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Hydrology and Earth System Sciences Discussions

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Assessing the potential hydrological impact of the Gibe III Dam on Lake Turkana water level using multi-source satellite data

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Abstract

Lake Turkana, the largest desert lake in the world, is fed by ungauged or poorly gauged river systems. To meet the demand of electricity in the East African region, Ethiopia is currently building the Gibe III hydroelectric dam on the Omo River, which supplies more than 80 % of the inflows to Lake Turkana. On completion, the Gibe III dam will be the tallest dam in Africa with a height of 241 m. However, the nature of interactions and potential impacts of regulated inflows to Lake Turkana are not well understood due to its remote location and unavailability of reliable in-situ datasets. In this study, we used 12 years (1998–2009) of existing multi-source satellite and model-assimilated global weather data. We use calibrated multi-source satellite data-driven water balance model for Lake Turkana that takes into account model routed runoff, lake/reservoir evapotranspiration, direct rain on lakes/reservoirs and releases from the dam to compute lake water levels. The model evaluates the impact of Gibe III dam using three different approaches such as (a historical approach, a knowledge-based approach, and a non-parametric bootstrap resampling approach) to generate rainfall-runoff scenarios. All the approaches provided comparable and consistent results. Model results indicated that the hydrological impact of the dam on Lake Turkana would vary with the magnitude and distribution of rainfall post-dam commencement. On average, the reservoir would take up to 8–10 months, after commencement, to reach a minimum operation level of 201 m depth of water. During the dam filling period, the lake level would drop up to 2 m (95 % confidence) compared to the lake level modelled without the dam. The lake level variability caused by regulated inflows after the dam commissioning were found to be within the natural variability of the lake of 4.8 m. Moreover, modelling results indicated that the hydrological impact of the Gibe III dam would depend on the initial lake level at the time of dam commencement. Areas along the Lake Turkana shoreline that are vulnerable to fluctuations in lake levels were also identified. This study demonstrates the effectiveness of using existing multi-source satellite data in a basic modeling framework to assess the potential hydrological impact of an upstream dam

HESSD

9, 2987–3027, 2012

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on a terminal downstream lake. The results obtained from this study could also be used to evaluate alternate dam-filling scenarios and assess the potential impact of the dam on Lake Turkana under different operational strategies.

1 Introduction

River basin developmental activities such as construction of dams/reservoirs, irrigation development, regulation of river flows, or land cover change often result in either a positive or negative impact on the hydrology of the river basin. Such activities require impact assessment to be performed before the developmental plans are to be commenced. However, most of the basins in developing countries, where basin developmental activities are currently being carried out, are mostly ungauged (Sivapalan, 2003) and data on key hydrologic variables such as rainfall, stream discharge, and evapotranspiration are unavailable, limited, or of poor quality. Thus, with limited to in-situ data, it becomes extremely difficult to carry out impact assessment studies. Challenges and issues pertaining to the hydrologic predictions in ungauged basins have been extensively discussed (Sivapalan, 2003; Seibert and Beven, 2009). Lake Turkana, the largest desert lake in the world, is fed by ungauged or poorly gauged river systems. Since it is a closed-basin lake, the fluctuations are determined by the influx from rivers and by the evaporation from the lake surface. Out of three rivers (Turkwel, Keiro, and Omo) that contribute to the lake, the Omo River contributes to more than 80 % of the Lake Turkana inflows (Ricketts and Johnson, 1996). The Ethiopian government is building series of dams on the Omo River primarily to generate electricity. These dams, the Gibe I, Gibe II, and Gibe III (under construction), regulate the flow of the Omo River and its tributaries that eventually flow into Lake Turkana.

The Gibe I dam (commissioned in 2004) is the first of the three hydroelectric projects built within the Ethiopian side of the Lake Turkana basin (Fig. 1). It is built on the Gilgel Gibe River, a small tributary of the main Gibe River, which flows into the Omo River. The Gibe II (commissioned in 2010) receives the water impounded by the existing

HESSD
9, 2987–3027, 2012

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Gibe I hydroelectric plant through a 26 km long tunnel directly into the Gibe-Omo River to hydroelectric plant located 500 m below Gibe I elevation. The resulting head is used to generate electric power. As this project does not impound any water by itself, we assume, it has no significant impact on the Lake Turkana water levels. The Gibe III dam is located on the Omo River about 150 km downstream of the Gibe II outlet (Fig. 1). Near the dam, the area is characterized by a large plateau with a long and relatively narrow canyon through which the river flows (The Gilgel Gibe Affair, 2008). Upon completion, a 150 km long lake (a valley dammed reservoir) would be created, flooding the whole canyon from the dam upstream to the Gibe River retaining about 14.7 billion m^3 of water at maximum capacity. The dam is expected to be commissioned by 2014. The mean annual inflows into the reservoir are estimated to be 438 $m^3 s^{-1}$ (13 800 million m^3), with seasonal inflows varying from less than a 62 $m^3 s^{-1}$ in March to over 1500 $m^3 s^{-1}$ in August (EEPCo, 2009). The impact of the Gibe III dam on Lake Turkana is still not clearly understood. As the Turkana basin is poorly gauged, the availability of in-situ gauge data on hydrologic parameters such as rainfall, streamflow, and evapotranspiration (ET) are very limited. However, satellite sensors provide data over large areas with consistent and repeated temporal coverage and thus offer several advantages in ungauged basins, so in this study we use a multi-source approach driven by satellite data to assess the potential hydrological impact of the Gibe III dam on Lake Turkana water levels.

Recently, few studies/reports on the impact of Gibe III are available (ARWG, 2009; EEPCo, 2004, 2009; Avery, 2010; Salini, 2010). However, there has not been consistency in the results obtained. Ethiopian Electric Power Corporation (EEPCo) performed an environmental impact assessment study of the Gibe II hydroelectric project and indicated that Lake Turkana will benefit from the Gibe I and Gibe II projects (EEPCo, 2004). Africa Resources Working Group (ARWG) provided a commentary on the environmental and socioeconomic impact assessment of the Gibe III dam and indicated that the lake would drop up to 10–12 m (ARWG, 2009). EEPCo (2009) only indicated that the Gibe III dam would have a positive impact on the lake. Recently, Avery (2010) published

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
HESSD
9, 2987–3027, 2012

the most comprehensive report on Lake Turkana and identified that the dam would cause up to a 2 m level drop in the Lake Turkana level. Furthermore, Salini (2010), the official agency building the dam, reported that initially lake water levels would drop up to 1.5 m. Some limitations of these studies are a lack of transparent and consistent methodology and a failure to model the impact beyond the initial period of dam filling. In this study, using transparent methodology, we present the impact assessment study that uses remotely sensed data and hydrologic modeling techniques to model the impact beyond the initial period of dam filling.

Objectives of this study

The objectives of this study are (i) to demonstrate the use of a calibrated multi-source satellite-driven water balance model to assess potential interactions between Lake Turkana and the Gibe III dam, (ii) to use existing satellite data (1998–2009) to model the potential impact of Gibe III dam, (iii) to study the response of Lake Turkana to regulated inflows from the dam under different operational strategies, and (iv) to model the impact of the dam on lake shoreline changes and identify vulnerable areas of change along the shoreline. In this study, we used three different approaches to simulate rainfall-runoff scenarios to study the potential hydrologic interactions between the Gibe III dam and Lake Turkana water levels.

2 Study area and data used

2.1 Study area

The study is conducted over the Lake Turkana basin, which extends over Ethiopia in the north, Kenya in the south, and Sudan and Uganda in the west (Fig. 1). Lake Turkana is one of the lakes in the Great Rift Valley of East Africa. It has a maximum depth of nearly 110 m and an average depth of 30 m, and it extends up to 250 km long and 15–30 km wide, with an average surface area of nearly 6750 km^2. Lake Turkana is known

HESSD
9, 2987–3027, 2012

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for its inter- and intra-annual fluctuations. The climate of Lake Turkana is hot, arid, and moderately stable all year. The driest months are from October through January and rainfall occurs from April through August. The average rainfall over the lake is less than 200 mm yr^{-1} (Halfman and Johnson, 1988). Seasonal variations in rainfall over the Omo River catchment cause a high influx of water during July–December. Thus, the lake shows minimum water levels during June–July and maximum levels during September–November. Generally, the lake level fluctuates annually with amplitude of about 1–1.5 m, but it also undergoes considerable long-term variations that exceed those of any other lake of natural origin (Butzer, 1971). Nyamweru (1989) suggested that the lake levels were about 80 m higher than the present levels when the lake was connected to the Nile during the Holocene period. The modern lake has no outlet and the lake fluctuates from about 360 m to 365 m a.s.l. (above sea level). Kallqvist et al. (1988) synthesized the Lake Turkana water levels for the last 100 years and summarized that around 1895, the lake was 20 m higher than the present, followed by a general decline during the first half of the 20th century. After a minimum in the 1950s, there was a rapid increase up to late 1970s. The most recent water level fluctuations captured by TOPEX/Poseidon show that the lake levels gradually increased to reach a level of 365 m a.s.l. by the end of the 20th century. The altimetry data show that lake levels by the end of 2011 were around 362.5 m a.s.l.

