Ethiopia's Gibe III Dam

its Potential Impact on Lake Turkana Water Levels

(A case study using hydrologic modeling and multi-source satellite data)

UNEP

Publication: Ethiopia's Gibe III Dam: its Potential Impact on Lake Turkana Water Levels (A case study using hydrologic modeling and multi-source satellite data)
ISBN: 978-92-807-3258-0
Job Number: DEW/1508/NA

Citation

UNEP (2013). Ethiopia's Gibe III Dam: its Potential Impact on Lake Turkana Water Levels (A case study using hydrologic modeling and multi-source satellite data). Division of Early Warning and Assessment (DEWA), United Nations Environment Programme, February 2013.

Produced by
UNEP Division of Early Warning and Assessment
United Nations Environment Programme
P.O. Box 30552
Nairobi, 00100, Kenya

Tel: (+254) 20 7621234
Fax: (+254) 20 7623927
E-mail: uneppub@unep.org
Web: www.unep.org

This publication is available from http://www.unep.org

Cover Photo: aocrane/Flickr.com

UNEP
promotes environmentally sound
practices globally and in its own activities. This
publication has not been printed as our distribution
policy aims to reduce UNEP's carbon footprint.

Ethiopia's Gibe III Dam

its Potential Impact on Lake Turkana Water Levels

(A case study using hydrologic modeling and multi-source satellite data)

ACKNOWLEDGEMENTS

RESEARCHERS:
Naga Manohar Velpuri (*Consultant)*
Gabriel Senay *(USGS)*

REVIEWERS:
Anil Hooda (*Consultant)*
Ashbindu Singh *(UNEP)*
Charles Sebukeera *(UNEP)*
Patrick Mmayi *(UNEP)*
Bruce Pengra *(ARTS)*

EDITORS:
Tom Adamson *(SGT, Inc)*
Jane Barr (*Consultant)*
Arshia Chander *(SGT, Inc)*

DESIGN AND LAYOUT:
Kim Giese *(SGT, Inc)*

We sincerely thank Mr. Mehret Debebe and Mrs. Azeb Asnake of Ethiopian Electric Power Corporation (EEPCo), Ethiopia for facilitating our field visit to Gibe III site and providing all the useful data for our study. We also thank Dr. John Malala of Kenya Marine and Fisheries Research Institute for sharing Lake Turkana water level data and facilitating our field visit to Lake Turkana.

TABLE OF CONTENTS

List of Figures

List of Tables

EXECUTIVE SUMMARY

Introduction

1. The Gibe III hydroelectric project is the third in a series of five dams the Ethiopian government is constructing on the Omo River to meet the demands of the region's power industry. Once completed, it will be the largest hydroelectric plant in Africa, with a power output of about 1 870 Megawatts (MW), more than doubling Ethiopia's total installed capacity from its 2007 level of 814 MW (EEPCo 2009b).

2. Lake Turkana is the largest permanent desert lake in the world. It lies in a low, closed basin in northwestern Kenya and southwestern Ethiopia. As a closed lake, the influx from rivers and evaporation from the lake's surface determine water-level fluctuations. Of the three rivers that contribute to Lake Turkana—Omo, Turkwel and Kerio—the Omo River, which flows from the Ethiopian highlands, contributes more than 80 per cent of the lake inflows (Rickets and Johnson, 1996).

Historical Lake Levels and Previous Studies

3. Lake Turkana experiences seasonal variations in its water level of 1–1.5 m over the year, and it has a long-term natural variability of 5–10 m. Although Lake Turkana's water level declined considerably over the last century—by more than 10 m—the trend shows a slight increase over 1992–2010.

4. Analysis of Lake Turkana's water levels from 1880 to 2008 obtained from Kenya's Marine and Fisheries Research Institute (KMFRI) shows that in the late 19th century, Lake Turkana's water level was about 20 m higher than the level in 2011 (362.5 m above sea level), followed by a general decline during the first half of the 20th century. The water level decreased to a minimum in the 1950s, and during the early 1900s, it was about 10 m higher than the 2011 level. There was a rapid increase in the 1960s through to the 1970s, with the level reaching a height of 366 m during the late 1970s and 1980s.

5. The most recent water-level fluctuations captured by the TOPEX/Poseidon satellite (between 1993 and 2009) show that the lake's level gradually increased to reach a maximum of about 365 m by the end of the 20th century. However, between 2000 and 2006, the level gradually declined to about 361 m. Satellite altimetry data show that by the end of 2011, the lake's water level was about 362.5 m.

6. There has been no considerable change in rainfall patterns in East Africa over the last few decades (Cheung and others, 2008). In our study, analysis of satellite rainfall estimates over the Turkana basin for 1998–2009 reveals a nearly constant overall trend in mean basin rainfall.

7. Avery (2010) determined that the dam would cause the lake's level to drop by up to 2 m. Salini Constructions (2010) reported that the potential hydrological impact of Gibe III on Lake Turkana's water levels would be a loss of up to 1.5 m during the initial impoundment period. These reports, however, limited their results to the reservoir's first impoundment period.

The Present Study

8. This assessment study uses multiple sources of satellite data from 1998 to 2009 and a hydrologic modeling approach (Velpuri and others, 2012) to study the potential hydrological impact of Gibe III on Lake Turkana water levels.

9. This study incorporates the operational strategies for the Gibe III dam published by the Ethiopian Electric Power Corporation (EEPCo) (2009b), which include discharge from the reservoir: (a) all-time environmental flow of 25 m^3/s, (b) artificial flood release of 1 000 m^3/s for 10 days in September each year, and (c) scheduled releases from the reservoir after power production.

10. This study also considers the potential impact of the dam beyond the reservoir's first impoundment period and analyzes the dam's impact on lake levels under different rainfall scenarios.

Hydrologic Impact Assessment: Results

11. Results indicate that because of the Gibe III dam, the peak flows into the lake are reduced and dry season flow is increased with a dam moderated average flow rate of 500-550 $m^3 s^{-1}$ including the initial impoundment period. Furthermore, the dam would have a greater impact when the basin receives above-normal rainfall and a smaller impact when the basin receives below-normal rainfall compared to conditions without the dam.

12. Three different approaches that use existing satellite data and various future rainfall scenarios were used to assess the potential impact of the Gibe III dam on the lake's water levels. The first approach is based on the simple assumption that the Gibe III dam was commissioned (start of reservoir filling) in the past (on 1 January 1998). Thus, we use the observed historical climatic data for the period 1998–2009 to assess the dam's impact had it actually been built at that time. The model's results show that the Gibe III reservoir would

have reached a minimum operation level (MOL) of 201 m depth of reservoir by August 1998 (in around 220 days). The results further indicate that during the initial period of dam/reservoir filling, the lake level would have dropped by up to 2 m (95 per cent confidence interval). This result is similar to the one reported by Avery (2010).

13. It is impossible to accurately predict the Turkana basin's future climate. In the second approach, however, we built future rainfall scenarios based on a knowledge and understanding of the frequency and distribution of rainfall over the Turkana basin region. The climate's past variability provides the context in which different below-normal (drier) and above-normal (wetter) rainfall years were combined to generate 20 likely rainfall scenarios and to assess the potential impacts of the dam on lake water levels. The results of this approach show that the Gibe III reservoir would reach MOL in 8–16 months, depending on the rainfall under different scenarios. When compared to lake levels modeled without the dam, there will be either no change (with above-normal rainfall) or a decline of up to 4.3 m in the below-normal rainfall scenario after the dam is commissioned. Lake-level variability due to regulated inflows after the dam's completion was found to be within the lake's natural variability (4.8 m).

14. The nonparametric resampling technique using the most recent 12 years of satellite data was used to generate several future scenarios of climate data and to evaluate the potential impact of Gibe III. The results indicate that in the median scenario, it would take about 10 months for the Gibe III reservoir to reach MOL. Results also indicate that the average decline in the lake's level because of the dam would range from 1.5 to 2.3 m upper confidence interval (UCI), 1.2 to 2.2 m (median), and 0.6 to 1.8 m lower confidence interval (LCI) under the three rainfall scenarios, respectively. Due to the regulation of lake inflows, the dam would have a greater impact when the basin receives above-normal rainfall and a smaller one when the basin receives below-normal rainfall.

15. Changes in the shoreline or surface area are associated with the lake-level variations. This study identified hot spots of shoreline change, such as the Omo River Delta, Ferguson's Gulf, and the Turkwel-Kerio River Deltas, which will show possible shrinking and expansion due to Gibe III. Further analysis is required to assess the impact of change in seasonal variations on the Omo River flows and the consequent impact on the ecology and fisheries in the lake.

16. The use of satellite-based data in this study, to estimate runoff and evapotranspiration, makes the modeling approach consistent and robust, especially for a basin where long-term historical runoff and climate data are scarce. The results obtained under different scenarios will be of great use to planners and others assessing the hydrological and environmental impacts of the dam under future climatic uncertainty.

17. This case study only considers the hydrologic impact of Gibe III dam on Lake Turkana water levels and does not include the potential irrigation scenarios from the Omo River. The eco-hydrological impacts of the dam, potential irrigation projects and accompanying socio-economic changes in the basin will be addressed in another study carried out by UNEP in collaboration with the Lake Turkana basin countries and stakeholders.

Overlooking Lake Turkana .

Rita Willaert/Flickr.com

1. INTRODUCTION

1.1 Lake Turkana

Lake Turkana is the largest saline lake among the most northerly of the Rift Valley lakes; its delta extends into Ethiopia, Kenya, Sudan and Uganda (Figure 1). The lake is 250 km long, 15–30 km wide, has an area of nearly 7 000 km^2, and is the fourth largest lake in Africa by volume. It has a maximum depth of 125 m and an average depth of 35 m. More than 80 per cent of inflows to the lake come from the Omo River in Ethiopia (Cerling 1986, Ricketts and Johnson 1996). The Omo River is perennial and flows nearly 1 000 km from north to south before ending in Lake Turkana. Most of the remaining inflows come from two southern tributaries, the Turkwel and Kerio Rivers. Lake Turkana is considered an endorheic or closed lake because there is no surface outlet and insignificant seepage. The outflow is almost wholly dominated by evaporation. The annual loss by evaporation is estimated to be a little higher than 2 m. Rainfall over the lake could be as low as 200 mm/year. The lake once provided drinkable water but is now becoming increasingly alkaline.

Boats on the lake shore along Ferguson's Gulf.

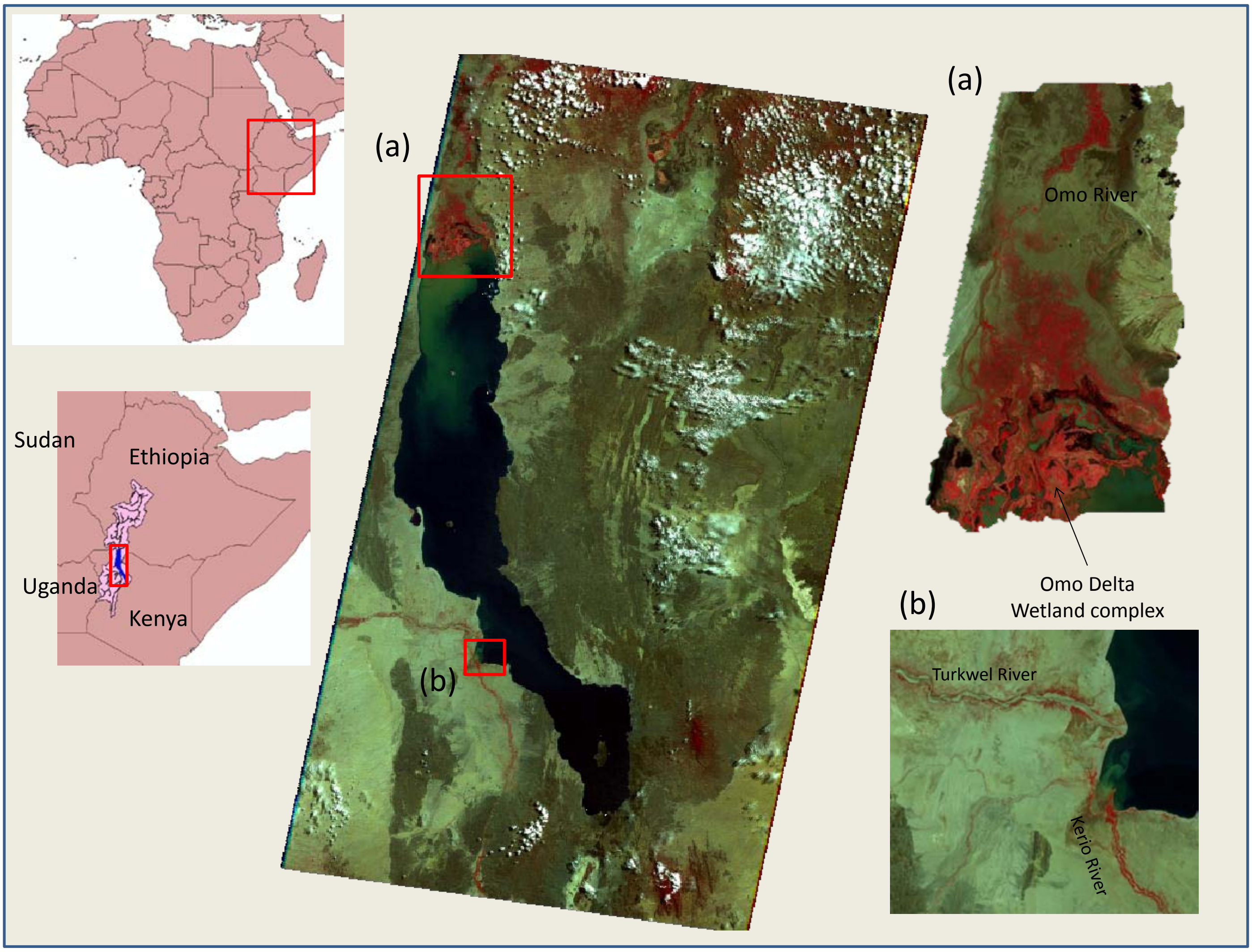


Figure 1: Location of Lake Turkana, East Africa.

Note: Landsat ETM+ imagery mosaic acquired on 6 August 2000 over Lake Turkana, Africa. Insets: (a) Omo River Delta (b) Turkwel and Kerio River Deltas.

Lake Turkana's water levels usually show seasonal fluctuations of 3–4 m. Generally, the annual amplitude of lake-level fluctuation is 1–1.5 m, but it also undergoes considerable long-term variations that exceed those of any other lakes of natural origin (Butzer 1971). Paleolimnological studies indicate that during the Holocene period, the lake's level was about 60–80 m higher than the present-day level and that it was connected to the Nile River (Yuretich 1976). The current lake has no outlet and the mean lake level is 360 m above sea level. In 1988, Kallqvist and others synthesized Lake Turkana's water levels for the previous 100 years and concluded that around 1895, the lake was about 20 m higher than in 1988. The lake declined gradually during the first half of the 20th century, reaching its lowest level in the 1950s, after which there was a rapid increase in the 1960s through the 1970s, with the peak level attained during late 1970s and 1980s.

Evidence of Lake Turkana water levels from the early 20th century until the end of 2008 (Figure 2) indicates fluctuations with respect to the Hopson's 1972 datum (365.4 m). Interestingly, the lake's water level fluctuated widely over the last century, on the order of about 10 m.

Currently, Ethiopia is constructing a series of hydroelectric dams on the Omo River: Gibe I and Gibe II are completed, and at the time of this writing (2012), Gibe III is under construction. Because the Omo River supplies more than 80 per cent of the inflow to Lake Turkana, it is speculated that damming the Omo River will lower Lake Turkana's water level and eventually dry up the lake. If this occurs, it would negatively impact nearly 300 000 people from different communities who depend directly or indirectly on Lake Turkana for their survival.

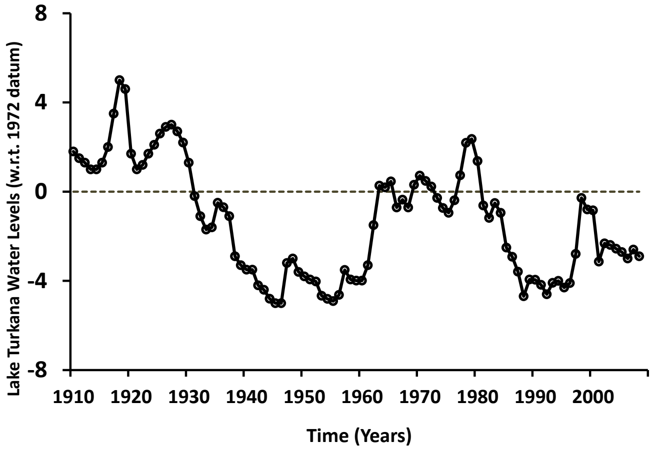


Figure 2: Lake Turkana water levels in the 20th century.
Source: KMFRI, Kenya

1.2 Past Studies

Over the past decade or so, several studies on Lake Turkana's water levels and related environmental issues have been carried out (Table 1). Initially, the Ethiopian Electric Power Corporation released a report on the Gilgel Gibe dam (EEPCo 1995). Although the document identified several hydrological and environmental implications of this dam, it did not report on the impact on Lake Turkana. EEPCo (2004) performed an environmental impact assessment of the Gibe II hydroelectric project, which indicated that Lake Turkana would benefit from the Gibe I and Gibe II projects. In 2008, the European Union performed an independent assessment of hydroelectric projects in Ethiopia and its published report, The Gilgel Gibe Affair (2008), included environmental and socioeconomic aspects, but it failed to identify the hydrological impact of these dams.

No.	Report	Focus of Impact Assessment	Impact on the Lake level
1	EEPCo 1995	Gibe I: Hydrologic impact assessment	Not reported
2	EEPCo 2004	Gibe II: Environmental Impact	Would have a positive impact
3	The Gilgel Gibe Affair 2008	Gibe I: Environmental and Socio-economical	Not reported
4	ARWG 2009	Environmental and Socio-economical	Would decrease up to 10-12 m
5	Avery 2009	Hydrological	Would decrease
6	EEPCo 2009a	Downstream	Would have a positive impact
7	EEPCo 2009b	Environmental and Socio-economical	Not reported
8	FoLT 2009	Hydrological, Environmental and Socio-economical	Would decrease
9	Hathaway 2010	Hydrological, Environmental and Socio-economical	Would decrease
10	Avery 2010	Hydrological	Would decrease up to 2 m
11	Salini Constructions 2010	Hydrological	Would decrease by 1.5 m

Table 1: Previous studies on the hydrological impact of Gibe III on Lake Turkana water levels.

In 2009, several agencies published hydrological, environmental and social impact assessment reports. ARWG (2009) concluded that the lake's water level would decline by up to 10–12 m. However, it is not clear how this estimate was derived. Based on preliminary results from a hydrological impact assessment, Avery (2009) reported that Lake Turkana's water level would decline due to commissioning (start of dam filling) of the Gibe III dam, but the loss was not exactly quantified. EEPCo's (2009a) downstream impact report predicts a positive impact on Lake Turkana. EEPCo (2009b) focuses on the environmental and social aspects of its impact assessment and does not report on the direct impact of Gibe III on Lake Turkana water levels. Based on these reports, others, such as those by Friends of Turkana (2009) and Hathaway (2010), concluded that lake levels would decline due to the construction of the Gibe III dam and advocated halting the dam.

