana

Figure 10: Omo River lake inflow hydrographs

Figure 11: Impact of the filling of Gibe III on Lake Turkana's water level

Figure 12: Impact of different abstraction rates on the Omo River

Figure 13: Lake Turkana's potential shoreline recession