2.2 Data used

The data used in this study are summarized in Table 1. The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) produces satellite-based daily rainfall estimates (RFE). RFE data is available in near-real time since 1995 with a spatial resolution of 0.1 degree. Validation studies of RFE over the Ethiopian highlands using gauge data suggested that RFE can be reliably used for early warning systems to empower the decision making process (Dinku et al., 2008; Beyene and Meissner, 2010). Reliable use of RFE data to model Lake Turkana water levels with reasonable accuracy was demonstrated by Velpuri et al. (2012). RFE data from

HESSD
9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

January 1998 to December 2009 are used in this study. The daily reference evapotranspiration (ET_0) data are produced at the USGS Earth Resources Observation and Science Center from 6-hourly Global Data Assimilation System (GDAS) climate parameters using the standardized Penman-Monteith equation, then downscaled to 0.1° for this study (Senay et al., 2008). Historical average dekadal Normalized Difference Vegetation Index (NDVI) datasets (1982–2006) described by Tucker et al. (2005) from the Advanced Very High Resolution Radiometer (AVHRR) are used to characterize the land surface phenology (LSP) and to estimate actual evapotranspiration (ET_a) on a pixel-by-pixel basis at 0.1° resolution. The canopy interception parameter is estimated using the global percent tree cover product produced from Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Field (Hansen et al., 2003). Area weighted average interception losses are estimated for each modeling pixel based on the percentage of bare, herbaceous, and tree cover for each pixel. The Digital Soil Map of the World (FAO, 1995) is used to estimate water holding capacity (WHC) for the dominant soil type for each grid cell at 1:5 million resolution. Landsat data are used to delineate the Gibe I reservoir and Lake Turkana. Digital elevation models (DEM) from Shuttle Radar Topography Mission (SRTM) 90-m Version 4.0 and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) global DEM (GDEM) 30 m Version 2.0 data are used to derive several hydrologic variables. Lake Turkana water level obtained from TOPEX/Poseidon (T/P), Jason-1/2, and ENVISAT altimetry data was used for validation of the modelled lake levels.

3 Methods

3.1 Deriving reservoir/lake depth-surface area-volume (*h*-*A*-*V*) relationships

In order to model the water levels, it is important to first understand the relationships between *h*-*A*-*V* for each reservoir and Lake Turkana. As the SRTM DEM acquired in 2000 provided pre-dam elevation for both land and area submerged under the reservoir,

HESSD
9, 2987–3027, 2012

it was used to generate the topographic-bathymetric (topo-bathy) data for the Gibe I reservoir. ASTER provided the high resolution pre-dam DEM data (30 m) for Gibe III, so it was used to generate the topo-bathy for the Gibe III reservoir. Since a pre-dam DEM was not available for Lake Turkana, bathymetry data obtained from Kallqvist et al. (1988) were draped on the SRTM DEM to develop seamless topo-bathy data. Finally, *h*-*A* relationships were developed from the lake/reservoir topo-bathy data. Based on the water levels, a simple GIS-based model was used to extract surface areas at every 0.5 m interval of lake level. Thus, a relationships that explains the variations in *h*-*A* were obtained. Similarly, changes in lake volumes (V) were derived as

$$V = \sum_{i}^{N} [(D - \mathrm{LTB}_i) \times A] \tag{1}$$

where D is the lake water level or depth [L], LTB_i is the bottom height [L] for each pixel i obtained from the topo-bathy data, A is the pixel area [L^2] of the topo-bathy data, and N is the total number of pixels in the topo-bathy data representing the surface area of the reservoirs or lake at a given water level. Using Eq. (1), lake volumes at regular intervals were extracted and *h*-*V* relationships were derived for the lake and Gibe reservoirs. Furthermore, SRTM elevation data were used to delineate hydrologic variables such as (a) the Lake Turkana watershed, (b) catchment areas and (c) streams and river networks.

3.2 Lake level modeling approach

In this paper we use the Lake Level Modeling (LLM) approach presented by Velpuri et al. (2012). This approach uses a multi-sensor approach to monitor lake water levels by integrating digital elevation data, satellite-based rainfall estimates, modelled ET, runoff data, and other satellite products. Lake levels modelled using this approach were found to be reasonable with <10 % errors when compared to satellite altimetry data (Velpuri et al., 2012). We introduced the Gibe I and Gibe III dams into the LLM approach and

HESSD

9, 2987–3027, 2012

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routed the runoff through dams before reaching the lake. Furthermore, operational strategies of the Gibe I and Gibe III dams are also incorporated into LLM approach.

3.2.1 Modelling runoff and ET

First, satellite rainfall and ET data are used to estimate runoff [L/T] on a pixel-by-pixel basis using the phenology-based model called VegET (Senay, 2008; Senay et al., 2009). The unique aspect of this model is the use of remotely sensed land surface phenology (LSP) to parameterize the spatial and temporal dynamics of ET and runoff on a grid-cell basis. Then VegET model estimates runoff (Q_{rf}) for each time step based on the principle of soil saturation excess, where soil water content in excess of the WHC of the soil is considered runoff. The modelling approaches in the VegET model can be explained by Eqs. (2) and (3):

$$\text{ET}_\text{a} = K_\text{cp} \times K_\text{s} \times \text{ET}_0 \tag{2}$$

$$Q_\text{rf} = \left[\text{SW}_{(t-1)} + ((1 - \text{ILC}_i) \times \text{RFE}_i) - \text{ET}_{\text{a}_i}\right] - \text{WHC} \tag{3}$$

where ET_a is the actual ET; K_cp is the LSP-based crop coefficient; K_s is the soil water stress coefficient (0–1) whose value depends on the state of soil water on a daily basis; ET_0 is the global GDAS reference ET; RFE is the satellite-based rainfall estimate; and SW represents soil water content. ILC_i is the interception losses coefficient, WHC is the water holding capacity of the soil determined as the difference between the field capacity and wilting point in the top one meter of soil, subscript t represents the current modelling time step, and subscript $t-1$ represents the previous time step. This approach produces a combined estimate of surface runoff and deep-drainage. Variables ET_a, ET_0, RFE, and SW all are in units [L/T]. Further description of this approach is found in Senay (2008), Senay et al. (2009), and Velpuri et al. (2012). Runoff generated using this approach is routed using a source-to-sink routing algorithm (Asante, 2000; Olivera et al., 2000; Velpuri et al., 2012) and total routed runoff volume contribution for each basin (Q_inf) is produced as outlined in Velpuri et al. (2012).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3.2.2 Calibration of runoff data

In order to accurately predict the volumetric changes in reservoirs and the lake, it is essential to calibrate modelled runoff/inflow data using ground-based observation. It is common knowledge that all satellite-based rainfall estimates show bias when compared to ground truth data (Dinku et al., 2008). Hence through calibration process we aim to perform (a) base flow and (b) bias correction for modelled runoff estimates. EEPCo (2009) published long-term (1964–2001) mean monthly Omo River flow data at the Gibe III site and at Lake Turkana. We used these data to calibrate modelled inflows for Gibe I, Gibe III, and Lake Turkana such that the calibrated data (1998–2009) would follow the general distribution of the historical data (1964–2001) for long-term trend and magnitude. First, we estimated base flow from the long-term mean monthly hydrographs using a constant discharge method (Linsley et al., 1975) for Gibe III and Turkana. By comparing long-term mean (1964–2001) streamflow data with mean monthly modelled runoff (1998–2009), monthly parameters for bias correction were obtained. Estimates of base flow and monthly coefficients for bias correction were used to calibrate modelled Gibe III basin runoff data for 1998–2009. We used bias correction coefficients obtained for Gibe III basin to calibrate modelled runoff for Gibe I basin (a sub-basin of Gibe III). Base flow information for Gibe I was obtained from EEPCo (2004). Since contributions from other rivers in the Turkana basin (Turkwel and Kerio) are negligible (Carr, 1998), we calibrated the combined Omo, Turkwell, and Kerio inflows with the long-term mean monthly inflow data for the Omo River at Turkana. For the Gibe III basin, 4 years of monthly flow data (1998–2001) were used to validate calibrated runoff. For Lake Turkana, only long-term mean monthly Omo River flow data were available, so validation could not be performed.