The recent report on the hydrological impacts of the Gibe III dam by Avery (2010) determined that it would cause the lake's level to drop by up to 2 m. The Avery study provides the most comprehensive information on Lake Turkana and Omo River and uses a water-balance model to evaluate the drop in lake level during the filling of the dam's reservoir; based on data for the period 1993–2009, the report indicates that the lake would have reached equilibrium after 15 years if the dam had been constructed in 1993. Salini Constructions (2010) reported that the hydrological impact of Gibe III on Lake Turkana water levels would result in a loss of up to 1.5 m during the initial impoundment period only. None of these reports account for the variability in climatic conditions and thus fail to provide information about the dam's impact in a situation of climatic change.

1.3 The Current Study

This study evaluates the likely hydrological impact of the Gibe III dam on Lake Turkana water levels. Remotely sensed data and hydrological modeling techniques were used to forecast the impact of the Gibe III dam on the lake's water levels using different rainfall scenarios and approaches. Several characteristics of this study make it different from previously published studies:

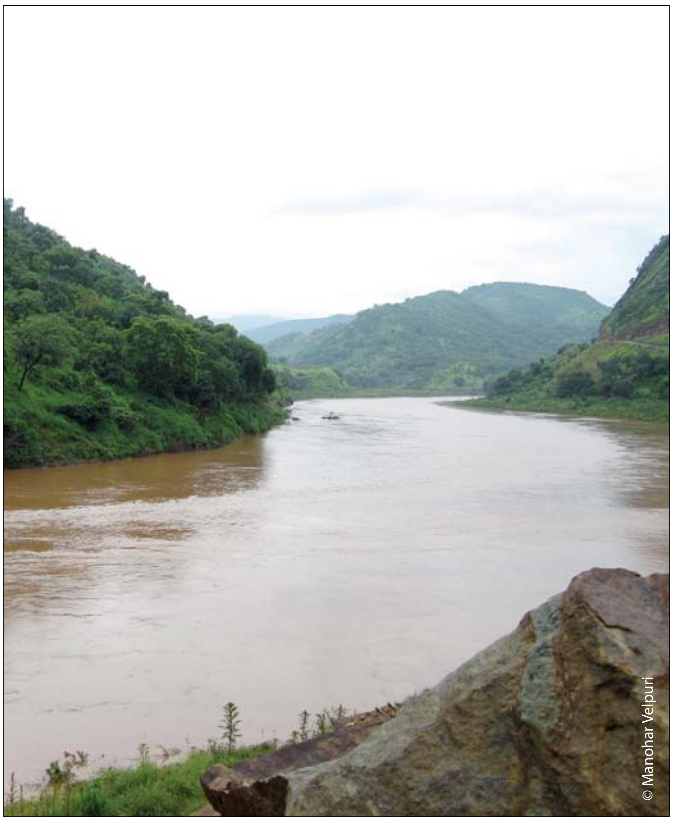
- *Uses consistent remote sensing data*
- *Analyzes the impact of Gibe III using three different approaches, including different climate scenarios*
- *Models the impact beyond the initial impoundment (beyond three years after dam commencement)*
- *Models the impact of the dam based on different initial lake water levels at the time of the dam's commencement*
- *Models the dam's impact on the lake's shoreline changes under different rainfall scenarios to identify hot spots of change*

1.4 Structure of the Report

This first chapter provides the background for examining the likely changes in Lake Turkana due to the construction of the Gibe III dam, the results of past studies on environmental impacts of the dam, and the need for the present study and its characteristics. Chapter Two briefly describes the status of dams on various continents, including Africa, and then more specifically, of the Gibe hydroelectric power project in Ethiopia. Chapter Three describes the Lake Turkana basin and various climatic and physical factors that influence lake levels and their variability over time. Chapter Four describes the satellite data and the modeling approaches used to determine the likely impact of the dam on lake levels. Chapter Five presents the results of the study by using three different approaches under a number of different climate scenarios. Finally, the last chapter presents the main conclusions of the study. Following are the chapters in this report.

1. Introduction
2. The Gibe Hydroelectric Power Projects in Ethiopia
3. The Basin's Climatic and Physical Factors Influencing Lake Levels
4. The Methodology to Model the Impact of the Dam on Lake Levels
5. An Impact Assessment of Gibe III on Lake Turkana Water Levels
6. Conclusions

Omo River near the GIBE III dam site.



Coffer dam at Gibe III dam site.

© Manohar Velpuri

2. THE GIBE HYDROELECTRIC POWER PROJECTS IN ETHIOPIA

2.1 Dams

Managing water for the benefit of humankind has always been regarded as a noble activity. Dams provide several benefits: water for irrigation, drinking and industrial uses; flood control; hydroelectric power generation; redirecting river flow; recreation; general surface-water management; and above all, water security. According to the World Commission on Dams (WCD), about 3 800 km^3 of freshwater is withdrawn annually from the world's lakes, rivers and aquifers; dams contribute the highest proportion of this water.

Although dams are promoted as an important way to meet water and energy needs and support economic development, they can be controversial due to their social and environmental impacts. Dams themselves affect many different ecological components of rivers. For example, they change water flows, interrupt fish migrations, contribute to soil erosion and sedimentation, and modify the water temperature, which consequently changes oxygen levels and creates inhospitable environments for many species. Furthermore, creating a reservoir requires flooding large areas of land at the expense of the natural environment and sometimes requires the displacement of villages, towns and small cities.

To understand the impacts (both positive and negative) and to make a judicious decision about whether to build a proposed dam, a complete impact assessment of the dam is needed before the project begins. Such an assessment is critical for the sustainable development of the river basin. Impact assessment studies can lack credibility when they are not performed comprehensively. Indeed, the environmental and social costs of large dams have been poorly accounted for in economic terms; consequently, in most cases, the true profitability of these schemes remains elusive.

After the World War II, there was an unparalleled increase in the number of large dams (larger than 15 m). See Figure 3. Nearly 5 000 large dams were built worldwide from 1970 to 1975. Since the 1980s, the pace of dam building declined, especially in North America and Europe where most technically attractive sites for dams are already utilized; activity is now focused on the management of existing dams, including rehabilitation, renovation and optimizing the operation of dams for multiple functions.

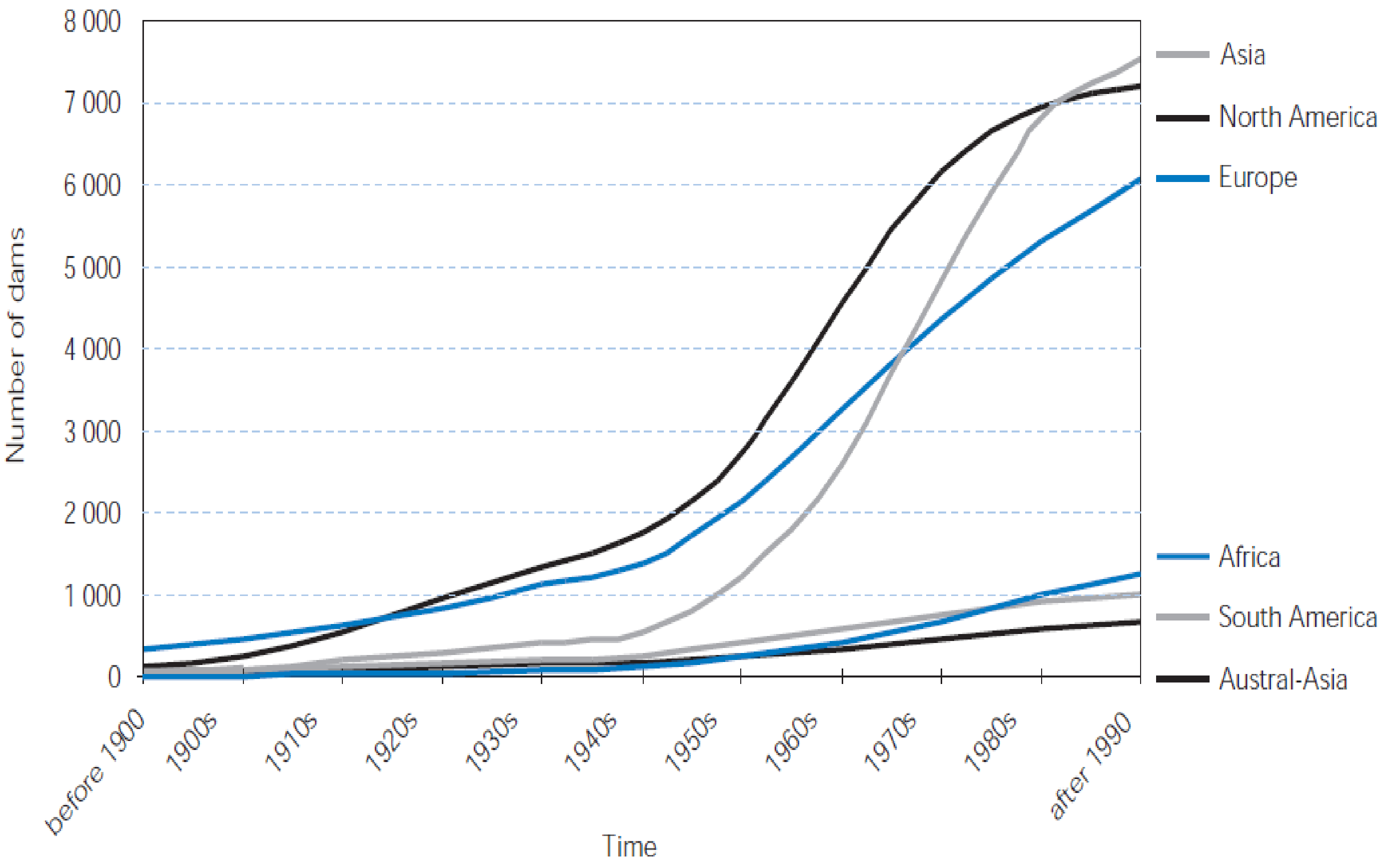


Figure 3: Trend in the global distribution of dams between 1900 and 2000.
Source: WCD 2000

Note: Information excludes the time-trend of dams in China.

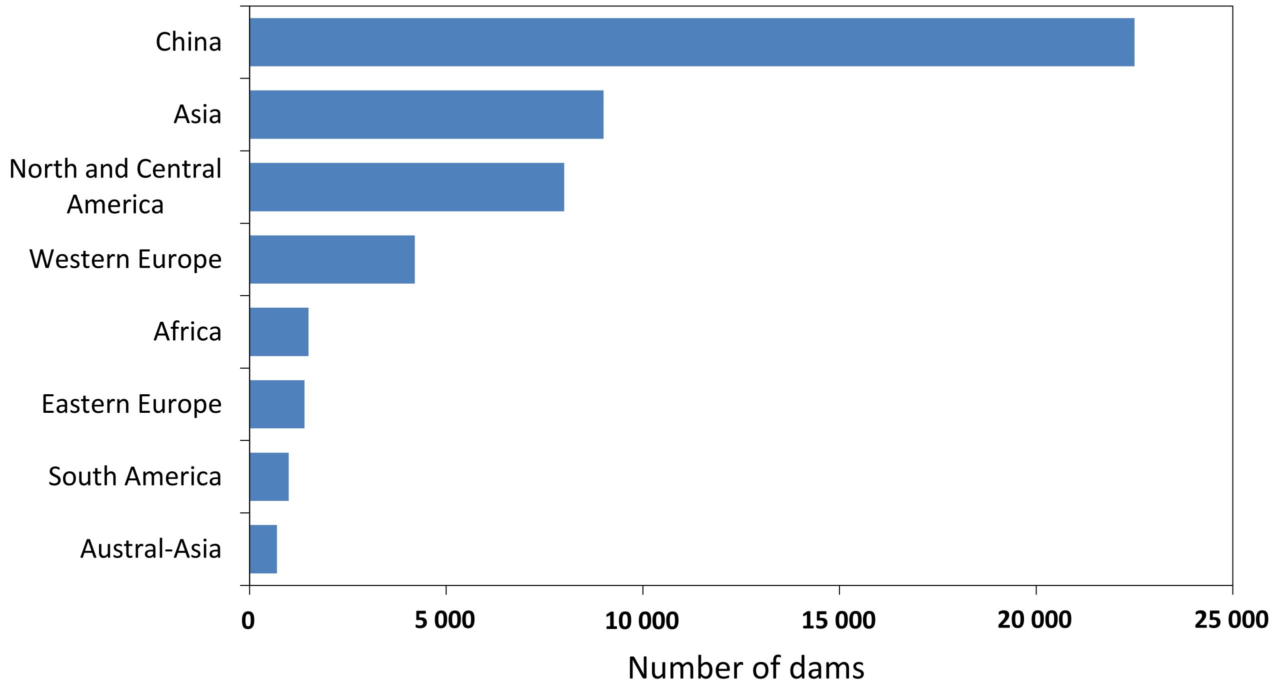


Figure 4: Regional distribution of large dams at the end of the 20th century.
Source: WCD 2000

The top five dam-building countries account for nearly 80 per cent of all large dams worldwide (ICOLD 1998). China alone has built around 22 000 large dams, or close to half the world's total number (Figure 4). Other countries among the top five dam-building nations include the United States (6 390 large dams), India (4 000 large dams), Spain (1 000 large dams) and Japan (1 200 large dams). Approximately two-thirds of the world's existing large dams are now in developing countries. An estimated 1 700 large dams have been under construction in other parts of the world in the last few years (Table 2).

2.2 Hydropower Projects in Africa

Hydroelectric power generation is currently the largest renewable energy source worldwide, and it has increased by 50 per cent since 1990. In 2008, global hydropower plants generated 3 288 terawatt-hours (TWh), which was roughly 16.3 per cent of worldwide electricity production. During 2009, China produced 17.8 per cent of the world's total hydroelectricity, or 585 TWh (McMahon and Price, 2001). Other major nations producing hydropower are Canada with 11.5 per cent (383 TWh), Brazil with 11.2 per cent (370 TWh), the United States with 8.6 per cent (282 TWh) and Russia with 5.1 per cent (167 TWh). Globally, approximately two-thirds of the economically feasible potential sites for dam construction remain undeveloped (Bartle, 2002). Untapped hydrologic resources are still abundant in Latin America, Africa, India and China.

Africa has plentiful water resources for hydroelectricity and can boost energy security and economic development by increasing hydropower development. Currently, electricity production in Africa is the lowest in the world.

Country	Number of Dams	Purpose
India	695-960	Irrigation, multipurpose
China	280	Flood control, irrigation, hydropower
Turkey	209	Irrigation, hydropower, water supply
South Korea	132	Irrigation, hydropower, multi-purpose
Japan	90	Mainly flood control
Iran	48 (< 60 m)	Irrigation, multipurpose

Table 2: Dams under construction globally by the end of 2000.
Source: WCD 2000

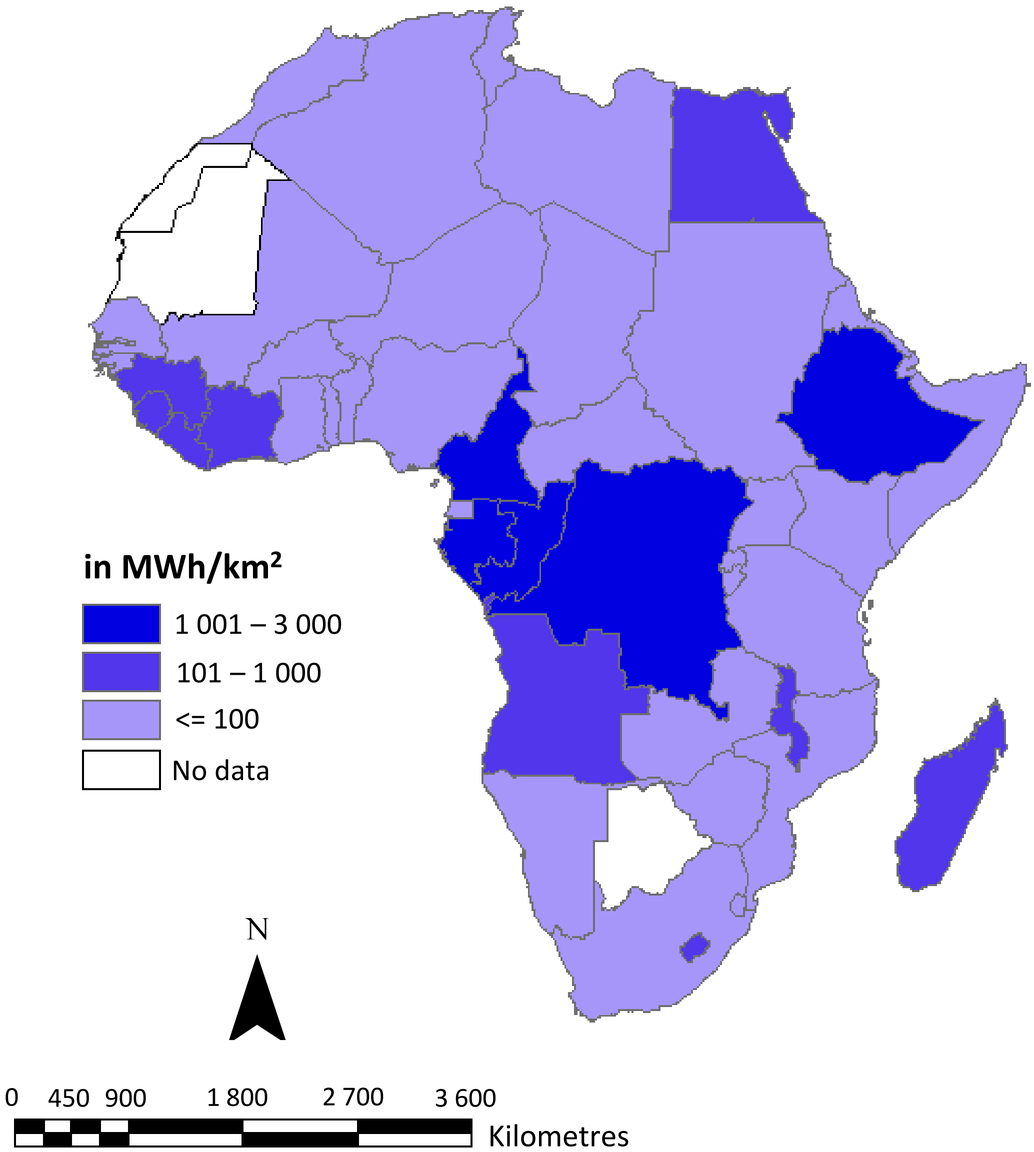


Figure 5: Gross theoretical hydropower potential in Africa.
Source: WEC 2004

Although Africa has the second largest population after Asia, it has the lowest energy consumption per capita of any continent. Many African nations have per capita electricity consumption of less than 80 kWh/yr, compared to 26 280 kWh/yr in Norway, 17 655 kWh/yr in Canada, and 13 800 kWh/yr in the United States (Bartel 2002). Africa's gross theoretical hydropower potential is 4 000 000 MWh (Figure 5), but its current hydropower production is about 20 per cent of that total potential. The technically feasible hydropower potential of Africa is around 1 750 TWh, which is about 12 per cent of the global capacity. Presently, only 5 per cent of this technically feasible potential is exploited.

Thus, Africa is referred to as an "underdammed" continent (The Economist 2010). Only 3 per cent of its renewable water is used, compared to 52 per cent in Asia and 21 per cent in Latin America. Assessments of the proportion of Africa's potential hydropower capacity that is actually used vary from 4 per cent (Bartel 2002) to 7 per cent (AfDB 2006) and 8 per cent (World Bank 2010) depending on the source. It is clear from these estimates that there is a lot of hydropower energy yet to be utilized.

In 2002, about 2 403 MW of new hydropower capacity was under construction in 18 African nations, and between 2000 and 2002, the production of hydropower throughout

Gibe III dam site (as of April, 2011).