3.2.3 Modelling Gibe I, Gibe III, and Lake Turkana water levels

Total daily over-the-lake/reservoir rainfall (Q_{rain}), ET (Q_{evap}) and the runoff volume contribution (Q_{inf}) were extracted. The lake level information for each time step is then

HESSD
9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

estimated using a water balance principle as shown in Eqs. (4)–(7). First, daily Gibe I reservoir levels are modelled as

$$\mathrm{G1}\,L_i = \mathrm{G1}\,L_{i-1} + \mathrm{G1}\,Q_{\mathrm{rain}} + \mathrm{G1}\,Q_{\mathrm{inf}} - \mathrm{G1}\,Q_{\mathrm{evap}} - \mathrm{G1}\,Q_{\mathrm{out}} \quad (4)$$

where G1 represent Gibe I reservoir; L_i [L/T] and L_{i-1} [L/T] represent reservoir levels for current and previous daily time steps and Q represents different fluxes; "rain" [L/T] is the direct rainfall over the reservoir; "inf" is the incoming calibrated runoff contribution to the reservoir; "evap" [L/T] is the over-the-lake evaporation; and "out" [L/T] is the outflow from the Gibe I reservoir which will eventually flow into the Gibe III reservoir. Then, daily Gibe III reservoir levels are modelled as

$$\mathrm{G3}\,L_i = \mathrm{G3}\,L_{i-1} + \mathrm{G3}\,Q_{\mathrm{rain}} + \mathrm{G3}\,Q_{\mathrm{inf}} + \mathrm{G1}\,Q_{\mathrm{out}} - \mathrm{G3}\,Q_{\mathrm{evap}} - \mathrm{G3}\,Q_{\mathrm{out}} \quad (5)$$

where G3 represents the fluxes of the variables for the Gibe III reservoir. According to EEPCo (2007), contribution of groundwater fluxes or seepage losses to and from the reservoirs are minimal. Hence, we ignore groundwater fluxes in Eqs. (4) and (5). $\mathrm{G3}\,Q_{\mathrm{out}}$, the surface outflow from the Gibe III reservoirs is estimated as

$$\mathrm{G3}\,Q_{\mathrm{out}} = \mathrm{G3}\,Q_{\mathrm{env}} + \mathrm{G3}\,Q_{\mathrm{flood}} + \mathrm{G3}\,Q_{\mathrm{pp}} + \mathrm{G3}\,Q_{\mathrm{spill}} \quad (6)$$

where $\mathrm{G3}\,Q_{\mathrm{env}}$ [L/T] is the environmental flows; $\mathrm{G3}\,Q_{\mathrm{flood}}$ [L/T] is the artificial flood released from Gibe III; $\mathrm{G3}\,Q_{\mathrm{pp}}$ [L/T] is the water discharged from the Gibe III power plant; and $\mathrm{G3}\,Q_{\mathrm{spill}}$ [L/T] represents spill flow or excess flow released when the Gibe III dam is at maximum level, which will eventually flow into downstream Lake Turkana. Finally, Lake Turkana water level is estimated as

$$\mathrm{LT}\,L_i = \mathrm{LT}\,L_{i-1} + \mathrm{LT}\,Q_{\mathrm{rain}} + \mathrm{LT}\,Q_{\mathrm{inf}} + \mathrm{G3}\,Q_{\mathrm{out}} - \mathrm{LT}\,Q_{\mathrm{evap}} \pm \varepsilon \quad (7)$$

where LT represents the fluxes of the variables for Lake Turkana; and ε [L/T] is the error term that accounts for the data and modelling errors. The estimate of ε (2 mm day^{-1}) for Lake Turkana obtained by Velpuri et al. (2012) is used in this study. As Lake Turkana is considered closed (Ricketts and Johnson, 1996), groundwater inflows and surface outflows are considered negligible (Cerling, 1986). A detailed description of the LLM approach is provided in Velpuri et al. (2012).

HESSD
9, 2987–3027, 2012

3.3 Operational strategies of the Gibe dams

In this study, we considered the operational strategies to be followed by EEPCo to simulate the potential impact of the dams. Following are the operational strategies for the Gibe I and Gibe III dams that are implemented in the modeling framework.

a. The rated outflow of 101.5 $m^3 s^{-1}$ and a continuous environmental flow of 1.3 $m^3 s^{-1}$ is released downstream of the Gibe I dam (EEPCo, 2004).

b. All time environmental flow at the rate of 25 $m^3 s^{-1}$ to be released from the Gibe III dam (EEPCo, 2009).

c. An artificial flood at the rate of 1000 $m^3 s^{-1}$ to be released from the Gibe III for 10 days in September to maintain the natural flooding conditions in the lower Omo basin (EEPCo, 2009).

d. The minimum operating level for commissioning of power generation is 854 m a.s.l. or a reservoir depth of 201 m (EEPCo, 2009).

e. The hydroelectric power plant would operate for 11 out of 24 h a day; i.e., a plant factor of 0.46 would be used to estimate the total power produced (Salini, 2010).

3.4 Gibe III impact assessment using satellite data

Since Gibe III is not commissioned at the time of performing this study, we used existing satellite-based estimates of hydrologic variables to forecast the potential hydrological impact of the Gibe III dam. The relatively short length of the available satellite data (1998–2009) precludes a complete characterization of the rainfall variability in the basin. This is a common problem especially in ungauged basins where in-situ data are either limited or unavailable. However, the modelled lake inflows are calibrated using long-term (1964–2001) mean monthly Omo River discharge data to minimize the impact of bias in the satellite rainfall and in the resulting modelled runoff estimate.

HESSD
9, 2987–3027, 2012

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Despite the short time series, we argue the calibrated runoff would follow the general distribution in trend and magnitude of historical data (1964–2001) and rainfall variability observed in the 12 years (1998–2009) could represent much of the seasonal and annual rainfall-runoff distribution of the basin. We used three different approaches to simulate rainfall-runoff scenarios and evaluate the potential impact of the dam on Lake Turkana.

3.5 Approach I – historical approach

In this approach we assumed a simple case that the Gibe III dam was commissioned sometime in the past (January 1998). First, using the LLM approach (Velpuri et al., 2012), Lake Turkana water levels for 1998–2009 were modeled without the dam. Then, the model was re-run assuming that the Gibe III Dam was commissioned on 1 January 1998, and the volume of the inflows routed through the dams was used to model lake levels. A comparison of the volume of inflows and the lake water levels with and without the dam yielded the impact of the Gibe III dam. Furthermore, the time taken for the Gibe III reservoir to reach minimum operation level (MOL) and loss in Lake Turkana water level was estimated.

3.6 Approach II – knowledge-based scenarios

Rainfall variability in the East African region has been thoroughly investigated (Kolding, 1992; Camberlin, 2001; Shongwe et al., 2009). Kolding (1992) studied the rainfall distribution over Lake Turkana and summarized that severe drought occurs roughly every 6 years. The summer rains in this region were found to be significantly correlated to the El-Nino Southern Oscillation (ENSO), which repeats on average every 5 years (Camberlin, 2001). Furthermore, Shongwe et al. (2009) reported that there has been an increase in the number of reported hydro-meteorological disasters in the region, from an average of <3 events per year in the 1980s to ∼10 events per year from 2000 to 2006, with a particular increase in floods. A quick analysis of rainfall data over 1998–2009

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

shows that there was a severe drought in 2000 (WFP, 2000) and below normal (BN) rainfall in 2003, 2004, 2005, and 2009. There were incidents of heavy rainfall due to the ENSO effect in 1998 (Behera, et al., 2005) and severe floods in 2006 (Moges et al., 2010), whereas above normal (AN) rainfall was observed in 2001, 2002, and 2006. Other years, 1999, 2007 and 2008, had near normal (NN) rainfall. These observed patterns grossly follow the trend observed by Kolding (1992) and Camberlin (2001), with one severe drought (2000) and 2 severe rainfall years (1998 and 2006). However, other patterns of BN and AN rainfall years could be explained by the observations made by Shongwe et al. (2009). Based on the knowledge of the regional climate, 20 different scenarios of AN, NN, and BN rainfall distributions were built such that the occurrence of a severe drought year (2000) or a severe flood year (2006) would not occur more than twice or, in rare cases, three times in a scenario. The choice of other years was purely based on random selection without any constraints. Table 2 shows various combinations of years under each scenario used. Under each scenario, simulations of lake levels were modeled and compared with and without the dam. Furthermore, the time taken for the Gibe III reservoir to reach MOL and subsequent loss in Lake Turkana water level was estimated.

3.7 Approach III – univariate nonparametric bootstrap resampling (NBR) technique

In this approach, we used 12 years of data (1998–2009) to simulate time series information on the possible scenarios of rainfall, lake inflows, and ET data using the nonparametric bootstrap resampling (NBR) technique. The NBR technique was first introduced by Efron et al. (1993) and has been widely used for the simulation of rainfall or inflows using historical data (Rajagopalan et al., 1997; Sharma et al., 1997; Srikanthan and McMahon, 2001). We used this approach as it does not require a preselected statistical distribution. This approach is useful for simulating data in ungauged basins where such simulated data is required to analyze the impact of alternative designs, operation policies, and other rules. Different methods of NBR are available. In this

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

study, we used a simple NBR method where the time series data of future scenarios are drawn at random from the data numerous times using the Monte Carlo approach. However, since we are using existing/historic data to predict future scenarios, the resampled scenarios represent plausible future scenarios under the assumption that the future would have similar statistical properties as the observed data. Furthermore, since observations are randomly resampled, serial dependence is not preserved. However, since we bag the daily data from the 12 different years and randomly draw a value from the set of observations for a given day, seasonality and distribution of observed rainfall are preserved. One of the main reasons to use the NBR technique is to construct a confidence interval attached to each estimate of modelled lake level. The NBR is mathematically explained in the following steps:

- *Step 1*:
  Let the parameter of interest (rainfall or runoff or ET variables for Gibe I, Gibe III and Turkana basins) be represented by the vector $\boldsymbol{Q}_{v,i}$, where the subscript v denotes index for 12 years ($v = 1, 2, \ldots 12$) and i denotes the series of daily data for a year ($i = 1, 2, 3, \ldots 365$). Then the **X**-matrix for 12 years of data can be shown as

$$\mathbf{X} = \begin{bmatrix} \boldsymbol{Q}_{1,1} & \boldsymbol{Q}_{1,2} & \cdots\cdots & \boldsymbol{Q}_{1,365} \\ \boldsymbol{Q}_{2,1} & \boldsymbol{Q}_{2,2} & \cdots\cdots & \boldsymbol{Q}_{2,365} \\ \cdots & \cdots & \cdots\cdots & \cdots \\ \cdots & \cdots & \cdots\cdots & \cdots \\ \boldsymbol{Q}_{12,1} & \boldsymbol{Q}_{12,2} & \cdots\cdots & \boldsymbol{Q}_{12,365} \end{bmatrix}. \tag{8}$$