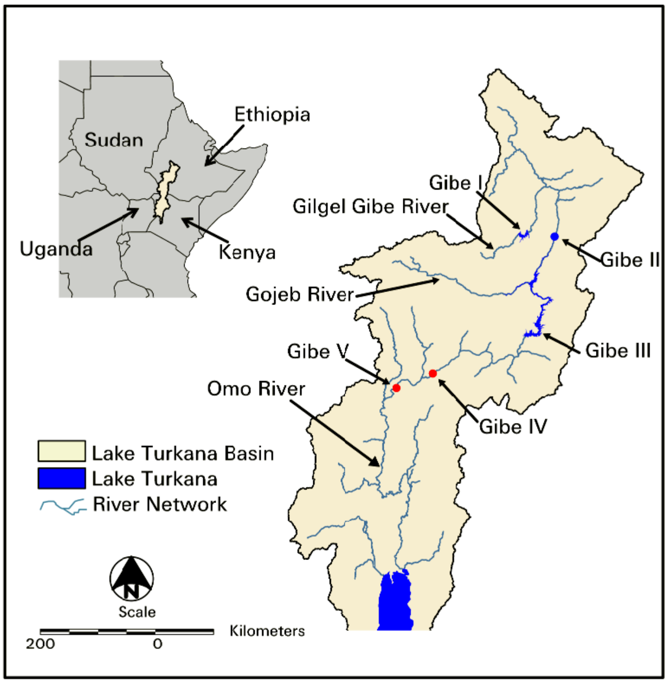


Figure 6: Lake Turkana and the cascade of Gibe reservoirs in Ethiopia.

the continent increased by more than 2 000 GWh/yr (Bartel 2002).

2.3 The Gibe Hydroelectric Power Projects in Ethiopia

With abundant rainfall and suitable physical features, Ethiopia has several potential sites for hydropower development. The Ethiopian government has started building a series of dams on the Omo River, primarily to meet the demands of the power industry in the East African region. Figures 6 and 7 show the location and distribution of the Gibe dams in Ethiopia. These dams on the main Omo River will also regulate the flow of water into Lake Turkana. Gibe I and Gibe II are already commissioned and operational. Gibe III is now under construction and Gibe IV and Gibe V are proposed dams. Table 3 describes the characteristics of the Gibe dams.

The Gilgel Gibe I dam (Gibe I) is the first of the three

Project	Power Capacity (MW)	Total Power Production (GWh/yr)	Dam Type	Dam Height (m)	Reservoir Storage Capacity (x10^6 m^3)	Catchment Area (km^2)	Status
Gibe I	184	722	Rock	40	657	4 225	Commissioned in 2004
Gibe II	420	1 635	RC	55	-	4 034	Commissioned in 2010
Gibe III	1 870	6 400	RCC	243	11 500	34 150	Under construction
Gibe IV	1 470	5 917	RCC	164	10 000	44 300	Proposed
Gibe V	662	1 937	RCC	60	-	49 000	Proposed

Table 3: Characteristics of existing and planned Gibe hydroelectric projects on the Omo River, Ethiopia.

Source: EEPCo 2004, 2009a,2009b; Note: RC - Reinforced Concrete; RCC - Roller Compacted Concrete

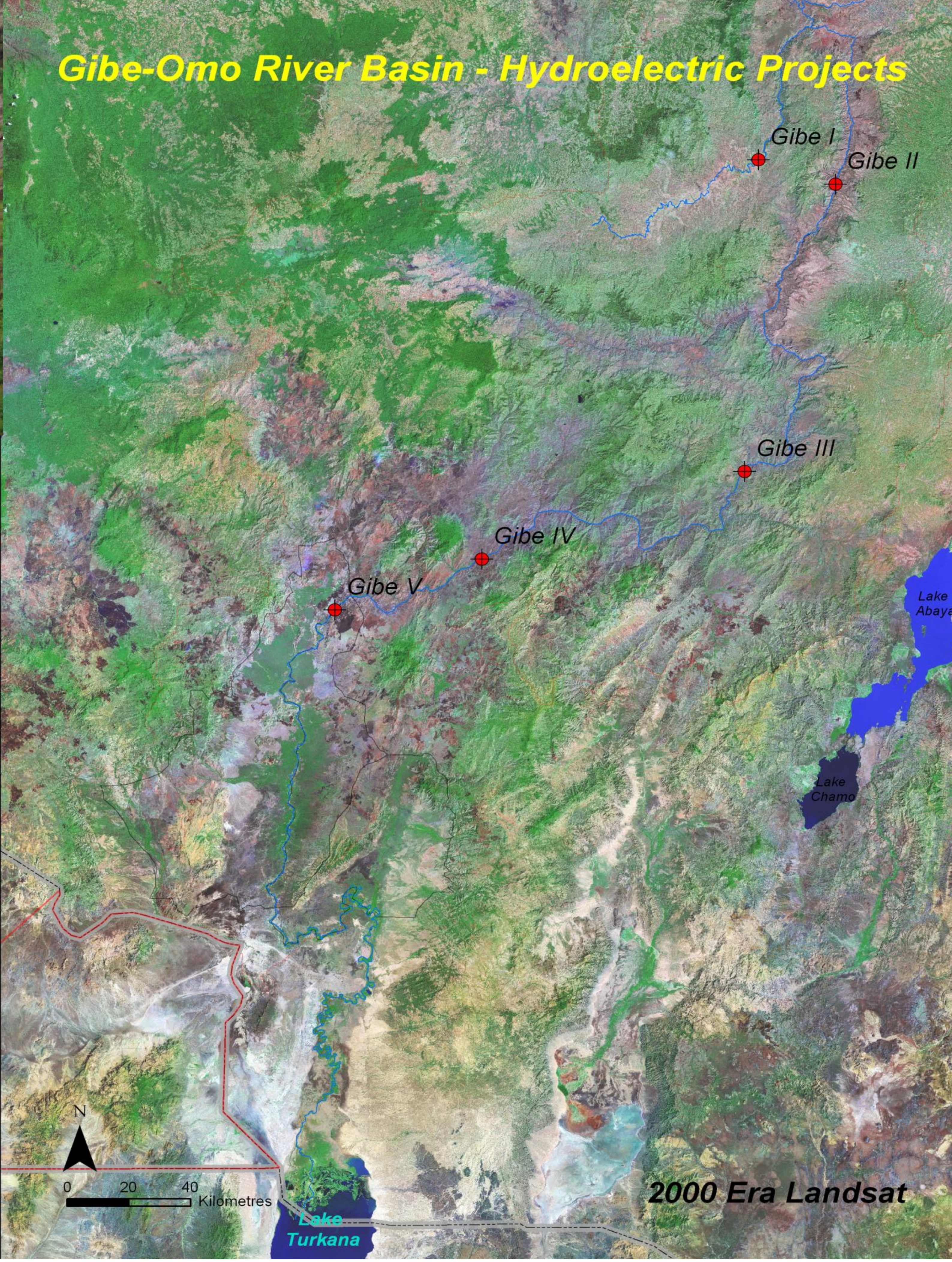


Figure 7: Map of Turkana basin showing locations of Lake Turkana and the cascade of Gibe reservoirs.

Source: USGS Landsat Mosaic / prepared by UNEP-GRID Sioux Falls

Gibe III Construction Site

Mountains surrounding the Gibe III dam site.

Roads along the Omo River leading to construction site.

Left bank dam excacation.

Looking down into the construction site (right abutment dam excavation).

Workers on the dam abutment excacation.

Left bank dam excavation.

Gibe III Diversion Canal

The Omo River.

Work on a diversion tunnel.

Diversion tunnel inlet canal.

Diversion tunnel inlet.

Diversion tunnel outlet.

Diversion tunnel outlet.

Figure 8: Gibe I reservoir on the Gilgel Gibe River, a tributary of the Omo River, Ethiopia.

hydroelectric projects built within the Lake Turkana basin. It was built on the Gilgel Gibe River, a small tributary of the main Gibe River, which flows into the main Omo River (Figure 8).

Commissioned in 2010, the Gibe II hydroelectric plant channels the water already impounded by the existing Gilgel Gibe I hydroelectric plant through a 26-km long tunnel directly into the Gibe-Omo River (Figures 6 and 9).

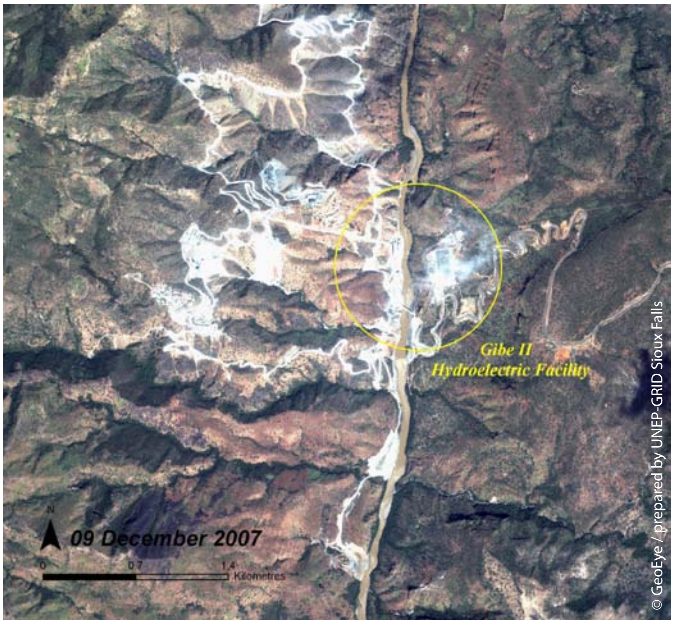


Figure 9: Gibe II (under construction) as seen by satellite imagery on 9 December 2007.

Figure 10: Gibe III dam site as seen by high-resolution satellite imagery on 21 March 2009.

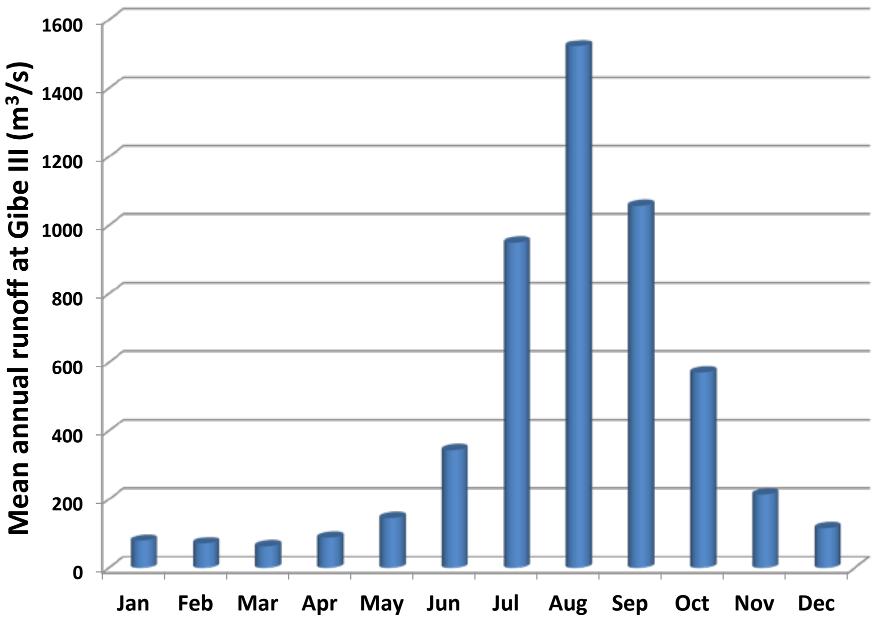


Figure 11: Mean annual runoff at the Gibe III site.
Source: EEPCo 2009b

The resulting 500-m head is used to generate 420 MW of electric power. As this project does not impound any water itself, it has no substantial impact on Lake Turkana water levels.

The Gibe III dam is located on the Omo River around 150 km downstream of the Gibe II outlet (Figures 6, 7, and 10). Near the dam, the area is characterized by a large plateau with a long and relatively narrow canyon through which the river flows (Gilgel Gibe Affair 2008). Upon completion, a 150-km dammed reservoir will 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. Upon completion, the Gibe III dam will be the tallest dam in Africa. It is estimated that the dam will be completed by 2013 and possibly be operational by mid-2014. The mean annual inflow or discharge into the reservoir is estimated to be 438 m^3/s (13 800 million m^3), with seasonal inflows varying from less than 62 m^3/s in March to over 1 500 m^3/s in August (Figure 11).

In terms of power generated, the capacity of Gibe III is one-third of the 10th largest project in the world (Figure 12). Despite its relatively smaller size/capacity, there is a need to evaluate the likely social, hydrological and environmental impacts of the Gibe III dam on the downstream water resources within the Turkana basin to avoid and/or to mitigate any adverse impacts by changing the design parameters and/or by developing suitable management strategies.

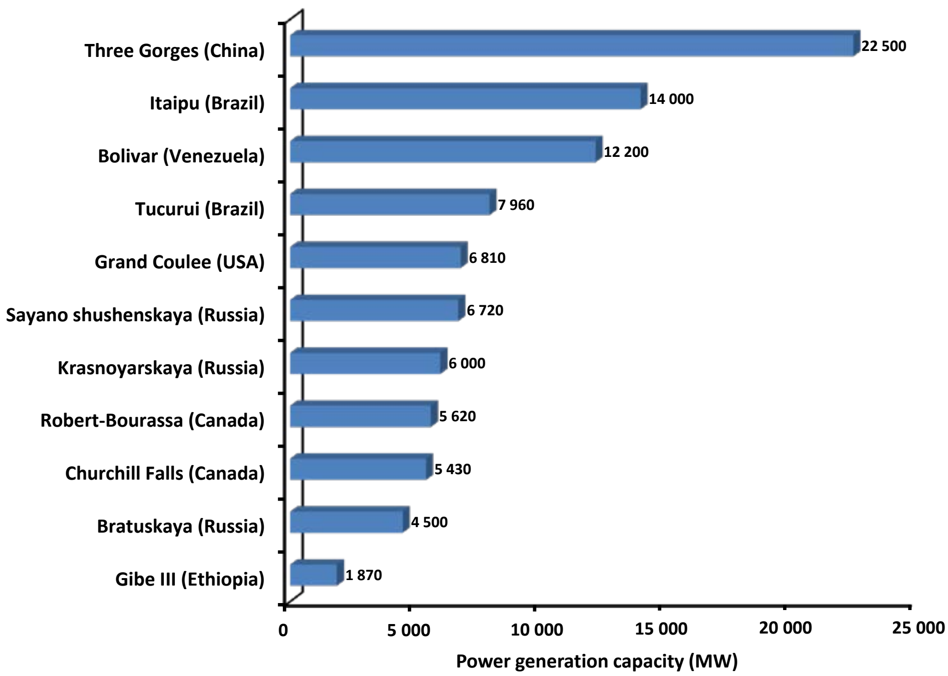


Figure 12: Gibe III hydroelectric project power generation capacity compared to the top ten hydroelectric projects in the world.
Source: WCD 2000

Children on the shore of Lake Turkana.

3. THE CLIMATIC AND PHYSICAL FACTORS IN THE TURKANA BASIN THAT INFLUENCE LAKE LEVELS

3.1 The Lake Turkana Basin

The Lake Turkana River basin extends over a portion of Ethiopia in the north and a part of Kenya in the south, with a small area extending into Sudan and Uganda in the west (Figure 13). The lake's watershed covers nearly 145 500 km^2. The climate is classified as tropical humid in the highland regions surrounding Jima and the headwaters of the Gojeb River in the northern part of the basin. Most of the other regions in the Gibe III watershed have a tropical sub-humid climate. In areas south of the Gibe III extending to Lake Turkana, the climate mostly varies between tropical humid to hot and arid. The seasonal variation in climate is associated with the oscillation of the Inter-Tropical Convergence Zone (ITCZ), a low pressure area of convergence. The ITCZ shifts northwards across southern Ethiopia from September to November and southwards from March to May, providing a wet season (from June to September) and a dry season (from December to April). During the wet season, the area is under the influence of Atlantic equatorial westerlies and southerly winds from the Indian Ocean, producing strong precipitation. During the dry season, the moist air comes from the Gulf of Aden and the Indian Ocean, producing short rains in the basin. Rainfall rates decrease strongly southwards, to less than 300 mm/year near Lake Turkana. Soils in the Turkana basin vary from Orthic Argisols in mountainous areas with steep slopes to Orthic Luvisols in hilly regions of the basin.

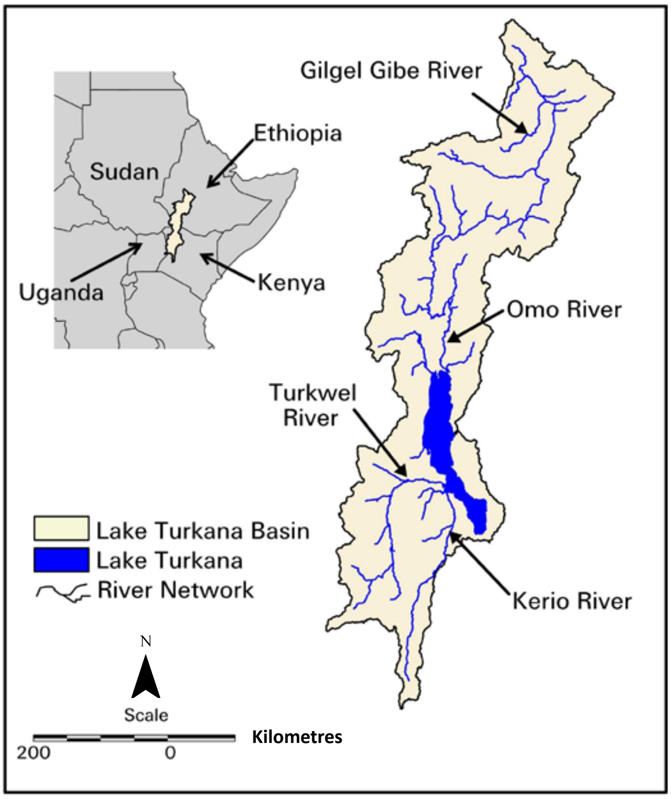


Figure 13: Location and extent of the Lake Turkana basin, East Africa.

3.2 Rainfall Variability in the Turkana Basin

The Lake Turkana basin has four distinct seasons, with two dry periods (December to February and July to August) and two rainy seasons (March to June and September to November). The rainfall ranges from over 1 900 mm/year in the northern and western part of the basin to about 200 mm/year in the southern part. As the main source of moist air is from the Atlantic Ocean in the southwest, the eastern parts of the highlands are mostly rain shadowed. Areas surrounding Jima (northern part of the basin) receive maximum rainfall in the basin. Rainfall declines sharply in the southern parts of the basin. Rainfall variability over the Turkana basin area was analyzed using the satellite-based rainfall estimates (RFE) for Africa for 1998–2009 (Figure 14) obtained from the U.S. Geological Survey (USGS) Famine Early Warning Systems Network (FEWS NET) website. Since June 1995, the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) has produced daily satellite-based RFE with a spatial resolution of 0.1 x 0.1 degrees for the FEWS project of the U.S. Agency for International Development (USAID).

The trend line associated with the 12 years of rainfall data indicates that the rainfall pattern in the basin during that time has been stable and there has been minimal change (Figure 14). Though there were some very dry years, such as 2000, 2003 and 2009, there were also very wet years, such as 1998, 2006 and 2007.

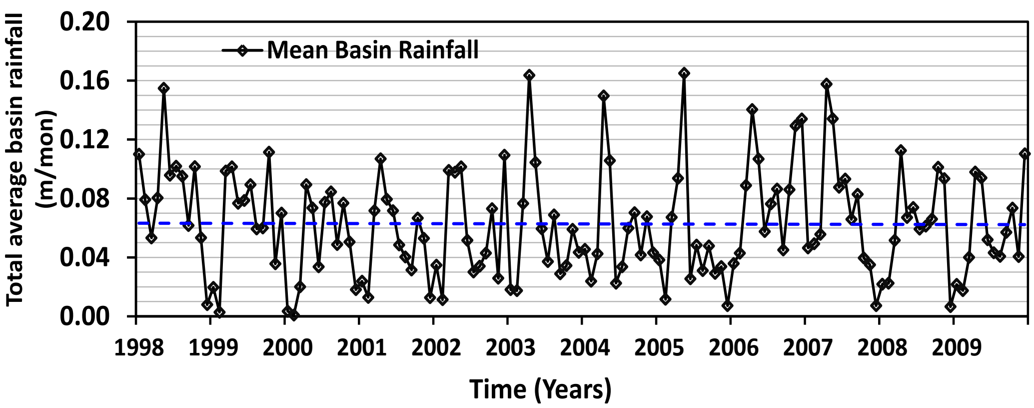


Figure 14: Modeled mean monthly rainfall in the Lake Turkana basin, 1998–2009. Blue line indicates statistical trend.

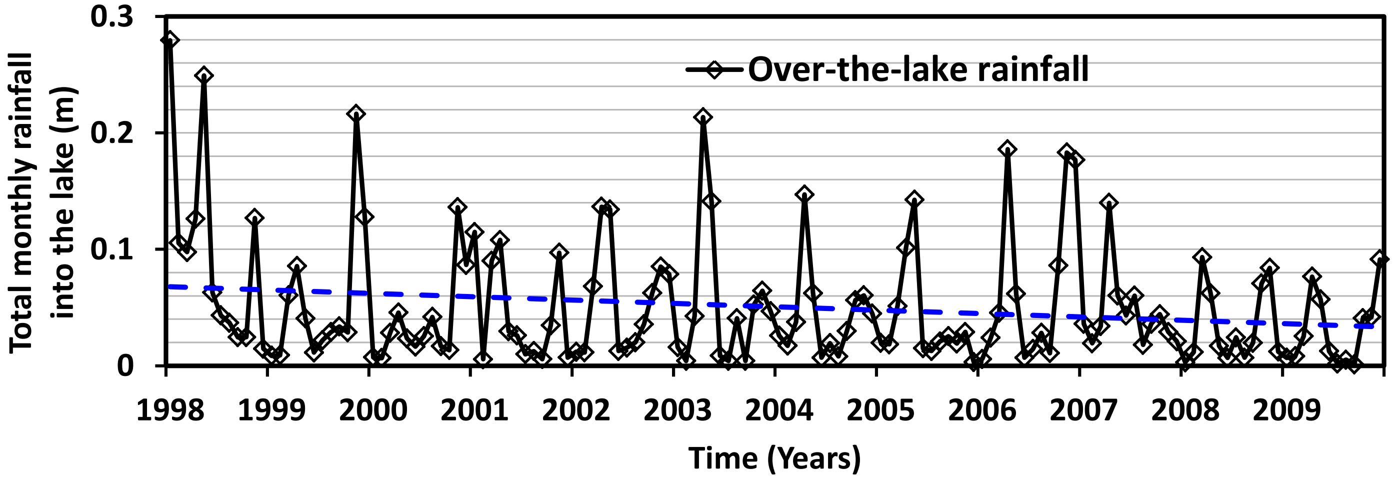


Figure 15: Total monthly rainfall pattern over Lake Turkana modeled from satellite-based rainfall estimates (RFE) for Africa. Blue line indicates statistical trend.

3.3 Rainfall Variability over the Lake

Data on rainfall over Lake Turkana were extracted from the RFE rainfall estimates; Figure 15 shows the monthly rainfall variability over the lake. The trend line (in blue) indicates that there has been a slight decline in rainfall over the lake since 1998. Over-the-lake rainfall declined from an average rate of 6.5 to 4 mm/month by the end of 2009.

3.4 Total Monthly Runoff in the Lake

Total monthly runoff, or inflows, to the lake for 1989–2009 were modeled using a lake-level modeling approach (Velpuri and others 2012) and is presented in Figure 16. The data indicate that there has been a slight increase in total monthly lake inflows of 0.05 m over the 12-year period.

3.5 Over-the-Lake Evapotranspiration

Similarly, over-the-lake evaporation losses were determined from modeled evapotranspiration (ET) data estimated using the VegET modeling approach (Senay and others 2008) and are presented in Figure 17. The data indicate that over the recent past, ET over the lake increased from an average of 0.18 m per month to 0.22 m per month.

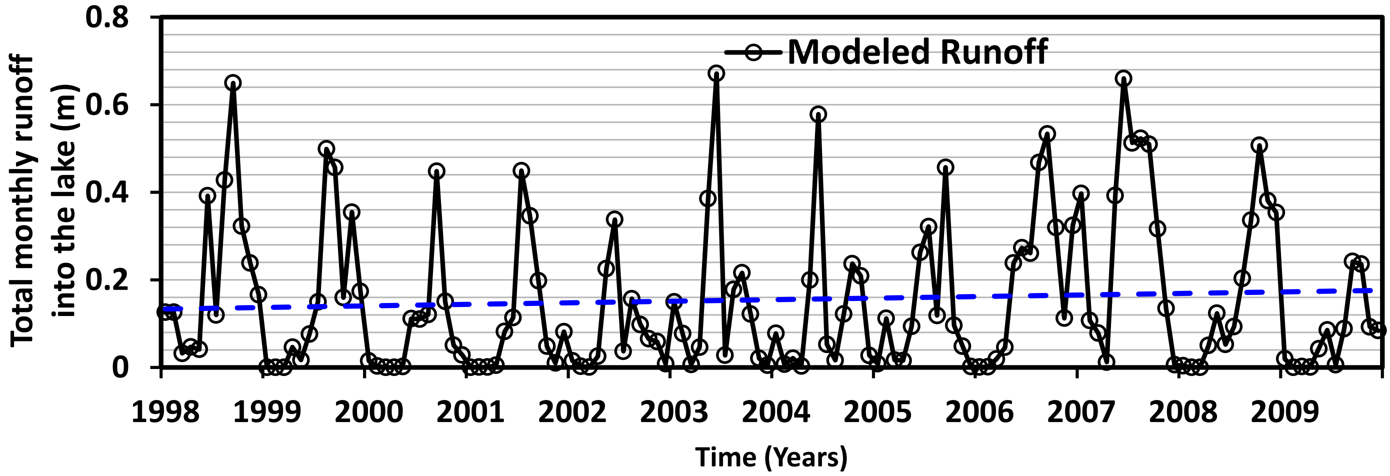


Figure 16: Modeled total monthly runoff over Lake Turkana basin, 1998–2009. Blue line indicates statistical trend.

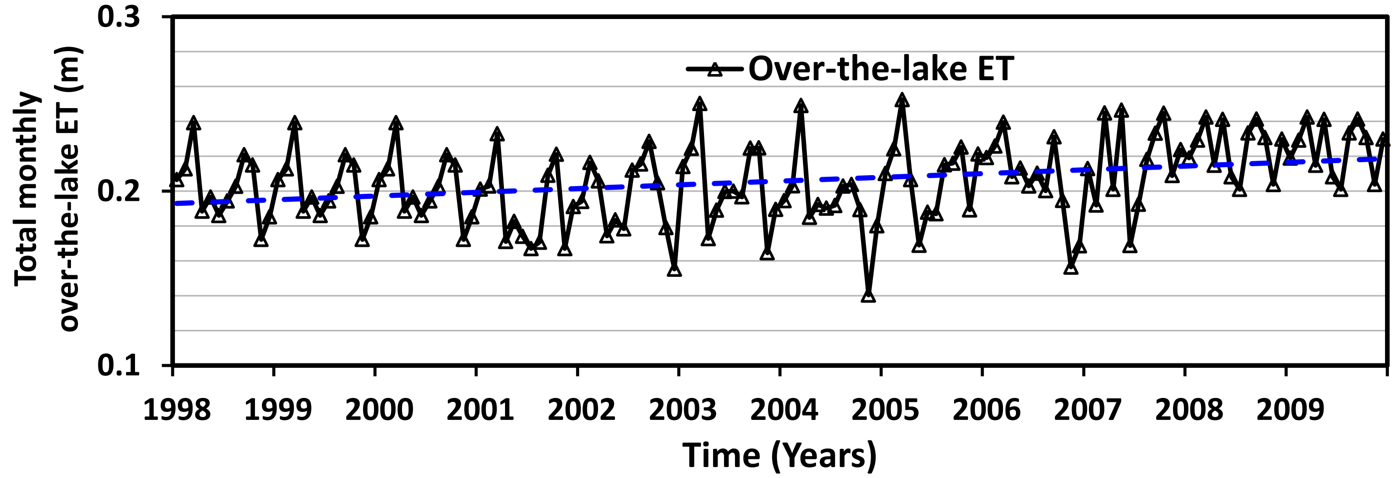


Figure 17: Total monthly evapotranspiration over Lake Turkana, 1998–2009. Blue line indicates statistical trend.

3.6 Land-Use/Land-Cover Dynamics in the Turkana Basin

The MODIS-based land-cover product—Land Cover Type Yearly L3 Global 500 m (MCD12Q1) (Friedl and others 2010)—incorporates five different land-cover classification schemes, derived through a supervised decision-tree classification method spanning a year's input of Terra and Aqua data. The primary land-cover scheme identifies 17 classes defined by the International Geosphere-Biosphere Program (IGBP), including 11 natural vegetation classes, three human-altered classes and three non-vegetated classes. For this study, we clipped out the 12-class IGBP classification product for the Turkana basin and summarized it into 10 classes: water; forest; shrublands; woody savannas; savannas; grasslands; wetlands; croplands; cropland and natural vegetation; and a combined barren, urban and built-up class, as shown in Figure 17. Yearly MODIS land-cover products from 2001 to 2009 were summarized.

The annual land-cover maps were generated from the MODIS land-cover product for 2001 to 2009 (not presented here). It is difficult to identify the areas that changed from the visual comparison of these annual images. There appears to be negligible change in the extent of important classes such as forests, croplands and wetlands. Land-cover change is better seen by a visual comparison of land-cover maps derived in 2001 and in 2009, which show the dynamics of land-cover change occurring in the basin (Figure 18).

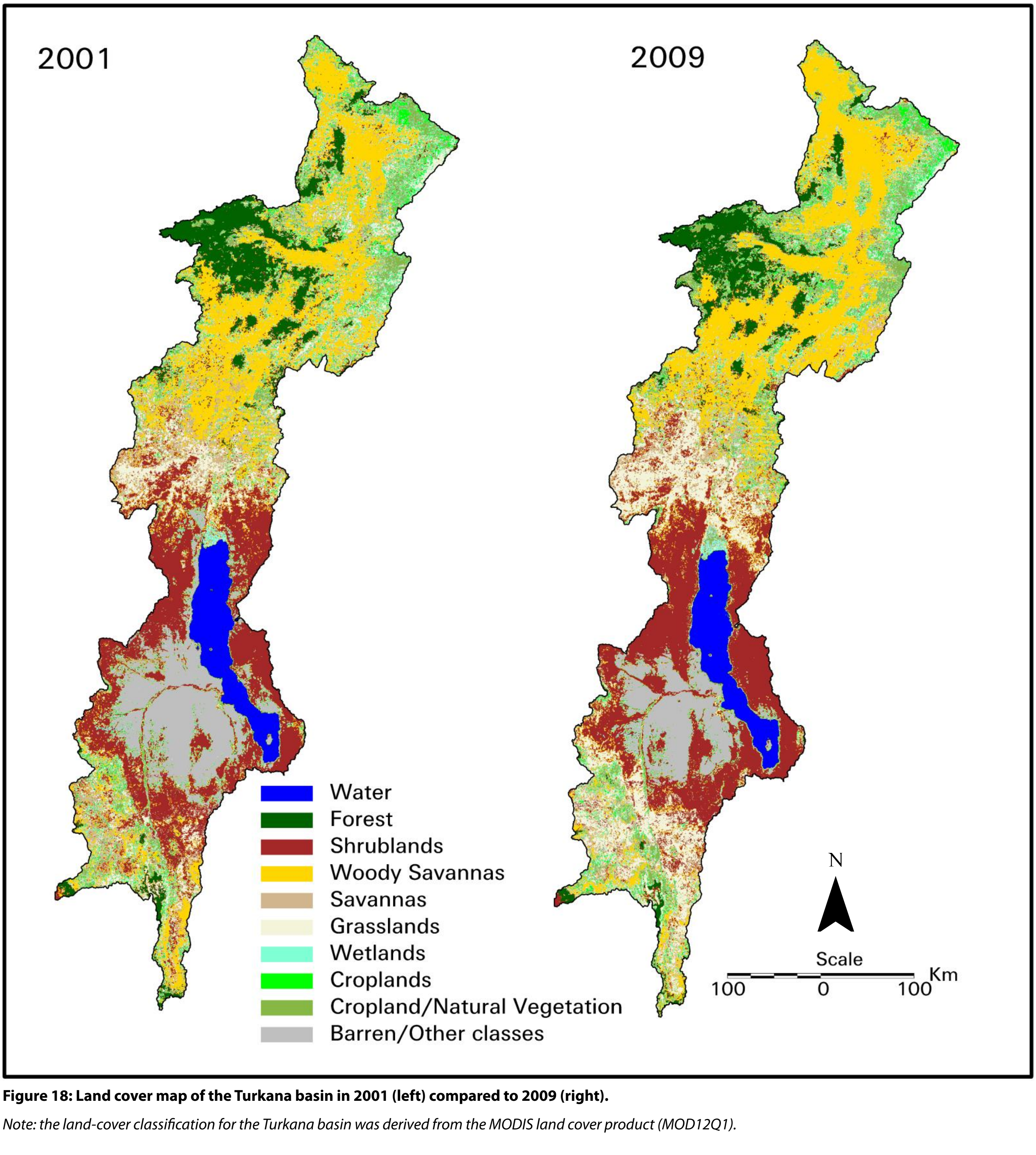


Figure 18: Land cover map of the Turkana basin in 2001 (left) compared to 2009 (right).

Note: the land-cover classification for the Turkana basin was derived from the MODIS land cover product (MOD12Q1).

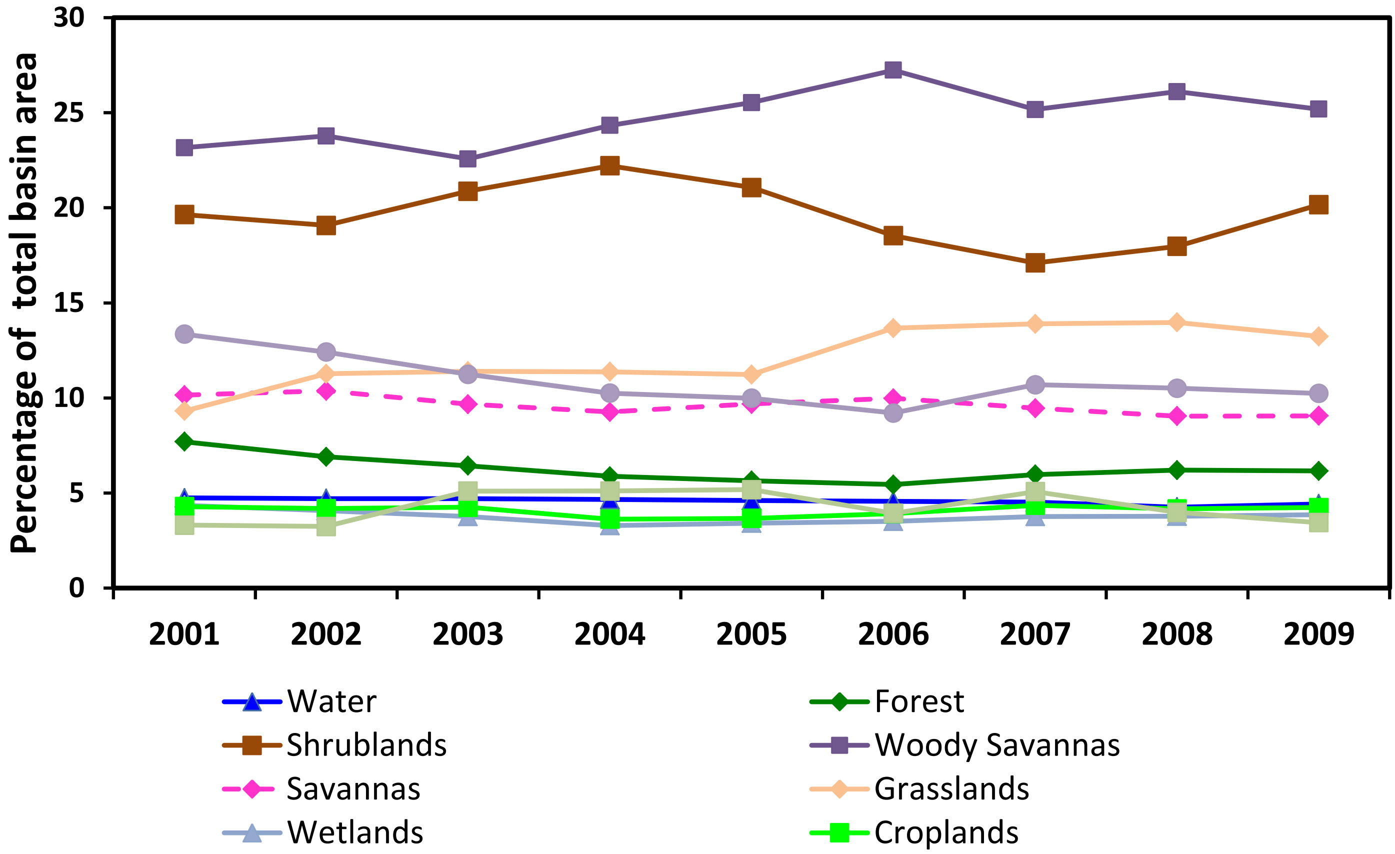


Figure 19: Land-cover dynamics for each land-cover class in the Turkana basin, as derived from the MODIS land-cover product, 2001–2009.

Land cover	Area	
	(ha)	(km^2)
River bank	555	6
Woodland	27 193	272
Riverine forest	19 754	198
Bush land - thick	44 804	448
Bush land - sparse	34 504	345
Bush land - other	44 762	448
Bare ground	27 681	277
Marshland	5 615	56
Cultivated land	2 938	29
Recession agriculture	801	8

Table 4: Area under different land-use/land-cover classes in the lower Omo River basin.

We found that for most land-cover classes, the percentage of area under each class remained almost unchanged, except for grasslands, shrublands and woody savannah, which showed less than 5 per cent change in area during 2001–2009 (Figure 19). For other classes, the extent of change over the last decade was found to be negligible.

3.7 Land Cover along the Lower Omo River

As part of the downstream impact assessment study, EEPCo released a series of land-cover maps for the lower Omo River basin. Understanding the land cover along the riverine plains of the lower Omo River is important because these areas would be directly affected by the Gibe III reservoir. Figure 20 shows the tiles of land-cover maps released by EEPCo on the left. These individual land-cover maps were stitched together in Geographic Information System (GIS) to produce a seamless map of land cover along the lower Omo flood plains (Figure 19). The area under each land-cover class was extracted (Table 4). Our analysis revealed that the area under cultivation or agriculture, including recession agriculture, was around 3 738 ha.

Land cover along the lower Omo Basin.