- *Step 2*:
  For each day of the year, the bootstrap resample is drawn with replacement from the corresponding column of data in Eq. (8) to build a matrix of resampled time-series shown as

HESSD
9, 2987–3027, 2012

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$$\mathbf{X}^* = \begin{bmatrix} Q^*_{1,1} & Q^*_{1,2} & \cdots\cdots & Q^*_{1,365} \\ Q^*_{2,1} & Q^*_{2,2} & \cdots\cdots & Q^*_{2,365} \\ \cdots & \cdots & \cdots\cdots & \cdots \\ \cdots & \cdots & \cdots\cdots & \cdots \\ Q^*_{12,1} & Q^*_{12,2} & \cdots\cdots & Q^*_{12,365} \end{bmatrix} \quad (9)$$

where $\mathbf{X}^*$ represents the resampled data matrix and $Q^*_{v,i}$ is a random sample for a day of the year equal to any of the 12 values for a particular day (a column of variables) in Eq. (8).

- *Step 3*:
  Using the LLM approach and independent matrices of resampled variables $Q^*_{v,i}$ generated in step 2, twelve years of lake water levels are modelled on a daily basis, by modifying Eqs. (4), (5), and (7) as

$$\text{G1}\, L^*_{v,i} = \text{G1}\, L^*_{v,i-1} + \text{G1}\, Q^*_{\text{rain}} + \text{G1}\, Q^*_{\text{inf}} - \text{G1}\, Q^*_{\text{evap}} - \text{G1}\, Q_{\text{out}} \quad (10)$$

$$\text{G3}\, L^*_{v,i} = \text{G3}\, L^*_{v,i-1} + \text{G3}\, Q^*_{\text{rain}} + \text{G3}\, Q^*_{\text{inf}} + \text{G1}\, Q_{\text{out}} - \text{G3}\, Q^*_{\text{evap}} - \text{G3}\, Q_{\text{out}} \quad (11)$$

$$\text{LT}\, L^*_{v,i} = \text{LT}\, L^*_{v,i-1} + \text{LT}\, Q^*_{\text{rain}} + \text{LT}\, Q^*_{\text{inf}} + \text{G3}\, Q_{\text{out}} - \text{LT}\, Q^*_{\text{evap}} \pm \varepsilon. \quad (12)$$

- *Step 4*:
  Large number of combinations are possible (12^{365}) to build data for a year (a row in Eq. 9). Hence, Step 1 through 3 are repeated numerous times ($B = 100\,000$ times), such that time-series data matrix for daily variables (rainfall, runoff, and ET) are used to generate a total of B independent array of lake levels as $(L^*)^{(1)}, (L^*)^{(2)} \ldots (L^*)^{(B)}$.

- *Step 5*:
  A 95 % confidence interval for a total of B estimates of $L^*_{v,i}$ is obtained by sorting individual estimates of $L^*_{v,i}$ in increasing order such that

HESSD
9, 2987–3027, 2012
Potential hydrological impact of the Gibe III Dam on Lake Turkana
N. M. Velpuri and G. B. Senay

$(L^*_{v,i})^{(1)} \leq (L^*_{v,i})^{(2)} \ldots \leq (L^*_{v,i})^{(B)}$. Then, the lower (LCI), median, and upper (UCI) bootstrap percentile 95 % confidence intervals for the $L^*_{v,i}$ are estimated as

$$\mathrm{LCI} = \left(L^*_{v,i}\right)^{(U)} \tag{13}$$

$$\mathrm{Median} = \left(L^*_{v,i}\right)^{(B/2)} \tag{14}$$

$$\mathrm{UCI} = \left(L^*_{v,i}\right)^{(B+1-U)} \tag{15}$$

where $U = 0.025B$ (Efron et al., 1993). For example, for a simulation that runs 100 000 times ($B = 100\,000$), $U = 2500$ and $B + 1 - U = 97\,501$ for a 95 % confidence interval.

3.7.1 Cross-validation of lake levels modelled using NBR technique

Velpuri et al. (2012) demonstrated the use of altimetry based lake level data for model validation especially when in-situ data is unavailable. Lake levels modelled using LLM approach based on NBR variables were cross-validated using altimetry based monthly lake level data obtained from TOPEX/Poseidon (T/P), Jason-1, and ENVISAT (Cretaux and Birkett, 2006). First, we ran the model to predict lake levels under natural conditions (without dam) for a particular year using data from other years i.e., predicting lake levels for 2006 using data from 1998–2005 and 2007–2009. Modelled lake level data were summarized on monthly basis to enable direct comparison with the satellite altimetry data. The correlation between the predicted and altimetry data is presented.

3.7.2 Impact of the Gibe III dam based on the initial lake water levels

Considering the Lake Turkana bathymetry and *h*-*A* relationships, we hypothesize that the impact of the dam would depend on the initial water level in the lake at the time

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of commencement of the dam. This is because, the higher the lake level, the higher the surface area, and larger volumes of inflows are required to cause a unit increase in lake level. Similarly, we argue that when the initial lake water level is low, the lake would stabilize faster with lesser volume of inflows. We test this hypothesis by modelling lake levels with different initial lake levels.

3.7.3 Application of NBR technique

Using different scenarios of time series data produced, lake water levels for a period of 12 years from the commencement of the dam are produced using Eqs. (10)–(12) considering both with and without the dam. The impact of the dam is assessed for different initial lake levels within the range of natural fluctuations of the lake (358–365 m). For each initial level, median and 95 % confidence intervals of lake levels are summarized. The time required for the reservoir to reach MOL and loss in lake level during this period is also reported for each initial lake level.

3.8 Analysis of shoreline changes using SRTM-based topo-bathymetry data

The overall impact of the Gibe III dam in terms of lake water shoreline is not completely understood unless the impact of frequency, timing, and duration of water level fluctuations on the lake shoreline is known. To derive lake shoreline changes, the LLM approach is run (with initial lake level of 362 m a.s.l.) using median, upper and lower 95 % confidence intervals of lake levels each representing NN, AN and BN rainfall scenarios. Mean lake level and surface area are estimated for each month. Finally, mean lake surface areas of the lake for each month are combined to estimate the frequency of wetting and drying along the lake shoreline. A value of one represents that the corresponding pixel will have water only for 1 month and a value of 144 represents that the pixel will hold water for all the months during the 12 years simulation period.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD

9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

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4 Results and discussion

4.1 Validation of calibrated lake inflow data

Figure 2 shows the results of validation of calibrated modelled runoff using river gauge data at the Gibe III dam site over 1998–2001. Initial comparison of modelled and observed runoff at the Gibe III site shows that modelled runoff underestimates up to 49 %. This could be due to the underestimation of RFE data used in this study (Dinku et al., 2008). Further runoff data modelled using the VegET approach is also found to underestimate the base flow, especially during dry season months. However, after calibration, monthly runoff for 1998–2001 shows a reasonable match with the observed data with an R^2 of 0.77 and an improved bias of −1.8 %.

4.2 Surface area and volume estimates for the Gibe reservoirs and Lake Turkana

The surface area and volume of the Gibe I reservoir modelled using topo-bathy data was 49 km^2 and 807 Mm^3, respectively, at a maximum operation level of 1671 m a.s.l. against the published surface area of 51 km^2 and volume of 839 Mm^3 (EEPCo, 2004). The surface area of 209.3 km^2 and total volume of 14.5 billion m^3 at a maximum operation level of 894 m a.s.l. or 241 m were obtained for Gibe III using ASTER elevation data against the actual reported values of surface area (210 km^2) and total volume (14.7 billion m^3) as reported by EEPCo (2009). The surface area and volume obtained for Lake Turkana at 365 m a.s.l. are 7685 km^2 and 233.4 billion m^3, respectively. These values are in close agreement with lake surface area and volume published in literature (Hopson, 1982).

4.3 Approach I – historical approach

The LLM approach was run without the Gibe III dam to derive lake levels for the period 1998–2009. The lake level for 31 December 1997 was obtained from the altimetry

HESSD
9, 2987–3027, 2012

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data. First, the model was run without the Gibe III dam. The average rate of inflows into the lake was found to be 650 $m^3 s^{-1}$ during 1998–2009 with wet season flow rate over 1500 $m^3 s^{-1}$ and dry season flow rate of 100–200 $m^3 s^{-1}$ (Fig. 3a). The lake level fluctuated between 360 and 365 m a.s.l. during 1998–2009. The model was then re-run by commissioning the Gibe III dam on 1 January 1998. The model results show that the dam moderated inflows into the lake after the first impoundment period, with regulated peak flows and increased base flows with an average flow rate of 400–500 $m^3 s^{-1}$ (Fig. 3a). Results indicated that the Gibe III reservoir would reach the MOL of 201 m in 8 months. During this period, the rate of inflow into Lake Turkana was found to be 58 % less than the rate without the dam. The difference between the lake levels with and without the dam was 0.65 m by the time the Gibe III reservoir reached MOL (Fig. 3b). The difference between the lake levels with and without dam conditions increased to slightly over 3 m by beginning of 2000 (Fig. 3c). Then, both the lake levels gradually declined until the middle of 2006 and increased by the end of 2007. The difference by the end of 12 year simulation period was found to be <1 m.