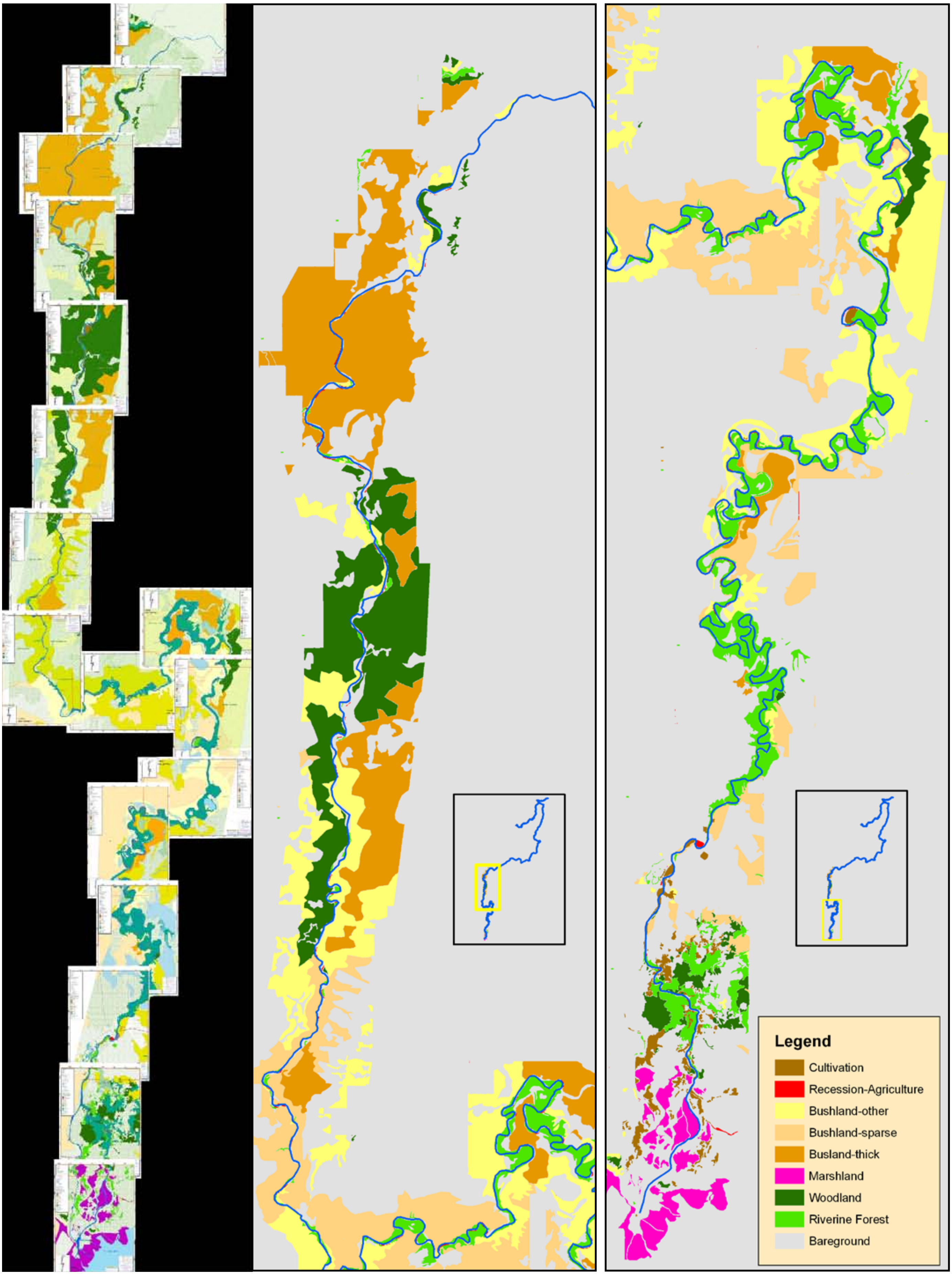


Figure 20: Land cover along the lower Omo River.
Source: Generalized from EEPCo 2008 maps

Fishing communities living along the Lake Turkana shore near Ferguson's Gulf.

3.8 Climate Change Impacts on Lake Turkana Water Levels

Against this background of high natural variability in lake inflows, as presented in Figure 16, climate-induced changes in rainfall and temperature will further increase the uncertainty of inflows to the lake. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report provides a comprehensive review of climate-model projections for different regions in Africa, which are based on a set of 21 models from the Multi-Model Data (MMD) set using the A1B emissions scenario (Christensen and others 2007). The climate models project warmer (+3.2°C) and wetter (+7 per cent) conditions in East Africa by the 2080s (Table 5).

According to Christensen and others (2007), projections of extreme events in the tropics remain uncertain. There is a tendency for monsoonal circulations to result in increased precipitation despite a tendency towards a weakening of the monsoonal flows themselves. The main and most understood climate drivers of inter-annual and decadal rainfall variability in Africa are Atlantic (and other) Ocean sea surface temperature (SST) patterns (West Africa and the Sahel), El-Niño Southern Oscillation (ENSO) behaviour (West, Southern and East Africa) and Indian Ocean dynamics (East and Southern Africa). Funk and others (2008) predict that rainfall patterns over East Africa will gradually decline by 2080 based on SST data over the Indian Ocean and other weather data. Current model simulations of future climates do not show clear tendencies in the future behaviour of these large-scale drivers (Conway and others 2007).

Overall, these results suggest that warming is likely to be greater than the global annual mean warming throughout the continent and in all seasons. On balance, higher temperatures are likely to increase evaporative demand throughout Africa. This increase in temperature would cause evapotranspiration to increase over the lake with a consequent decrease in the lake's level. On the other hand, annual rainfall over East Africa may increase by 7 per cent (Figure 21). This increase in rainfall would mean increased basin discharge and a subsequent rise in lake level. Because both temperature and rainfall show an increase, negative impacts on lake levels would increase in below-normal rainfall years and decrease in above-normal rainfall years. However, based on the currently available IPCC projections for East Africa, temperature and rainfall impacts would balance each other out in the long term; therefore, it is anticipated that climate change will not have a major impact on Lake Turkana water levels. However, the dam's impact on lake water levels would depend directly on rainfall distribution and pattern after the dam is operational.

Recent climate variability provides a rich source of empirical detail to provide context for the implications of uncertain climate change in the future. The most recent water-level fluctuations (1993–2009) captured by TOPEX/Poseidon satellite altimetry (Cretaux and others 2011) show that the lake's level gradually increased to a maximum of about 365 m above sea level (asl) by the end of the 20th century (Figure 22). However, between 2000 and 2006, the level gradually declined to reach about 361 m asl. Even recent lake levels show fluctuations of up to 5 m. Over the 18 years, Lake Turkana water levels show a slightly increasing trend. Natural causes, such as variation in rainfall

Region	Temperature: Annual (inter-model range)	Seasonal *	Precipitation: Annual (inter-model range)	Seasonal *
East Africa (12°S, 22°E to 18°N, 52°E)	+3.2°C (+1.8 to +4.3°C)	Warming in all seasons:+3.1°C (DJF, SON) to +3.4°C (JJA)	Increase of 7 per cent (–3 to +25 per cent)	Increase in all seasons: 4 per cent (JJA) to 13 per cent (DJF)

Table 5: Changes in mean temperature and precipitation between the present and the 2080s.
Note: Multi-model means and model range are shown, based on Christensen and others 2007.
* DJF: December, January, February; MAM: March, April, May; JJA: June, July, August; SON: September, October, November.

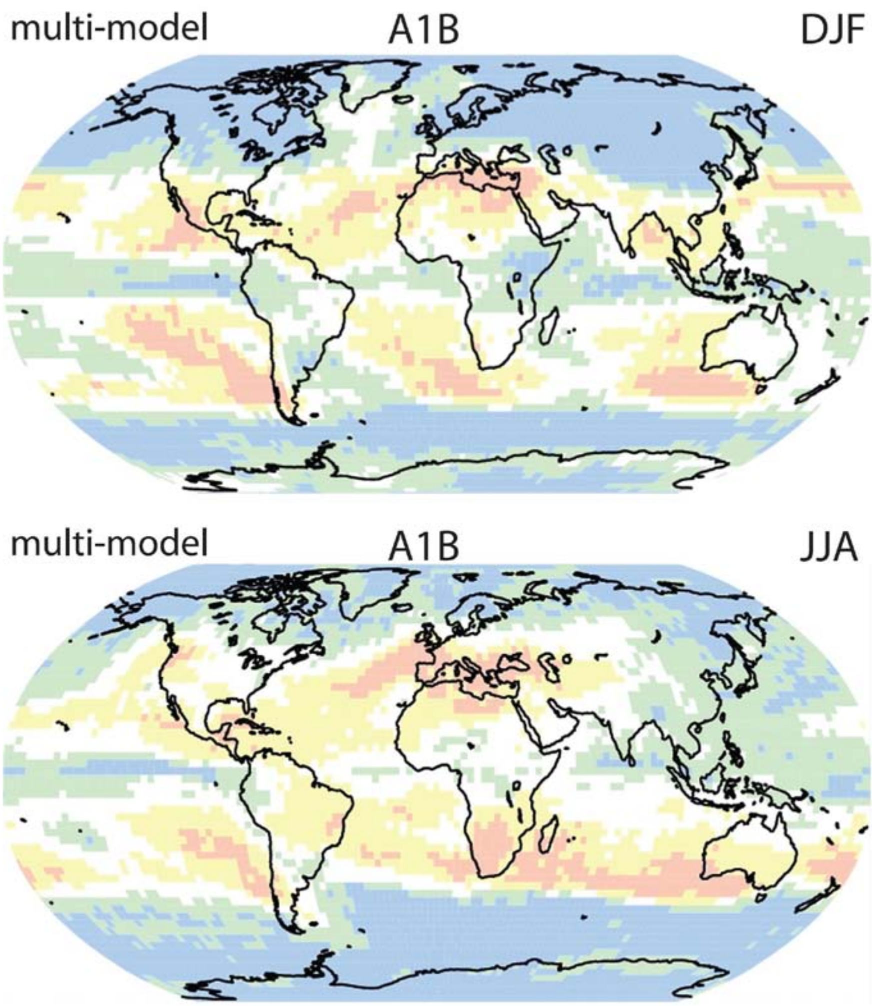


Figure 21: IPCC rainfall projections, 2000-2100.
Source: Christensen and others 2007
Note: By the end of the century, blue and green areas on the map are projected to experience increases in precipitation, while precipitation is projected to decrease in areas in yellow and pink. The top panel shows projections for the December, January and February period, while the bottom panel shows projections for June, July and August (Christensen and others 2007).

and temperature, are considered to be the main drivers of these fluctuations in the lake's level. Human activities are also beginning to impact these fluctuations, but their influence is yet to be understood.

It is not yet possible to predict future climate change with a known degree of confidence. There are large uncertainties in the climate scenarios derived from Global Climate Models (GCMs), particularly regarding precipitation changes. The knowledge-based scenarios presented in the analysis in section 5.3 are therefore not predictions; mixes of dry and wet futures have been used to highlight the variability. It is not yet possible to produce reliable estimates of future basin discharge taking into account the effects of climate change; therefore, we consider a range of possibilities.

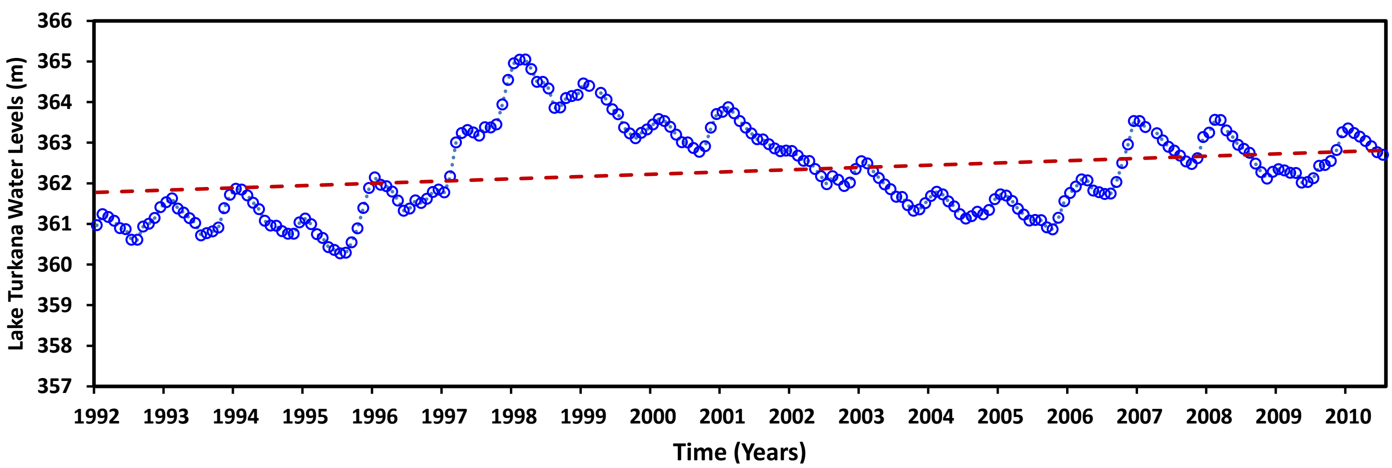
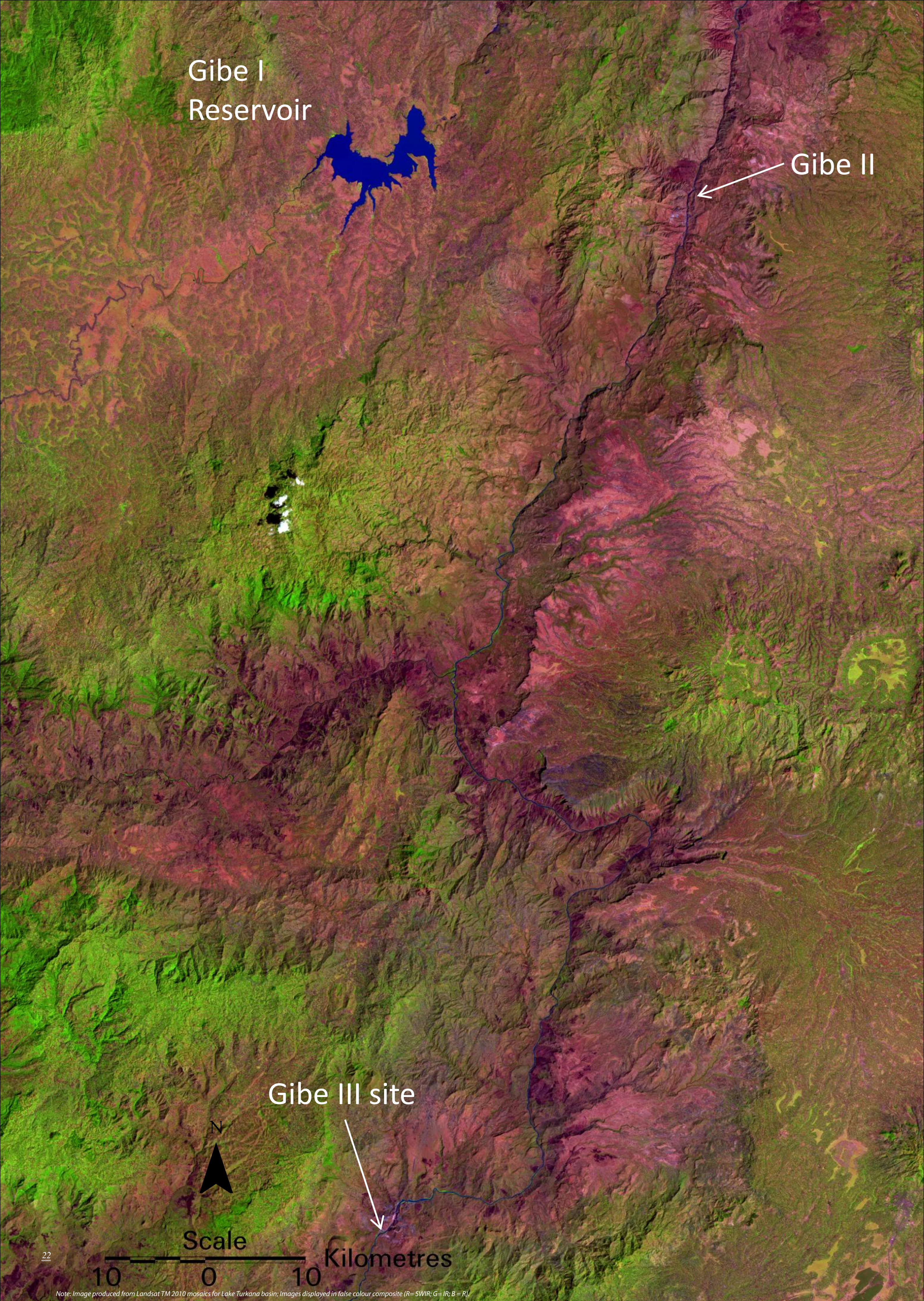
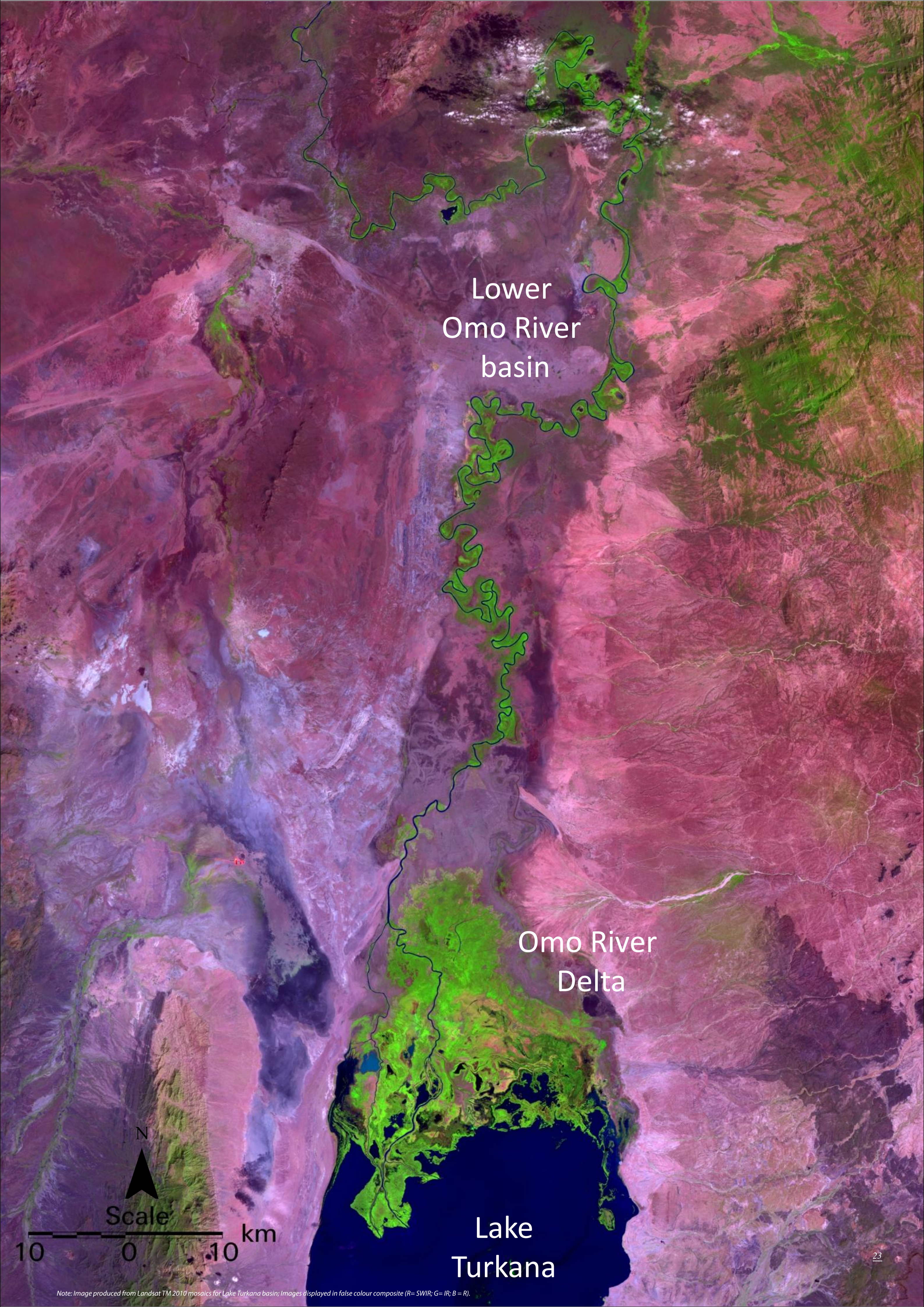


Figure 22: Recent Lake Turkana water-level fluctuations based on TOPEX/Poseidon satellite altimetry data. Red line indicates statistical trend.