4.4 Approach II – knowledge-based scenarios

The LLM approach was run for the 20 knowledge-based scenarios (Table 2) both with and without the Gibe III dam. Results of this analysis are shown in Fig. 4 and Table 3. The Gibe III dam would reach MOL in 8 months (scenarios 6, 7, 8, 12, and 15) to up to 16 months (scenarios 16 and 18) with an average period of 10 months. The time to reach MOL would depend on the amount and distribution of rainfall received after the dam commencement. During the first impoundment period, a BN rainfall year would prolong this time to more than a year. However, AN to NN rainfall year would help the dam to reach MOL in less than a year. Due to regulated inflows during the first stage of reservoir impoundment, with respect to without the dam, Lake Turkana water levels would drop up to a minimum of 0.8 m (scenarios 1, 16, and 18) to a maximum of 1.6 m (scenario 6). After first impoundment period, with respect to without the dam, the lake levels would fluctuate anywhere between 0 to over 4 m with an average loss up to

HESSD
9, 2987–3027, 2012

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1.8 m. The dynamic ranges of fluctuations in each scenario are illustrated in Fig. 4 and Table 3.

Results also indicate that the impact of the dam would be higher in scenarios 6, 14, 15, 18, and 19, with over 4 m drops in lake levels. In all these scenarios, the highest impact occurred only over the years with AN rainfall. Scenarios 2, 3, 10, 11, and 16 shows the least impact with <0.5 m difference with respect to without the dam. These scenarios have more years of BN rainfall. It is interesting and counterintuitive to see a smaller impact on the lake level when there is BN rainfall, and a higher impact on the lake level when there is AN rainfall. This is because, during the dry years, the natural inflows into the lake are reduced. With the dam in place, an average inflow of 400–500 $m^3 s^{-1}$ is always guaranteed hence, the lake levels with the dam will not actually drop as much as they should drop in a dry years without the dam. However, this requires the initial condition that the dam reservoir is above MOL. On the other hand, during the wet years, the lake would always receive moderated inflows, which would be much less than the natural inflows (without the dam) and hence the relative impact on the lake would be higher in wet years.

4.5 Approach III – univariate nonparametric bootstrap resampling technique

Results from cross-validation are shown in Fig. 5. Lake levels are predicted for each year using data from other years. Combined results provided an R^2 of 0.76. However, certain years such as 1998, 2001, 2005, 2006, 2007, and 2008 yielded high correlation ($R^2 > 0.5$), while others yielded lower correlation ($R^2 < 0.5$). The years that showed distribution different from long-term distribution yielded low correlation. The results of simulated lake levels using NBR technique are shown in Fig. 6 and Table 4. Results indicate that the time required for the Gibe III reservoir to reach MOL is about 10 months for the median scenario. However, the upper and lower 95% confidence interval (UCI and LCI) indicates that the reservoir would reach MOL in 5 and 15 months respectively. During initial impoundment, the lake would drop up to 1.2 m depending on rainfall conditions and initial lake level. The loss in lake level at the end of the simulation period

HESSD
9, 2987–3027, 2012

(with respect to without the dam) was found to range from 1.5 to 3.1 m (UCI); 1.1 to 2.9 m (median), and 1.0 to 2.2 m (UCI) depending on the initial lake level. Our results also indicate that, as the Gibe III dam would moderate the flows into the lake, peak season flows would reduce but with increased base flow. The seasonal fluctuations in lake level will be dampened from 1.5 m to <0.5 m (Fig. 6). Furthermore, based on the results obtained, we accept the hypothesis that the total impact of the dam would depend on the initial Lake Turkana water level at the time of commencement of the dam. The impact at different initial lake levels was estimated by identifying the difference between the lake levels derived without the dam and with the dam at the end of simulation period. Our results indicate that the impact is lowest when the initial lake level is low, and it increases as the initial lake level increases (Fig. 7).

4.6 Analysis of Lake Turkana shoreline changes

The impact of changing lake level along the shoreline under three possible scenarios of rainfall is presented (Fig. 8). The dark blue areas in the figure indicate intact regions of the lake that would have water all the time during the modeling period of 12 years. Any color other than dark blue indicates that the lake would have water for fewer months during the modelling period. Figure 8a indicates modelling results for the BN rainfall scenario (lower 95 % confidence interval), where the lake would shrink up to 5 m from the initial lake level of 362 m. This could cause the lake shoreline to shrink up to 1–2 km and result in periodic wetting and drying of the shoreline in regions of Omo River delta and Todenyang in the north; Ferguson's Gulf and the Turkwell and Kerio deltas in the west; South and North Sandy bays, Allia Bay, and Koobi Fora in the west. A total of 22 % of the lake surface area (areas other than dark blue) would show wetting and drying conditions. For the NN rainfall (median) scenario, the lake would only show small fluctuations (Fig. 8b). With NN rainfall, the lake would shrink in the Omo River delta, Ferguson's Gulf, the Turkwell and Kerio deltas, and south of Allia Bay, but would soon recover and possibly expand in these regions. Nearly 9 % of the lake surface would show wetting and drying. Finally, for the AN rainfall scenario (upper 95 % confidence

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

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interval), the lake does not show any shrinking (Fig. 8c). On the other hand, model results indicate that the lake would expand inundating the Omo River delta, Ferguson's Gulf, the Turkwell and Kerio deltas, Allia Bay, and regions of Koobi Fora. The lake would expand up to 2–3 km along the shoreline in these areas. A total of 10 % of the area along the lake shoreline would show wetting and drying. Future research should focus on the implications of decrease or increase in lake level and wetting and drying conditions along the lake shoreline on fisheries, ecology, and hydrology of the lake.

4.7 Use of multi-source satellite data for Gibe III impact assessment: opportunities and challenges

4.7.1 Use of calibrated satellite data-driven water balance model

Reliable in-situ data on hydrologic parameters are either limited or unavailable in most ungauged basins. Remote sensing satellites and model-assimilated global weather data sets offer consistent and reliable estimates of hydrologic variables required for water balance modelling at shorter time scales. However, satellite-based estimates of hydrologic variables often show bias when compared to ground truth data and require site specific calibration or bias correction to improve model accuracies (Velpuri et al., 2012). In this study, therefore, we demonstrate the use of a calibrated water balance model driven by satellite data for the Gibe III impact assessment. We calibrated and validated the runoff data using Omo River flow data obtained from EEPCo (2009) and cross-validated NBR approach results using satellite altimetry data.

4.7.2 Use of existing satellite data for the Gibe III impact assessment

The main challenge of using remote sensing data for hydrologic predictions is lack of longer time series of data from remote sensing platforms. The data little over a decade are only available from remotely sensed platforms. In this study, we use 12 years (1998–2009) of satellite-based estimates of rainfall, modelled ET, and runoff data to

HESSD
9, 2987–3027, 2012

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assess the potential hydrological impact of the Gibe III dam on the Lake Turkana water levels. However, this study is based on the assumption that the rainfall after the commencement of the dam would follow the general distribution of the historical data (1964–2001) for magnitude and (1998-2009) for variability. Nevertheless, the actual rainfall may deviate from the observed mean distribution, so the results obtained from this study should be used with caution. In spite of this, we recommend the use of existing satellite data in poorly gauged basins, as they would at least help us understand the possible impacts of the upstream basin developmental activities such as dams or irrigation on downstream water resources. As more years of satellite and global data sets become available, the method will become more robust and reliable.

4.7.3 The use of topo-bathy data for shoreline changes

In closed-basin lakes such as Lake Turkana, changes in inflows drives changes in the lake level. The Gibe III impact assessment study would be incomplete without understanding the impact of the fluctuating lake level on the lake shoreline. The frequency and distribution of the wetting and drying of the Lake Turkana shoreline is highly important for fisheries and ecological studies in the lake. In this study, we present an approach to use topo-bathy data produced by combining SRTM DEM and bathymetry data to (a) understand the impact of fluctuating lake level on shoreline changes, (b) identify areas vulnerable to change along the lake shoreline, and (c) identify regions that are prone to periodic wetting and drying along the shoreline. However, the application of this method is highly dependent on the availability and accuracy of bathymetry data.

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

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5 Conclusions

The main objective of this study is to assess the interactions and potential hydrological impact of the Gibe III dam on Lake Turkana water levels using a calibrated water balance model driven by satellite and model-assimilated global weather data. The impact of the Gibe III dam on the lake water levels is assessed using three different approaches that use existing satellite data and various future scenarios of rainfall-runoff. First, we assessed the impact of the dam using a historical approach assuming that the dam was commissioned in the past. In the second approach, we generated future rainfall scenarios based on the knowledge of frequency and distribution of droughts and floods in the region. In the third approach, we used the NBR technique to generate different rainfall-runoff scenarios and predict the impact of the Gibe III dam. All the approaches provided comparable and consistent results.