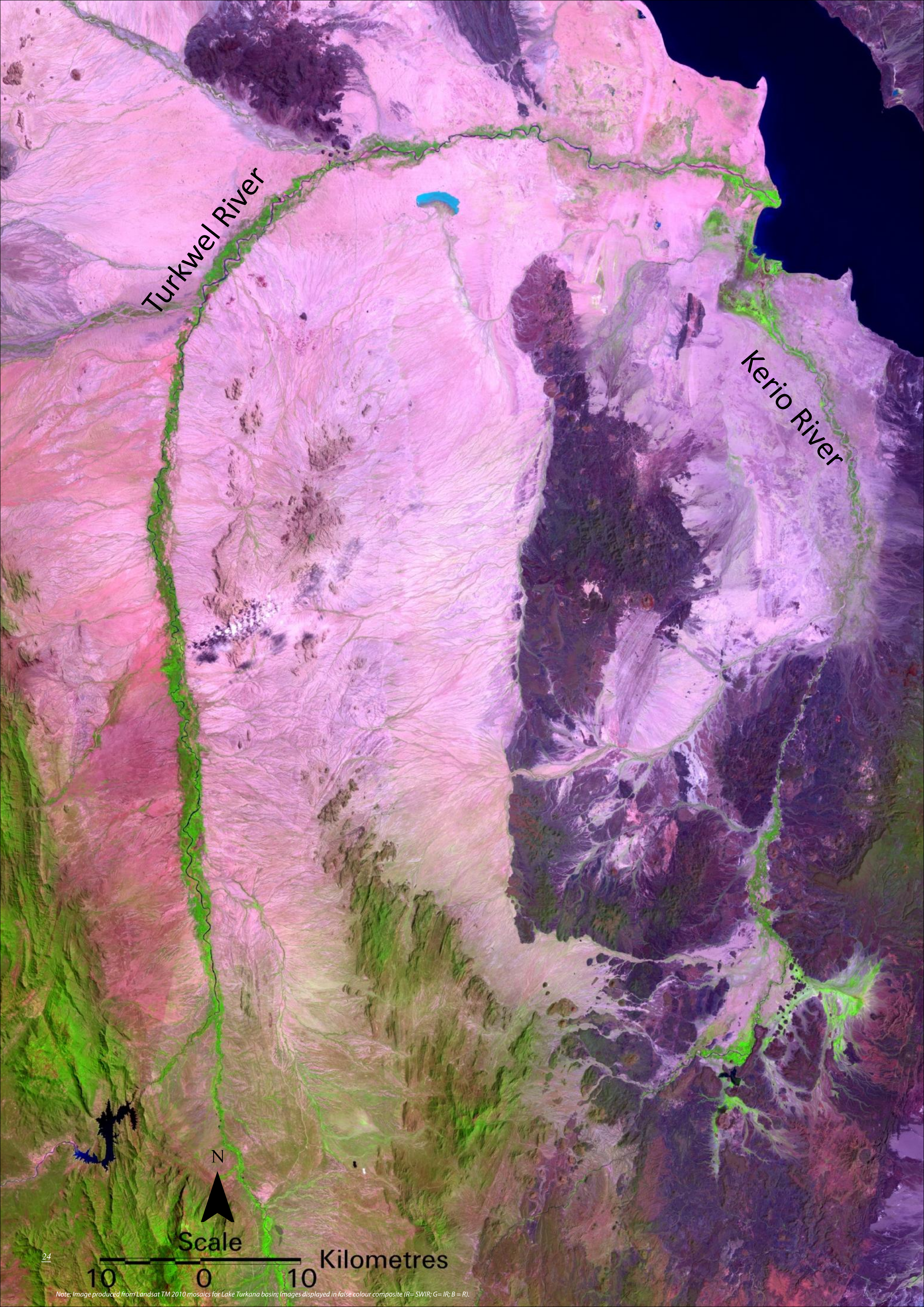
Source: Cretaux and others 2011



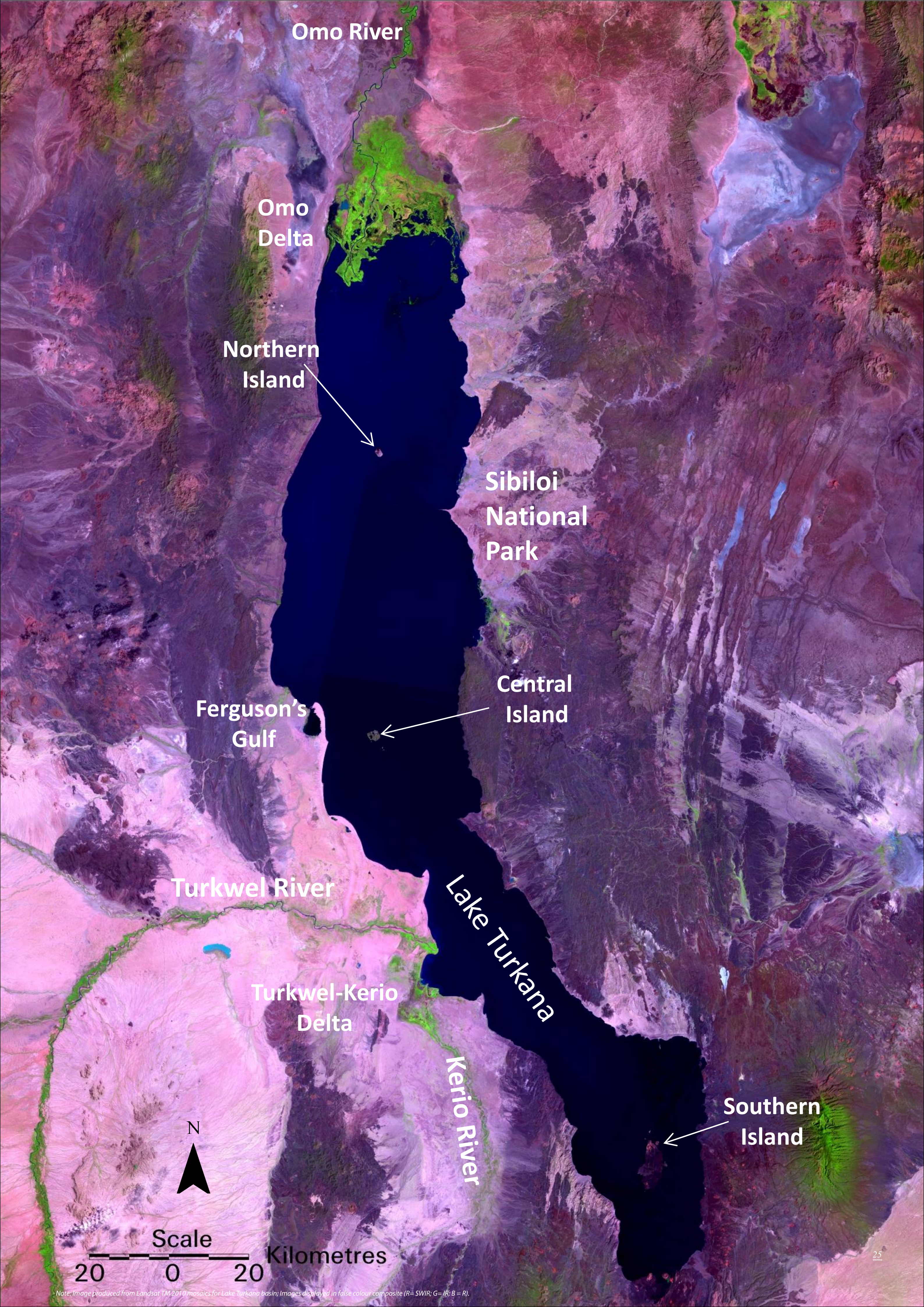
Note: Image produced from Landsat TM 2010 mosaics for Lake Turkana basin; Images displayed in false colour composite (R= SWIR; G= IR; B = R).



Note: Image produced from Landsat TM 2010 mosaics for Lake Turkana basin; Images displayed in false colour composite (R= SWIR; G= IR; B = R).



Note: Image produced from Landsat TM 2010 mosaics for Lake Turkana basin; Images displayed in false colour composite (R= SWIR; G= IR; B = R).


Omo River
Omo Delta
Northern Island
Sibiloi National Park
Central Island
Ferguson's Gulf
Turkwel River
Lake Turkana
Turkwel-Kerio Delta
Kerio River
Southern Island
N
Scale
20 0 20 Kilometres
Note: Image produced from Landsat TM 2010 mosaics for Lake Turkana basin; Images displayed in false colour composite (R= SWIR; G= IR; B = R).

Abandoned Lake Turkana Lodge along lake shore near Ferguson's Gulf.

© Manohar Velpuri

4. METHODOLOGY USED TO MODEL THE DAM'S IMPACT ON LAKE LEVELS

4.1 Satellite Data

The satellite data used in this study are summarized in Table 6 and Figure 23. NOAA CPC produces satellite-based RFE for the FEWS project of USAID, which have been produced daily with a spatial resolution of 0.1 x 0.1 degree since June 1995 and are available to the public in near-real time. Validation studies of RFE rainfall over the Ethiopian highlands using gauge data suggest that RFE can be reliably used for early warning systems to empower decision making (Dinku and others 2008). Velpuri and others (2012) have used RFE data for Africa to model Lake Turkana water levels with reasonable accuracy. For this study, we used RFE data from January 1998 to December 2009 and we also used daily reference evapotranspiration (ETo) data 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 degree (Senay and others 2008).

Historical average decadal (10-day) Normalized Difference Vegetation Index (NDVI) datasets (1982–2006) described by Tucker and others (2005) from the Advanced Very High Resolution Radiometer (AVHRR) were used to characterize the land-surface phenology (LSP) and to estimate actual evapotranspiration (ETa) on a pixel-by-pixel basis at 0.1 degree resolution.

To estimate the canopy interception parameter, we used the global percentage tree cover product produced from the MODIS Vegetation Continuous Field (Hansen and others 2003). Area weighted, average interception losses were estimated for each modeling pixel based on the percentage of bare, herbaceous, and tree cover area for each pixel. The interception coefficient for each modeling unit varies from a minimum of zero in bare-cover types to a high of 35 per cent in areas with a dense forest cover.

We used the Digital Soil Map of the World (FAO 1995) to estimate water holding capacity (WHC) for the dominant

No.	Data	Satellite Sensor / Source	Frequency	Resolution/ Scale	Reference
1	Rainfall estimate for Africa	SSM/I, AMSU	Daily	0.10 x 0.10	Herman and others 1997; Xie and Arkin 1996
2	Global GDAS reference Evapotranspiration (ET)	Model assimilated satellite data	Daily	0.10 x 0.10	Senay and others 2008
3	Climatological NDVI	NOAA AVHRR	Dekadal	8 km	Tucker and others 2005
4	Landsat	TM/ETM	Multiple dates	30 m	-
5	MODIS Landcover map	MODIS Terra	2000-2009	1 km	Friedl and others 2010
6	Digital soil map of the world	National statistics	Single date	1:5000000	FAO 1995
7	Global per cent tree cover map	MODIS VCF	Single date	500 m	Hansen and others 2003
8	Digital Elevation Model	SRTM	Single date	90 m	Farr and others 2000
9	Lake Turkana water levels	TOPEX/Poseidon, Jason-1, ENVISAT	Daily	> 200 m	Birkett 1995
10	Lake Turkana bathymetry data	-	Single date	-	Kalqvist and others 1988
11	Lower Omo River basin Landcover data	-	Single date	-	EEPCo 2008

Table 6: Satellite data and products used in the Lake Level Modeling (LLM) approach.

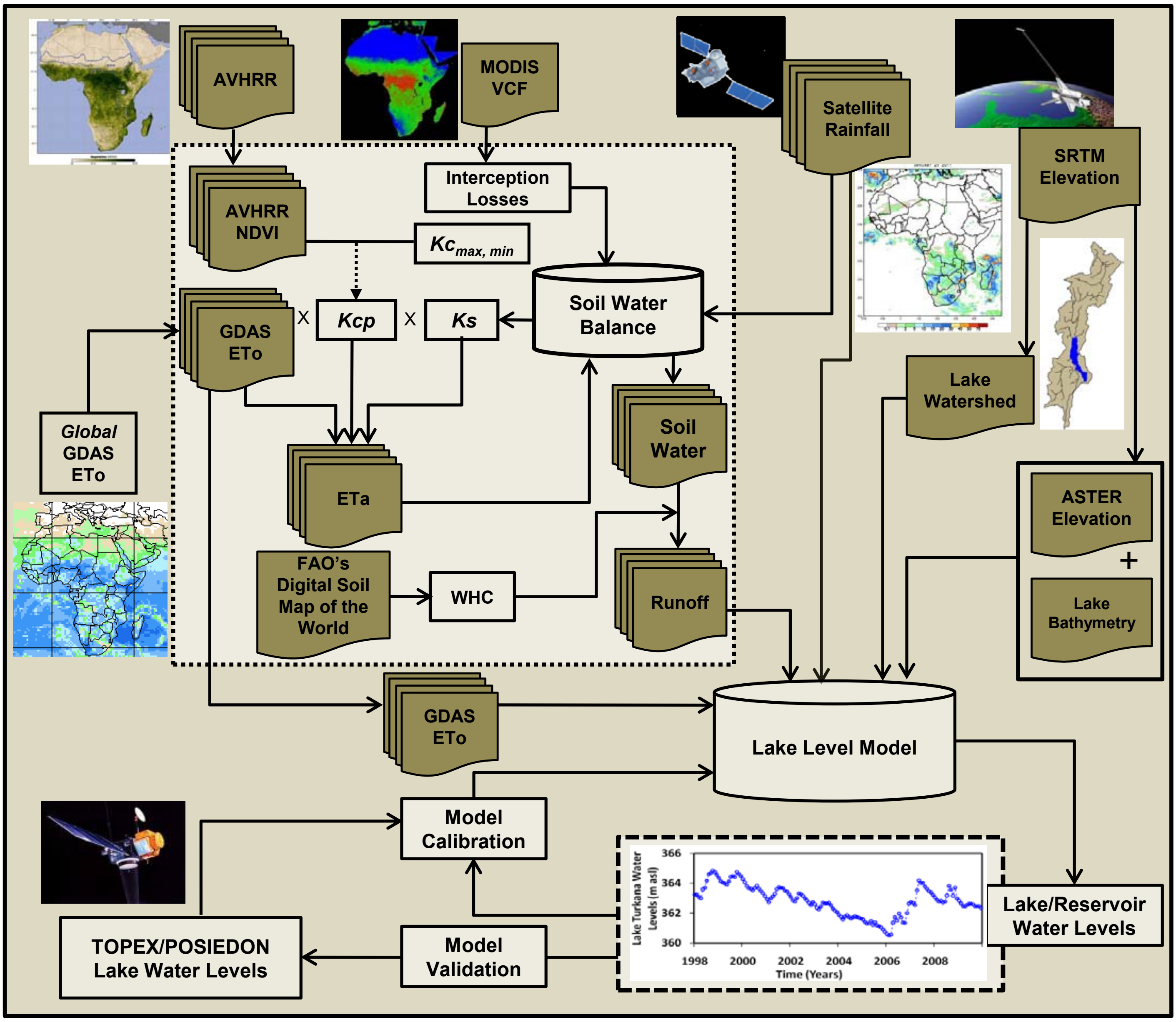


Figure 23: Illustration of the satellite data and methodology used in this study.
Source: Modified from Velpuri and others 2012

soil type for each grid cell. Shuttle Radar Topography Mission (SRTM) 90-m and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Map (GDEM) 30-m digital elevation model (DEM) data were used to derive several hydrological variables.

4.2 Lake-Level Modeling Approach

Figure 23 illustrates the type of data and scheme for lake-level modeling (LLM) used in this study using multi-source satellite data. Velpuri and others (2012) provide a detailed description of the LLM approach. First, satellite rainfall and evapotranspiration data were used to estimate runoff [m] on a pixel-by-pixel basis using the phenology-based ET model (Senay 2008, Senay and others 2009). The runoff for each time step was estimated based on the principle of soil saturation excess, where soil-water content, after meeting other demands such as evapotranspiration and interception losses, is compared to the soil's WHC. The excess soil water with respect to the WHC is then considered runoff. Runoff generated using this approach is routed using a source-to-sink routing algorithm (Asante 2000, Olivera and others 2000, Velpuri and others 2012), and total routed runoff volume contribution for each basin (Qinf) is produced as outlined in Velpuri and others (2012). Modelled routed-runoff data were calibrated using long-term (1964–2001) mean monthly Omo River flow data at the Gibe III site and at Lake Turkana obtained from EEPCo (2009b). Finally, lake-level height for each time step was estimated using the water-balance principle shown below.

$$D_i = D_{i\text{-}1} + Q_{rain} + Q_{in\_flows} + Q_{gwin} - Q_{evap} - Q_{gwout} - Q_{outflow}$$

where D_i and D_{i-1} are lake or reservoir depths for current and previous time steps and Q represents the fluxes in variables for the current day; *rain* is direct rainfall over

Lake level measurement gauges along Lake Turkana's shoreline.

the lake or reservoirs; *in_flows* refers to inflows into the lake or reservoirs; *evap* is over-the-lake/reservoir ETo; and *outflow* is the outflow from the lake/reservoir. As Lake Turkana is considered endorheic with no surface outlet, its groundwater fluxes and surface outflows (Rickett and Johnson 1996) are considered negligible. Furthermore, according to EEPCo (2007), contributions of groundwater fluxes to and from the reservoirs are minimal. Hence, we ignored groundwater fluxes (gwin and gwout) in equation 1. Surface outflows ($Q_{outflow}$) for the Gibe I reservoir include a rated outflow of 101.5 m^3/s and a continuous environmental flow of about 1.3 m^3/s released downstream of the Gibe I dam and any excess flow from the reservoir when Gibe I is at its maximum level. Surface outflows ($Q_{outflow}$) for the Gibe III reservoir include the environmental flow released from the reservoir (25 m^3/s), the artificial flood released from Gibe III (1 000 m^3/s) for 10 days in September every year, the water discharged from the Gibe III power plant and any excess flow (spill flow) from the reservoir when Gibe III is at its maximum level. The lake water levels modeled using this approach have been validated using satellite altimetry data and found to be in reasonable agreement with a Pearson's correlation coefficient of 0.90.

Looking up the mountain side at the roller-compacted concrete plant conveyor.