Modelling results indicate that, on average, the reservoir would take up to 8–10 months to reach MOL of 201 m. During the initial period of dam/reservoir filling, the lake level would drop up to 2 m (95 % confidence interval). These results are similar to the results published by Avery (2010) and Salini (2010). When compared to the lake level modeled without the dam, the lake levels will decline on average 1.5–2 m with extremes ranging from no loss in lake levels (AN rainfall scenario) to a little more than 4 m (BN rainfall scenario). We also made an interesting finding that the impact of the Gibe III dam would depend on the initial level of Lake Turkana at the time of commencement of the dam where the relative impact of the dam is larger at higher initial lake levels than lower initial lake levels. The variability of lake levels caused by regulated inflows was found to be within the natural variability of the lake of 4.8 m. In this study, we also identified areas along the Lake Turkana shoreline that are vulnerable to fluctuations in lake levels. Under the NN rainfall scenario, the lake shoreline would not show much change; however, under the BN rainfall scenario, the lake's shoreline would shrink 1–2 km, and in the AN rainfall scenario the lake shoreline would expand 2–3 km in some regions. This study demonstrated the use of existing multi-source data for

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
9, 2987–3027, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
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(a) impact assessment of an upstream dam on downstream lakes/reservoirs in regions where in-situ data are limited and (b) analyzing the impact of regulated lake inflows on water level fluctuations and shoreline changes. Results obtained from this study can be used to understand the impact of different operational strategies on the hydrology of the lake. Because this study only focused on the hydrological impact, further study is required to assess the potential impact of regulated Omo River flows on the ecology and fisheries of Lake Turkana and lower Omo basin.

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HESSD

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HESSD

9, 2987–3027, 2012

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Table 1. Satellite data, products, and other ancillary data used in this study.

No	Data	Satellite sensor/ source	Frequency	Resolution/ scale	Reference
1	Rainfall estimate for Africa	SSM/I, AMSU	Daily	$0.1^\circ \times 0.1^\circ$	Herman et al. (1997); Xie and Arkin (1996)
2	Global GDAS reference Evapotranspiration (ET)	Model assimilated satellite data	Daily	$0.1^\circ \times 0.1^\circ$	Senay et al. (2008)
3	Climatological NDVI	NOAA AVHRR	Dekadal	8 km	Tucker et al. (2005)
4	Landsat	TM/ETM	Multiple dates	30 m	–
5	Digital soil map of the world	National statistics	Single date	1:5 000 000	FAO (1995)
6	Global percent tree cover map	MODIS VCF	Single date	500 m	Hansen et al. (2003)
7	Digital elevation model	SRTM V 4.0	Single date	90 m	Farr et al. (2000)
8	Digital elevation model	ASTER GDEM V 2.0	Single date	30 m	Tachikawa et al. (2011)
9	Lake Turkana water levels	TOPEX/Poseidon, Jason-1, ENVISAT	Daily	>200 m	Birkett (1995)
10	Lake Turkana bathymetry data		Single date	–	Kalqvist et al. (1988)
11	Omo river inflow data	EEPCo (2009)	1964–2001	–	EEPCo (2009)

HESSD
9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

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Table 2. Scenarios of rainfall generated based on the knowledge of regional climate in the East African region.

Years	Knowledge-based scenarios																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Y1	2005	2000	2009	2000	2008	2006	1998	1998	2008	2009	2009	1998	2009	2001	2006	2003	2004	2003	2000	2001
Y2	2009	2002	2002	1998	2000	2001	2004	2000	1999	2001	2006	2004	2007	2006	2005	2000	2009	1998	2000	1998
Y3	2007	2006	2006	2004	1998	2006	2005	2007	2005	2003	2005	2000	2000	2002	2004	2002	2000	2007	2004	2000
Y4	2000	2004	2005	2001	2004	2001	2009	2002	2006	2006	2000	2006	2003	2003	1999	1998	2007	2009	2007	2002
Y5	2006	2009	1998	2000	2000	2007	2000	2000	1999	2008	2004	2001	2005	1998	2003	2000	2004	2006	1999	2007
Y6	2001	1998	2009	2009	2009	2009	2009	2008	2004	2003	2005	2007	2009	2002	2000	2008	2008	2003	2004	2001
Y7	2004	2001	2002	2001	2002	1998	2005	2001	2002	2007	2004	2009	2006	2005	2002	2000	1998	2002	2006	2006
Y8	2002	2009	2003	2007	2008	2001	2008	2004	2004	2008	2000	2002	2000	1998	1999	2002	2005	2005	2001	2003
Y9	1998	2000	2000	2002	2006	2004	2006	1999	2000	2009	2001	1999	1998	2007	2004	2002	2000	2000	2007	2005
Y10	2004	2000	2002	2006	2005	2000	2005	2001	2008	2009	2008	2000	2004	2007	2007	2006	2008	2008	2008	2005
Y11	2000	2001	2001	2007	2007	2002	2000	2006	2001	2006	2006	2004	2002	2009	1998	2001	2004	2002	2009	2003
Y12	2002	2003	2007	2008	2004	2003	2005	2008	2007	2001	2007	1998	1999	2000	2003	2008	2006	2005	2006	2000

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

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Table 3. Impact of the Gibe III dam on the Lake Turkana water level assessed using knowledge-based scenarios.

Knowledge based scenarios	Time to fill Gibe III reservoir (reach MOL*) [Months]	Loss in Lake Turkana levels with respect to no-dam			
		During first impoundment [m]	After the first impoundment		
			Max [m]	Mean [m]	Min [m]
1	10	0.8	2.9	1.6	0.7
2	10	1.0	2.9	1.3	0.4
3	9	1.1	2.6	1.0	0.0
4	10	1.0	2.9	1.7	0.7
5	9	1.2	2.6	1.6	0.6
6	8	1.6	4.0	2.4	1.3
7	8	1.1	3.0	1.7	0.5
8	8	1.1	3.4	2.1	1.0
9	9	1.2	3.5	2.1	0.8
10	10	1.1	2.2	1.1	0.3
11	10	1.1	3.0	1.2	0.4
12	8	1.1	3.8	2.5	1.0
13	10	1.1	3.1	1.4	0.4
14	15	0.9	4.2	1.9	0.6
15	8	1.6	4.3	2.2	1.0
16	16	0.8	2.4	1.1	0.3
17	10	1.4	3.3	1.9	0.7
18	16	0.8	4.0	2.4	0.7
19	10	1.0	4.1	2.3	0.6
20	15	0.9	2.8	1.7	0.8
Average	10	1.1	3.2	1.8	0.6

Note: * – MOL: minimum operation level.

HESSD
9, 2987–3027, 2012

Potential hydrological impact of the Gibe III Dam on Lake Turkana

N. M. Velpuri and G. B. Senay

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Table 4. Lake level fluctuations modeled using a nonparametric bootstrap resampling (NBR) technique for the period of 12 years from the commencement of the dam.

Initial lake level	Time to reach MOL* of 201 m [Months]			Loss in lake level before reaching MOL [m]			Lake level at the end of 12 years with respect to without the dam [m]		
[m]	UCI**	Med**	LCI**	UCI**	Med**	LCI**	UCI**	Med**	LCI**
358	<5	8	15	0.0	0.8	1.3	1.5	1.1	1.0
359	<5	8	15	0.0	0.9	1.4	1.6	1.2	1.0
360	<5	8	15	0.0	0.9	1.5	1.7	1.2	1.0
361	<5	8	15	0.0	1.0	1.6	1.9	1.2	1.1
362	<5	8	15	0.0	1.0	1.7	2.2	1.5	1.1
363	<5	8	15	0.0	1.1	1.8	2.5	2.1	1.3
364	<5	8	15	0.0	1.1	1.8	2.8	2.6	1.8
365	<5	8	15	0.0	1.2	1.9	3.1	2.9	2.2

Note: * – MOL = minimum operation level; ** – UCI and LCI denote upper and lower bootstrap percentile 95 % confidence intervals respectively and Med represents median value.

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9, 2987–3027, 2012

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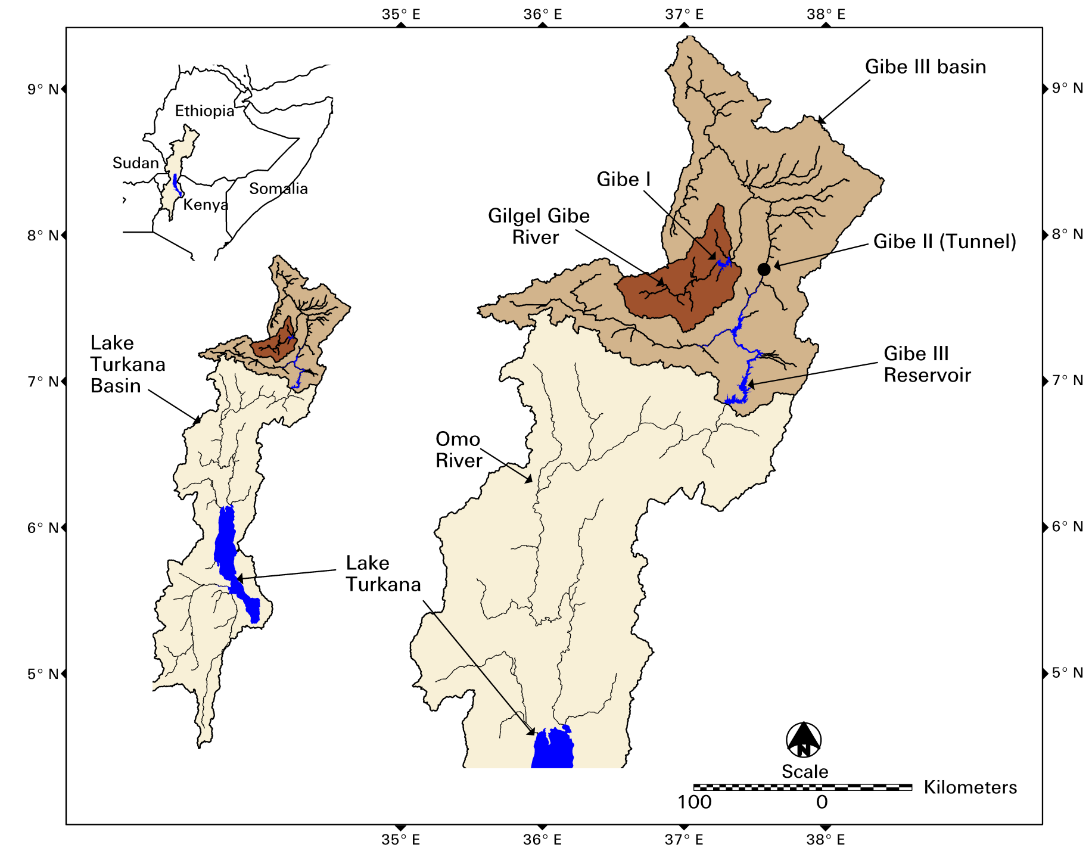

Fig. 1. Study area showing Lake Turkana and its watershed; location of Gibe dams on the Omo River, Ethiopia are also shown.

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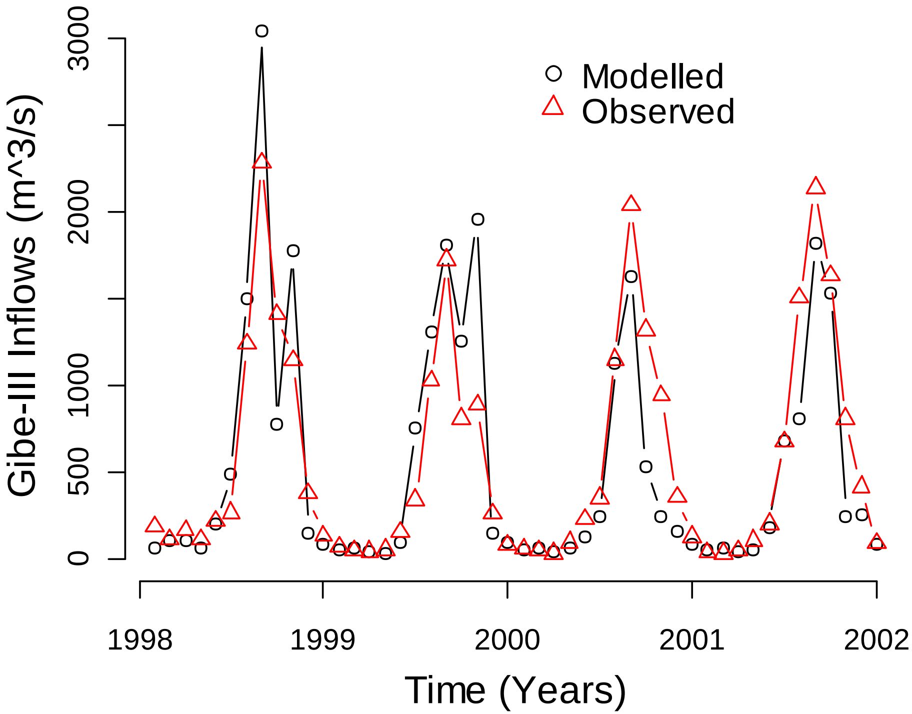

Fig. 2. Validation of modelled runoff data (after calibration) with observed monthly inflows (1998–2001) at the Gibe III dam site obtained from EEPCo (2009). Model calibrated using mean monthly streamflow data (1964–2001).

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

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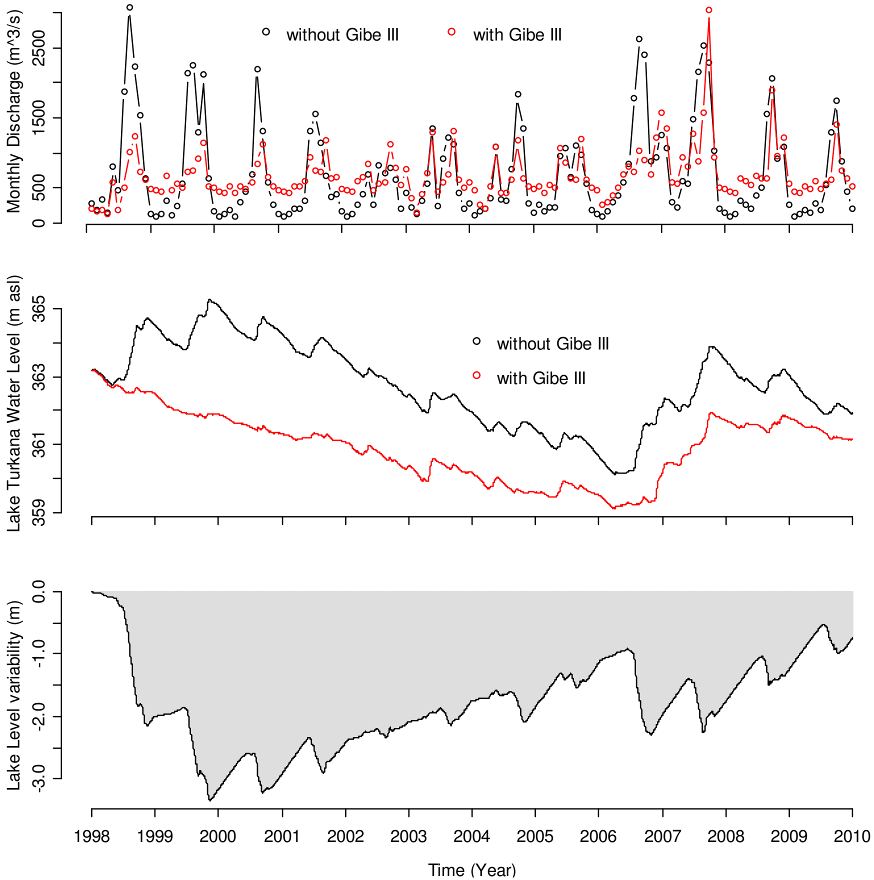

Fig. 3. Impact of the Gibe III dam evaluated using historical approach. Top panel: Total monthly Lake Turkana inflows; middle panel: the lake water levels; and bottom panel: the difference in lake levels; with (red line) and without (black line) the Gibe III dam. The model was run assuming the dam was commissioned on 1 January 1998.

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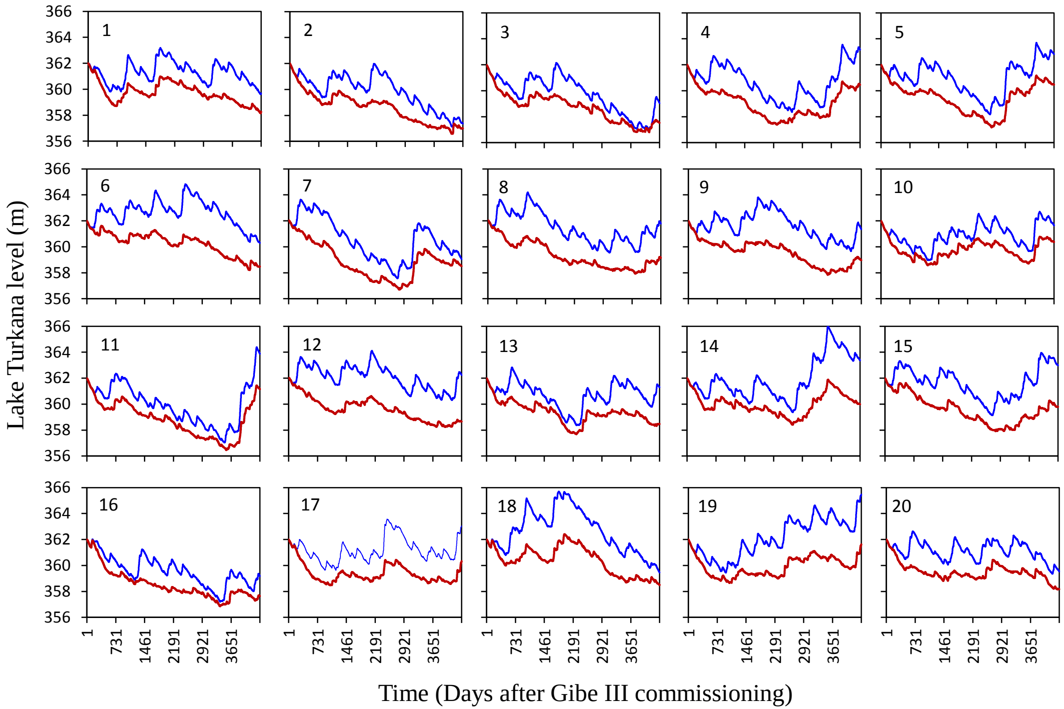

Fig. 4. Impact of the Gibe III dam on Lake Turkana water levels assessed based on 20 knowledge-based rainfall scenarios. The blue line shows the lake level fluctuations under each scenario without the Gibe III dam, and the red line shows the lake level fluctuations after the commissioning of the Gibe III dam.