5. IMPACT ASSESSMENT OF GIBE III ON LAKE TURKANA WATER LEVELS

To assess the impact of the Gibe III dam on the lake levels, the LLM approach was modified to include a simple hydrologic algorithm that would route the basin runoff through the Gibe I and Gibe III dams before flowing into the lake. This study attempts to evaluate the impact of the dam on the lake's water level using existing data. However, to reliably perform the impact assessment of the Gibe III dam on the lake's level, data over longer time periods (>30 years) are required to account for the variability in the hydrologic variables under study. Also, the study is carried out in an ungauged basin where the available data are limited, so satellite-based estimates of hydrologic variables, which are available for a limited period, were used to forecast the potential impact of the Gibe III dam. Therefore, a complete characterization of the variability in lake inflows is not feasible. This is a common problem, especially in ungauged basins where ground-truth data are either limited or unavailable.

5.1 Operational Strategies of the Gibe III Dam

The LLM modeling approach takes into account the operational strategies to be followed by EEPCo to simulate the dam's possible impact. The following operational strategies were implemented in the modeling framework:

1. All-time environmental flow would be released from the Gibe III dam at the rate of 25 m^3/s.
2. An artificial flood at the rate of 1 000 m^3/s would be released from the Gibe III reservoir for the duration of 10 days in September to maintain natural flooding conditions in the lower Omo basin.
3. The minimum operating level for operational power generation is 854 m asl or 201 m absolute depth of the reservoir.
4. The maximum operating level of the Gibe III dam is 894 m asl or 241 m.
5. Operational power production would begin in the first year if the basin experiences above-average or average rainfall.
6. Operational power production would begin in the second year if the basin experiences below-average rainfall.
7. The hydroelectric power plant would work only for 11 out of 24 hours a day. Hence, a plant factor of 0.46 would be used to estimate the total power produced.

Three different approaches were used to determine the potential hydrological impact of the Gibe III dam on Lake Turkana water levels.

5.2 Evaporation losses from the Gibe reservoirs and Lake Turkana

Quantifying evaporation losses from the Gibe reservoirs is important as the water is lost from the reservoirs (consumptive use) and would never reach Lake Turkana. GDAS ETo was used to estimate the evaporation losses from Gibe I, Gibe III and Lake Turkana. Based on the analysis of GDAS ETo data from 2001-2009, we found that Gibe I and Gibe III would lose up to 1.34 and 1.46 m per year of water respectively due to evaporation. The evaporation loss of 1.46 m per year from Gibe III reservoir resulted in the reduction of Lake Turkana inflows by 10 m^3/s. On the other hand, evaporation losses from Lake Turkana would account for up to 2.2 to 2.4 m.

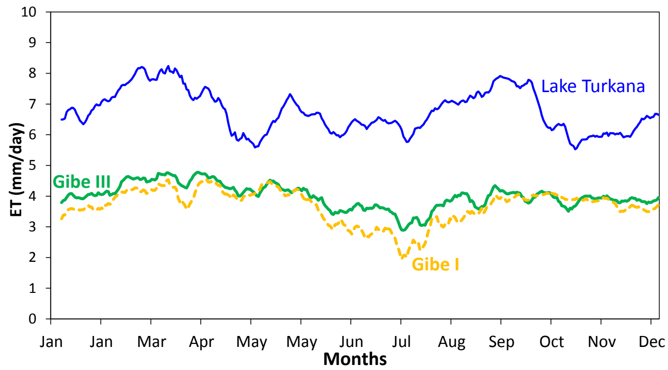


Figure 24: Comparison of evaporation losses from the Gibe reservoirs and Lake Turkana. A 7-day moving average evapotranspiration rate (mm/day) is shown here.

5.3 Approach I: The Impact of the Gibe III Dam under the Assumption it was Commissioned in the Past

In this approach, a simple scenario is used to test the potential impact of the Gibe III dam. We make an assumption that the Gibe III dam was commissioned sometime in the past. Using existing satellite data of rainfall, runoff and ET for the period 1998–2009, we used the LLM approach to model Lake Turkana water levels without the dam. We estimated the volume of inflows to Lake Turkana (without the dam) for each month and modeled Lake Turkana water levels for 1998–2009. Since January is a dry period in the Lake Turkana basin, we re-ran the LLM approach under the assumption the dam was commissioned on 1 January 1998 and used volumes of the inflows routed through the dams to model lake water levels. A direct comparison of the volume of inflows and the lake's water levels with and without the dam provides an estimate of the impact of the Gibe III dam using existing datasets. We then estimated the time taken for the Gibe III reservoir to reach minimum operation level (MOL).

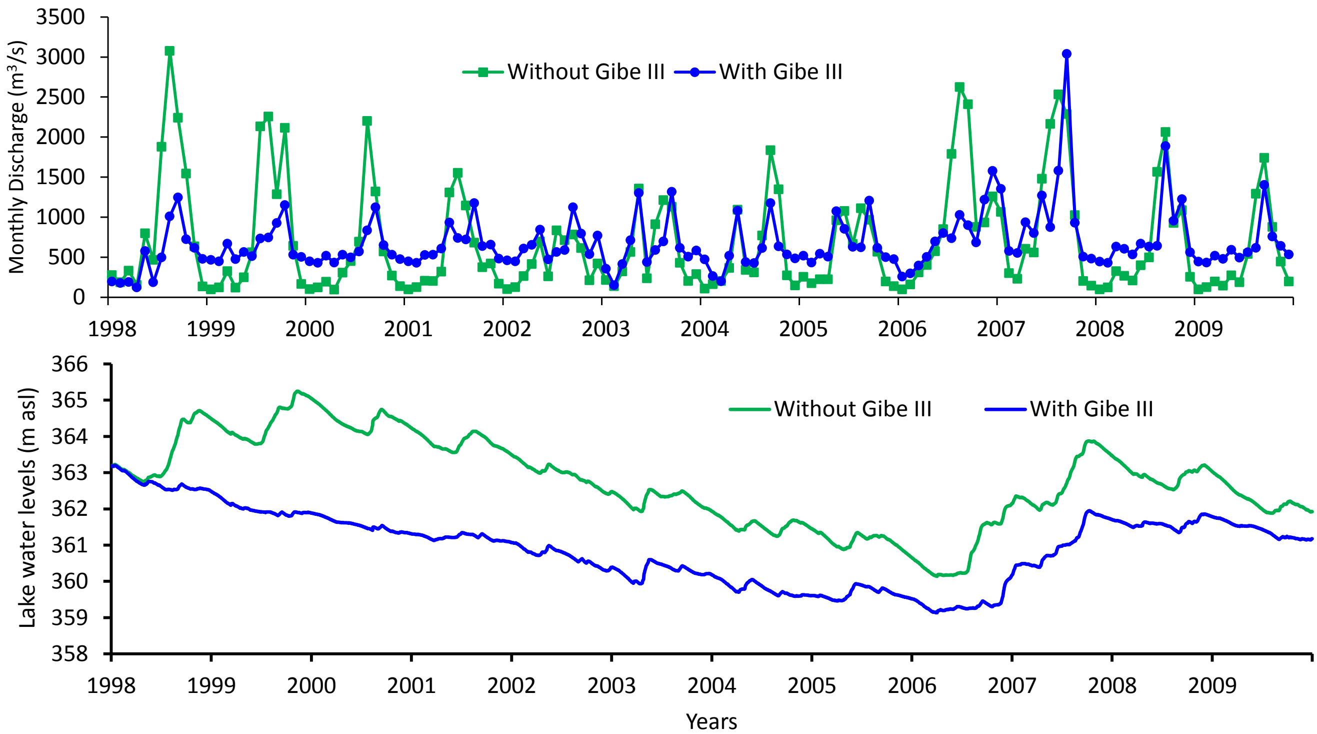


Figure 25: Total monthly inflows to Lake Turkana (top) and lake water levels (bottom) with and without the Gibe III dam.
Source: Velpuri and Senay (2012)
Note: The model was run assuming the dam was commissioned on 1 January 1998.

This simulation uses the actual lake level for 31 December 1997 obtained from the satellite altimetry data as the initial lake level. First, the model was run to derive Lake Turkana levels without the dam. During this time period, the long term median rate of inflows into the lake was about 400 m^3/s and lake levels varied between 365.25 m and 360.14 m asl (Figure 25).

The model was then re-run assuming that the dam was commissioned on 1 January 1998. The model predicts that the Gibe III reservoir would reach the MOL of 201 m absolute depth of the reservoir in around 220 days (by the first week of August). During the first impoundment period, the volume of lake inflow rate was found to be 58 per cent lower when compared to the rate without the dam. Due to this reduction in inflows, by the time the Gibe III reservoir reaches the MOL, the difference between the lake levels with and without the dam appears to be around 0.65 m (Figure 25). The lake's level decreases further during the impoundment period, and the difference between the lake level with and without the dam gradually increases to slightly over 3 m by the beginning of 2000 (Figure 25).

The lake's level then continuously decreases both without the dam and with the dam due to low rainfall until the middle of 2006. However, the difference between the two levels is gradually reduced to about 1 m. Lake levels then rise as a result of good rainfall, and the difference in lake levels under the two situations—with and without the dam—is further reduced. Lake inflow is moderated after the first impoundment period, with reduced peak flows in the wet season and an increased base flow during the dry season, as shown in Figure 25.

5.4 Approach II: The Impact of the Dam under Knowledge-Based Scenarios

Kolding (1992), Camberlin (2001), and Shongwe and others (2009) investigated past rainfall variability in the East African region. A classification of rainfall patterns and trends in the Turkana basin over 1998–2009 shows that there were severe droughts with a prolonged dry period in 2000 (WFP 2000) and below-normal rainfall in 2003, 2004, 2005 and 2009. In 1998, there was an incidence of heavy rainfall due to the El Niño effect (Behera and others 2005) and there were severe floods in 2006 (Moges and others 2010), and above-normal rainfall was observed in 1998, 2001, 2002 and 2006. Normal rainfall occurred in the other years: 1999, 2007 and 2008. Existing satellite-based rainfall for 1998–2009 is classified as below-normal, normal and above-normal in the Gibe III and Lake Turkana basins, as shown in Table 7.

Basins	Below-Normal Rainfall Years	Normal Rainfall Years	Above-Normal Rainfall Years
Gibe III basin	2000 to 2003, 2005, 2009	2004, 2008	1998, 1999, 2006, 2007
Turkana Basin	2000, 2003, 2005, 2009	1999, 2007, 2008	1998, 2001, 2002, 2006

Table 7: Classification of satellite-based rainfall (1998–2009) for the Gibe III and Lake Turkana basins.

Kolding (1992) studied the rainfall distribution over Lake Turkana and summarized that severe drought occurs roughly every 6 years. He found the summer rains in this region to be significantly correlated to ENSO, which repeats at average intervals of 5 years (Camberlin and others 2001). However, Shongwe and others (2009) summarized that in recent years, East Africa has suffered frequent episodes of both excessive and deficient rainfall. They found an increased frequency of anomalously strong rainfall-causing floods, from an average of less than three events a year in the 1980s to more than seven events a year in the 1990s and almost ten events a year from 2000 to 2006. The patterns observed during the 12 years of data largely follow trends established by Kolding (1992) and Camberlin and others (2001), with one severe drought in 2000 and 2 years of severe rainfall in 1998 and 2006. However, the observations of Shongwe and others (2009) may explain other patterns of years of both below-normal and above-normal rainfall.

Based on knowledge of the regional climate and using three categories of rainfall years observed over 1998–2009, we built 20 scenarios comprising different combinations of above-average, below-average and near-normal rainfall distributions based on the likely occurrence of droughts and floods. Our analysis was restricted to 20 scenarios generated randomly to capture the impact of rainfall variability on the Gibe III dam and resulting Lake Turkana water levels. Scenarios were built such that the occurrence of severe drought years such as 2000 or severe flood years such as 2006 would not occur more than three times each in a selected scenario. The choice of other years was based purely on random selection, without any constraints. Table 8 presents various combinations of these scenarios used to assess the impact of the dam. Under each scenario, simulations of lake levels with and without the dam are modeled and compared. Furthermore, we estimated the time taken for the Gibe III reservoir to reach MOL and the loss in Lake Turkana water level during the first reservoir impoundment.

Based on the results obtained from the 20 different knowledge-based scenarios, we estimated the time required for the reservoir to reach MOL. Figure 26 and Table 9 show the results of the analysis using approach II. The dam's reservoir would reach the MOL level of 201 m in 8 months (in the case of scenarios 6, 7, 8, 12 and 15) to up to 16 months (in the case of scenarios 16 and 18), depending on the rainfall under different scenarios. The time to reach MOL would depend on the amount and distribution of rainfall received after the dam commencement. Simulation results indicate that on average, it would take up to 10 months to reach MOL. During the period of first impoundment, a below-normal rainfall would prolong the time to reach MOL by more than a year. However, a year of above-average to near-normal rainfall would cause the reservoir to reach MOL in less than a year.

Compared to without the dam scenario, regulated inflows during the first stage of reservoir impoundment would cause Lake Turkana's water level to drop by a minimum of 0.8 m (in the case of scenarios 16 and 18) to a maximum of 1.6 m (in the case of scenario 6). In general, above-normal rainfall is more desirable than below-normal rainfall: above-normal rainfall provides increased inflow to the reservoir and increases power production, resulting in increased discharge and a subsequent rise in Lake Turkana's water level. After reaching MOL, the dam becomes operational and much of the water would be released back into the river, which would help the lake to stabilize. The results predict a maximum loss in lake levels of 3.4 m (an average of 1.8 m) compared to without the dam scenario after the first impoundment period (Figure 25). After the period of first impoundment in the case without the dam, lake levels would fluctuate anywhere between no-change to a little over 4 m. The dynamic range of fluctuations in each scenario is illustrated in Figure 26.

Results from approach II indicate that the dam's impact would be higher in scenarios 6, 14, 15, 18 and 19, in which lake levels drop by over 4 m compared to lake levels without the dam. In all these scenarios, the highest impact occurred only during years with above-normal rainfall, such as in 2006 and 2007. Scenarios 2, 3, 10, 11 and 16 show the least impact with < 0.5 m difference with respect to the case without the dam. These scenarios have more years of below-normal rainfall.

During the period of first impoundment, below-normal rainfall causes a smaller impact on the lake's level and above-normal rainfall causes a higher impact. During dry years, natural inflow into the lake is regulated. With the dam in place, there is always an average inflow of 400–500 m^3/s, so the lake level with the dam will not actually drop as much as it would in a naturally dry condition. Hence, the difference in lake level, or the impact, appears to be smaller in dry periods. However, this outcome requires the initial condition of an already-full reservoir. On the other hand, with wet conditions, the lake would naturally receive heavy inflows, so lake levels would increase without the dam. However, with the dam, the lake would always receive moderated inflows that would be smaller than the natural inflows during wet years and hence the impact on the lake would be greater in wet years.

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

Table 8: Rainfall scenarios to simulate rainfall and ET using historical data using the knowledge-based scenarios approach.
Source: Velpuri and Senay (2012)

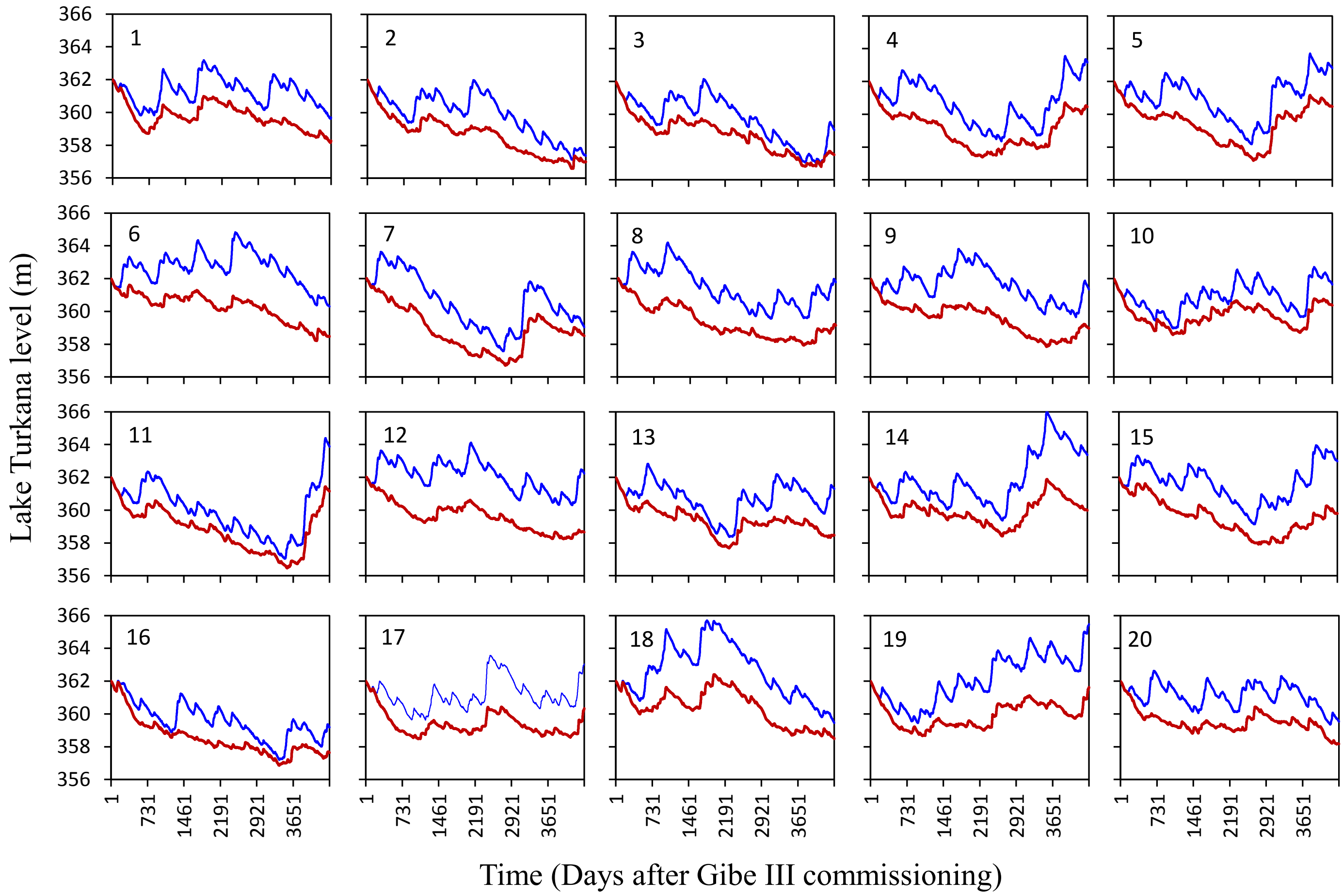


Figure 26: Impact of Gibe III on Lake Turkana Water levels based on 20 knowledge-based rainfall scenarios. The red and blue lines indicates lake level fluctuations under each scenario with and without the Gibe III dam, respectively.
Source: Velpuri and Senay (2012)
Note: The blue line shows the lake level fluctuations under each scenario without Gibe III dam and the red line shows the lake level fluctuations after the commissioning of the Gibe III dam.

Knowledge-Based Scenarios	Time to fill Gibe III reservoir (reach minimum operation level of 201 m)	Loss in Lake Turkana level with respect to without the dam			
		During first impoundment	After the first impoundment		
			Max	Mean	Min
	[Months]	[m]	[m]	[m]	[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

Table 9: Likely impact of the Gibe III dam on the Lake Turkana water level using knowledge-based scenarios.
Source: Velpuri and Senay (2012)

5.5 Approach III: Univariate Nonparametric Resampling Technique

In this approach, 12 years of existing lake rainfall, evaporation and inflows data (1998–2009) are used to simulate time series information on the potential scenarios of rainfall, lake inflows and ET data using nonparametric resampling techniques. The nonparametric bootstrap resampling technique, first introduced by Efron and Tibshirani (1993), is employed because it does not require preselected distribution or models to be fitted to data or sampling distribution of the data. This technique has been widely used for simulation of rainfall or inflows using historical data (Rajagopalan and others 1997, Sharma and Lall 1997, Srikanthan and McMohan 2001). This approach is highly useful for simulating inflows using satellite data in ungauged basins/lakes where simulated data are required to analyze the future impact of alternative designs, operation policies, lake-management studies and other rules for water resource systems.