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9, 2987–3027, 2012

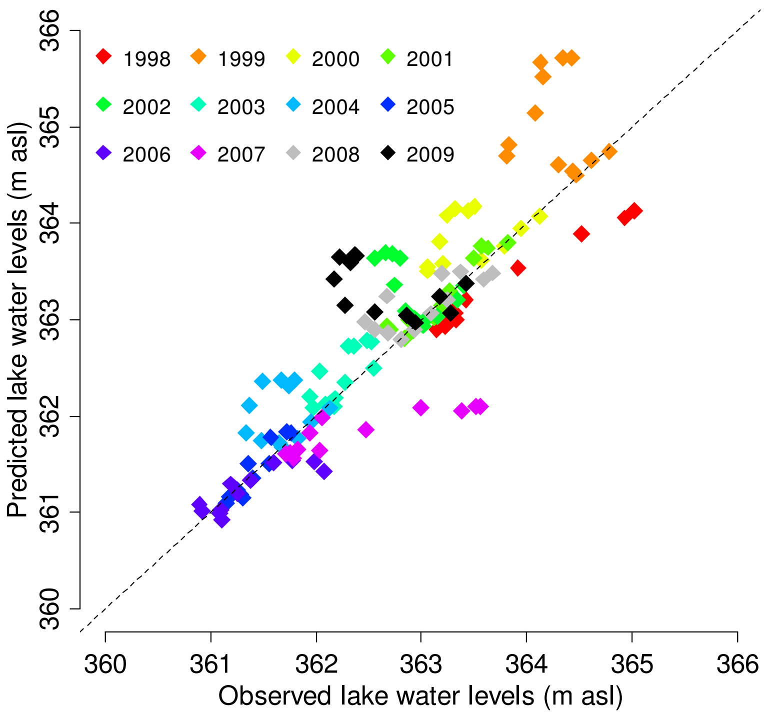

Fig. 5. Cross-validation of lake levels forecasted using a nonparametric bootstrap resampling (NBR) technique. Lake levels are predicted for each year using data from other years. For example, lake levels for 2006 are predicted using data from 1998–2005 and 2007–2009. The dotted line is the 1:1 line.

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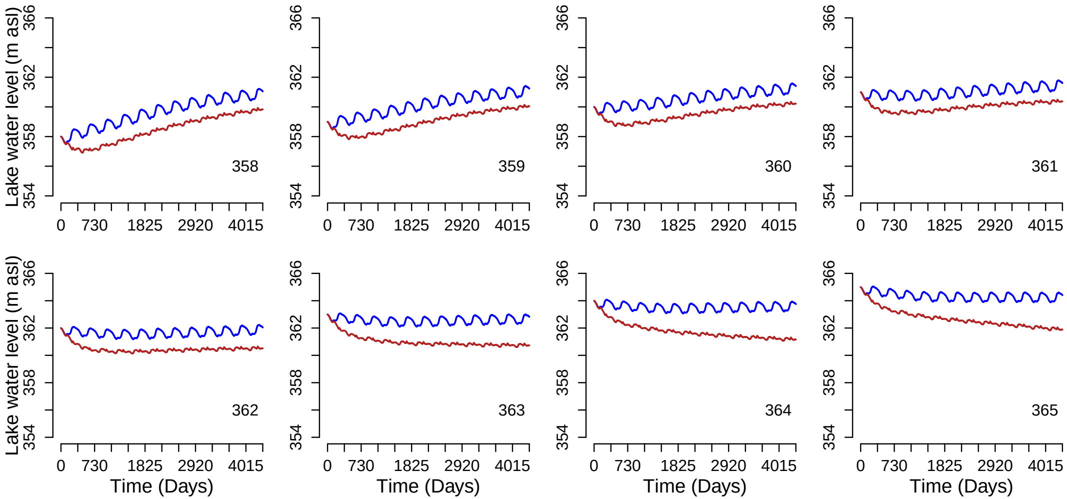

Fig. 6. Impact of the Gibe III dam on the Lake Turkana water levels simulated using the LLM approach and nonparametric bootstrap resampled (NBR) data. The impact of the dam is simulated for different initial lake levels from 358 m through 365 m a.s.l., shown on the y-axis. The x-axis shows time (days after the commencement of the dam). The blue line indicates lake level simulated without the dam; the dark red line indicates lake level simulated with the dam.

HESSD
9, 2987–3027, 2012

N. M. Velpuri and G. B. Senay

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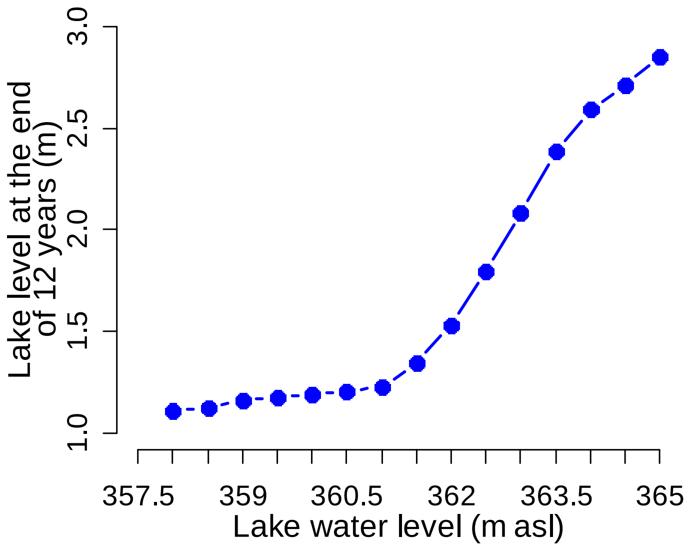

Fig. 7. Impact of the Gibe III dam (difference between with and without dam) at the end of 12 year simulation period is a function of initial lake level at the time of commencement of the dam.

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9, 2987–3027, 2012

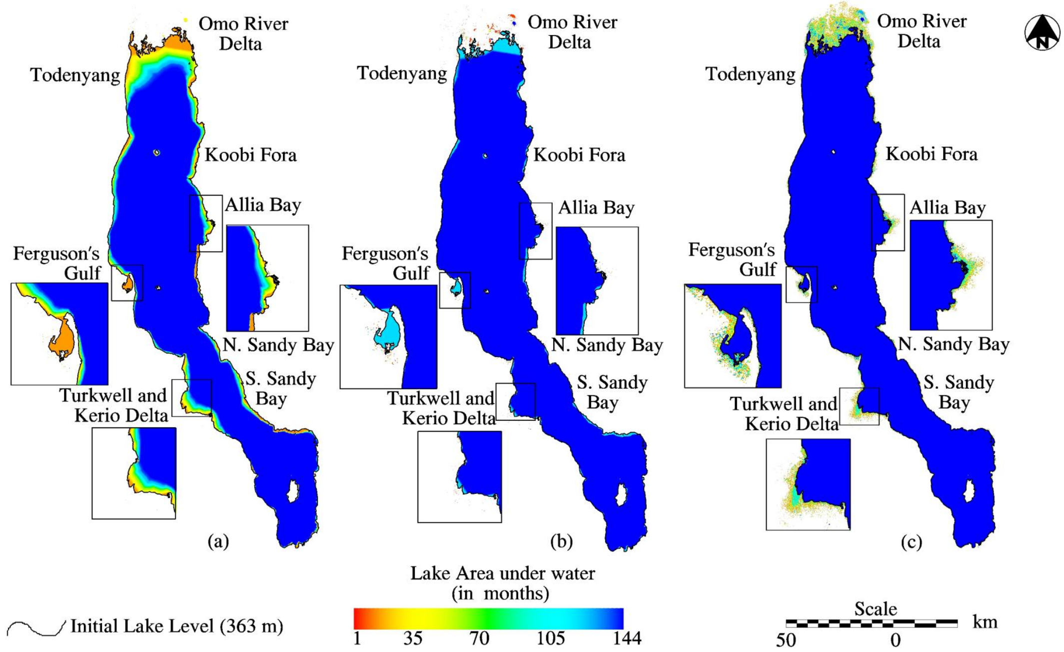

Fig. 8. Simulation of the impact of the Gibe III dam on Lake Turkana shoreline changes under three potential scenarios: **(a)** below normal rainfall scenario (lower 95 % confidence interval) – The lake shoreline would shrink up to 4 m inwards from the initial lake level **(b)** near normal rainfall scenario (median) – the lake shoreline would not show much variability from the initial lake level **(c)** above normal rainfall scenario (upper 95 % confidence interval) – the lake shoreline would grow outwards from the initial lake level, flooding several regions along the shoreline. The color denotes the time in months the lake is under water.

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