Different methods of nonparametric resampling are available. In a simple nonparametric bootstrap resampling method, the Monte Carlo approach is used numerous

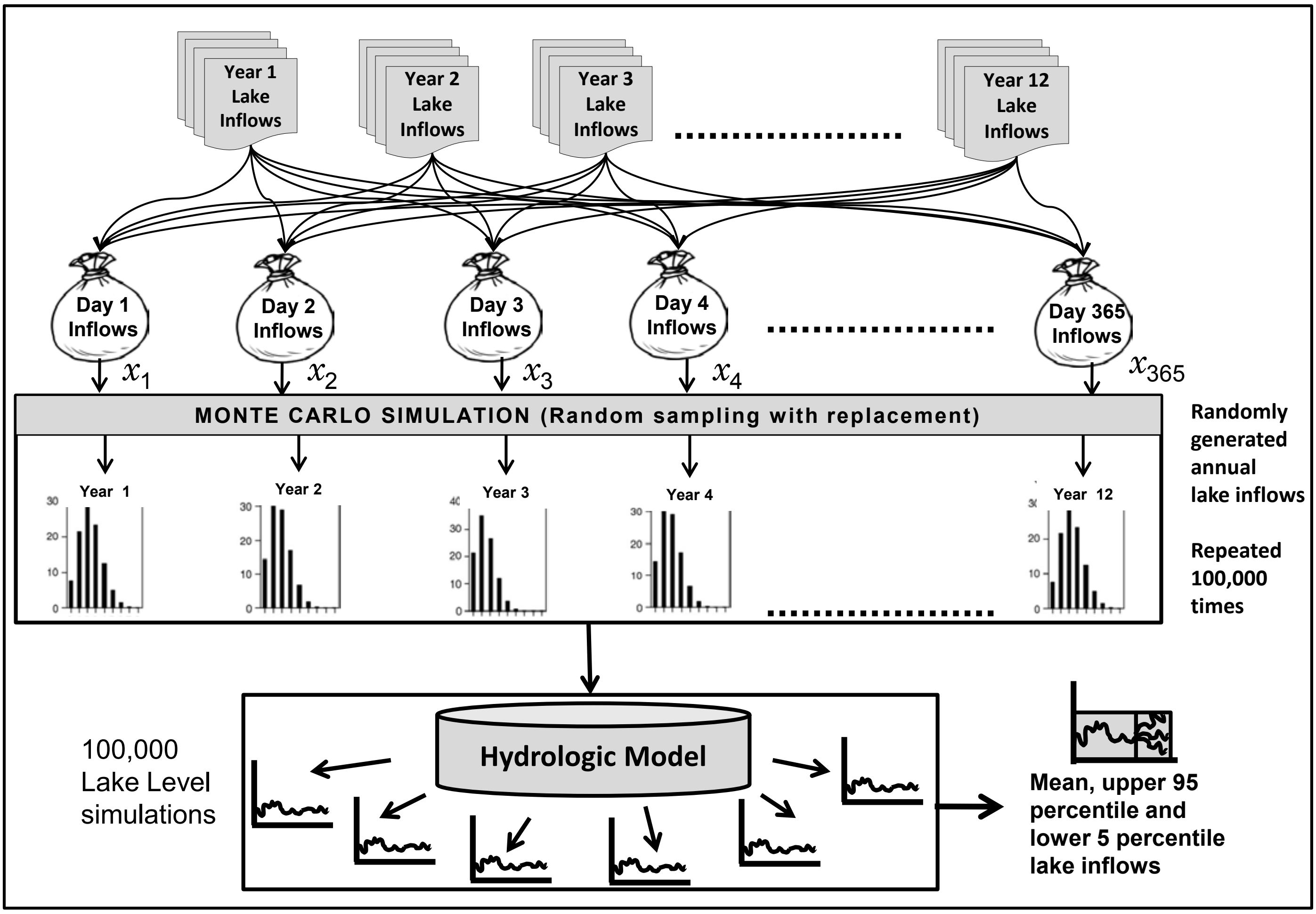


Figure 27: Schematic representation of univariate non-parametric resampling of lake inflows.

times to draw time series data of plausible future scenarios at random from the historical data (Figure 27). Using this approach, the simulated data would have the same distributional properties as historical data because the resampled scenarios representing plausible future inflow scenarios use the historical data under the assumption that the future will be similar to the past. Because observations are randomly resampled with replacements using the Monte Carlo approach, serial dependence is not preserved. However, the daily observations are bagged, values from the set of observations for that day are randomly drawn, and the seasonality and distribution of observed rainfall is preserved in this modeling technique.

First, the model was run numerous times (100 000) and lake water levels were derived for cases with and without the dam. For each scenario, this approach provided three estimates: an upper 95 per cent confidence interval (UCI), a median, and a lower 95 per cent confidence interval (LCI), where UCI can be interpreted as an above-normal rainfall scenario, the median as a scenario in which the basin receives normal rainfall and an LCI scenario that represents below-normal rainfall. An estimate of the time required for the reservoir to reach the maximum level was made. The loss in lake level during the first impoundment period in the case without the dam was also estimated. Finally, the lake level at the end of the 12-year simulation was measured in the case without the dam. Because we do not know the lake level at the time of the dam's commencement, we ran this approach for various initial lake levels from 358 to 365 m.

The results of the approach using simulated lake levels and nonparametric inflows are shown in Figure 28 and Table 10. The results indicate that the time required for the Gibe III reservoir to reach MOL is about 10 months in the median scenario. However, the reservoir would reach MOL in less than half a year with above-normal rainfall (UCI). With below-normal rainfall (LCI), it would take up to 15 months to fill the reservoir if the rainfall fails after commissioning of the dam. During initial impoundment, the lake would lose up to 1.2 m depending on rainfall conditions and the initial lake level. The loss in lake level at the end of the 12-year simulation in the scenario without the dam was found to range from 1.5 to 2.3 m (UCI), 1.2 to 2.2 m (Median), and 0.6 to 1.8 m (LCI) under the three rainfall scenarios, respectively.

These results indicate that the impact of the dam would also depend on Lake Turkana's initial water level at the time the dam begins operation. The impact at different initial lake levels was estimated by identifying the difference

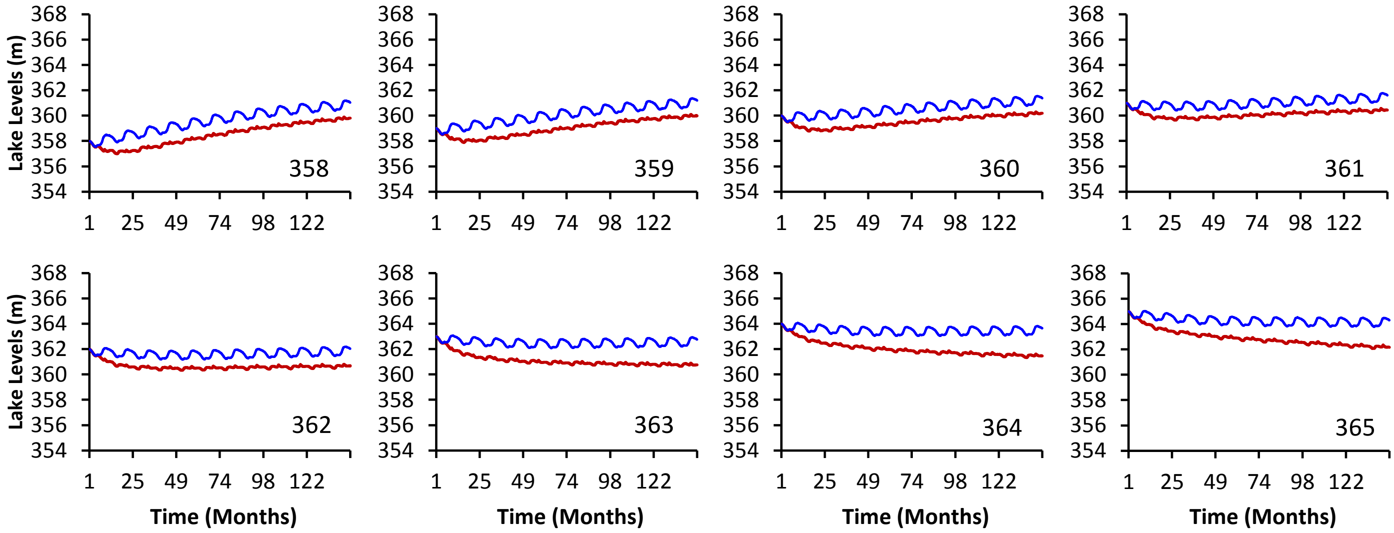


Figure 28: The impact of the Gibe III dam on Lake Turkana water levels simulated using the LLM approach and non-parametric resampled data.
Source: Velpuri and Senay (2012)
Note: The impact of the dam is simulated for each initial lake level from 358 m through 365 m asl as shown on the Y-axis. The X-axis shows Time (months after the commencement of the dam). The blue line indicates the lake level simulated without the dam and the red line indicates the lake level simulated with the dam.

between the lake levels derived without the dam and with the dam at the end of simulation period. Due to the relationship between runoff volume and surface area, our results indicate that the impact is lowest when the initial lake level is low, and it increases as the initial lake level increases (Figure 29).

The results also show another effect of the dam on the lake's water level: because of the dam, the seasonal fluctuations in lake levels over a year (up to 1.5 m) are dampened and would reduce to less than 0.5 m, because peak flows would decline while base flow would rise, resulting in an increase in summer flows in the Omo River (Figures 25, 26, and 28).

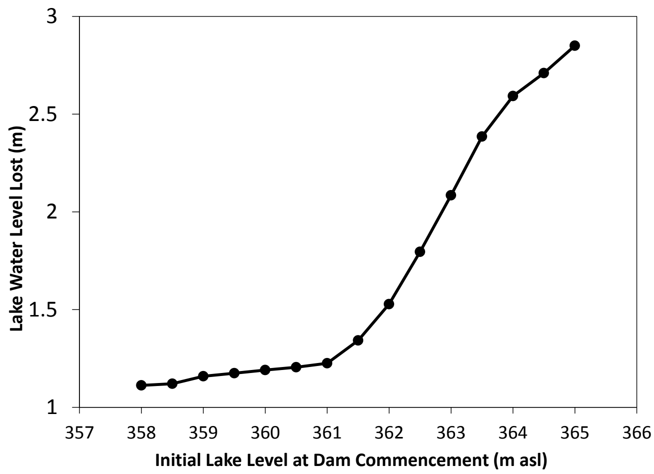


Figure 29: Impact of the Gibe III dam (difference between with and without dam) at the end of 12 yr simulation period is a function of initial lake level at the time of commencement of the dam.
Source: Velpuri and Senay (2012)

Initial Lake Level	Time to reach MOL - minimum operation level of 201 m			Loss in lake level in the case without the dam before reaching MOL of 201 m			Lake level at the end of 12-yr simulation in the case without the dam		
	[Months]			[m]			[m]		
[m]	UCI	Med	LCI	UCI	Med	LCI	UCI	Med	LCI
358	< 5	8	15	0.0	1.1	1.3	1.5	1.2	0.6
359	< 5	8	15	0.0	1.1	1.2	1.6	1.2	0.8
360	< 5	8	15	0.0	1.0	1.2	1.8	1.3	0.8
361	< 5	8	15	0.0	1.0	1.1	1.9	1.3	0.9
362	< 5	8	15	0.0	1.0	1.1	2.2	1.5	0.9
363	< 5	8	15	0.0	0.9	1.1	2.3	2.1	1.3
364	< 5	8	15	0.0	0.9	1.1	2.3	2.2	1.8
365	< 5	8	15	0.0	0.9	1.1	2.3	2.2	1.8

Table 10: Impact of the Gibe III dam on Lake Turkana water levels modeled using approach III (Nonparametric bootstrap resampling technique).
Note: UCI and LCI denote upper and lower bootstrap percentile 95 per cent confidence intervals respectively; Med represents median value.

5.6 Analysis of Shoreline Changes Using SRTM Elevation and Bathymetry Data

The overall impact of the Gibe III dam in terms of lake water levels cannot be clearly understood unless the impact of frequency, timing and duration of water-level fluctuations on the lake shoreline is known. To understand the impact of shoreline changes, we combined SRTM elevation data (outside-the-lake elevation data) with the lake's bathymetry data to generate a seamless elevation model. Using this approach, we first modeled the lake's shoreline at various elevations, ranging from a minimum lake level of 355 m to a higher lake level of 365 m, as shown in Figure 30. Outputs of this analysis are (a) the lakes' shoreline changes based on the changes in lake levels and (b) the identification of areas that are more prone to changes in lake level, or "hot spots" of change.

This analysis, however, would provide only baseline information of changes in the lake's shoreline with respect to changes in lake water levels. To evaluate the impact of a decline in lake levels due to the Gibe III dam under various rainfall conditions, we modeled the impact of changes in lake levels using three scenarios from approach II. The lake-level modeling approach was used under three different rainfall scenarios: (a) below-normal, (b) near-normal, and (c)

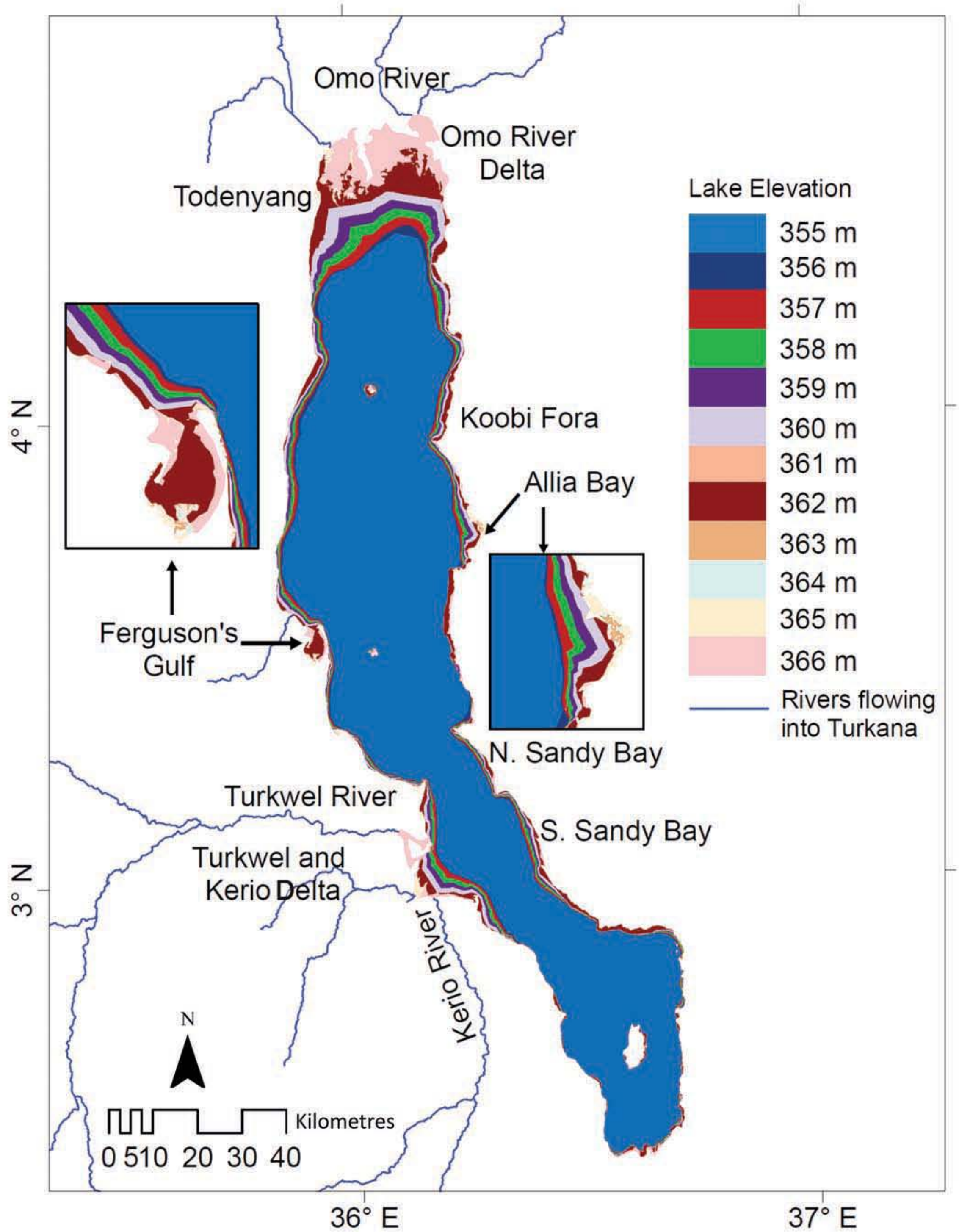


Figure 30: Changes in the Lake Turkana shoreline in relation to the depth modeled using SRTM and lake bathymetry elevation data.

Source: Velpuri and others 2012

above-normal. We recorded monthly lake levels obtained under each scenario and determined surface areas of the lake. Finally, we combined the lake's surface areas obtained for each month to understand the shoreline changes due to the fluctuation in lake level.

The model was run for a period of 12 years with three possible scenarios of rainfall, and we studied the impact of changing lake levels along the shoreline (Figure 31). The dark blue areas in the figure indicate intact regions in the lake that would have water all the time during the modeling time period. Colours other than dark blue indicate that the lake would have water for fewer months than the modeling time period. Figure 31a indicates modelling results for a below-normal rainfall scenario, where the lake would shrink up to 5 m from the initial lake level of 363 m. Results indicate that the lake would shrink along the following areas: the Omo River Delta; the Todenyang in the north; Ferguson's Gulf; the Turkwel and Kerio Deltas in the west and South and North Sandy Bays; Allia Bay; and Koobi Fora in the west. These regions would experience periodic wetting and drying of the shoreline. A total of 22 per cent of the lake-surface area (areas other than dark blue) would show wetting and drying conditions. Furthermore, due to below-normal rainfall in the basin, Ferguson's Gulf could stay dry for a longer period as lake levels would go below 362 m (Figure 31a).

The near-normal rainfall scenario (Figure 31b) shows low fluctuations in lake level. With near-normal rainfall in the basin, the lake would shrink in areas such as the Omo River Delta, Ferguson's Gulf, Turkwel and Kerio Deltas and regions south of Allia Bay and would soon recover and possibly expand in these same areas. These areas of shrinking and expansion correspond to up to 9 per cent of the total lake-surface area. Under near-normal rainfall conditions, Ferguson's Gulf would retain water for more than 10 years over the 12-year modelling period. Finally, in the above-normal rainfall scenario, the lake does not show any shrinking (Figure 31c). On the other hand, the model results indicate the lake would expand and inundate the areas of the Omo River Delta, Ferguson's Gulf, the Turkwel and Kerio Delta, Allia Bay and regions of Koobi Fora. A total of 10 per cent of the regions along the lake shoreline would show wetting and drying conditions. Future research is needed to evaluate the implications of this decrease or increase in lake level and wetting and drying conditions along the lake shoreline on the lake's fisheries, ecology and hydrology.

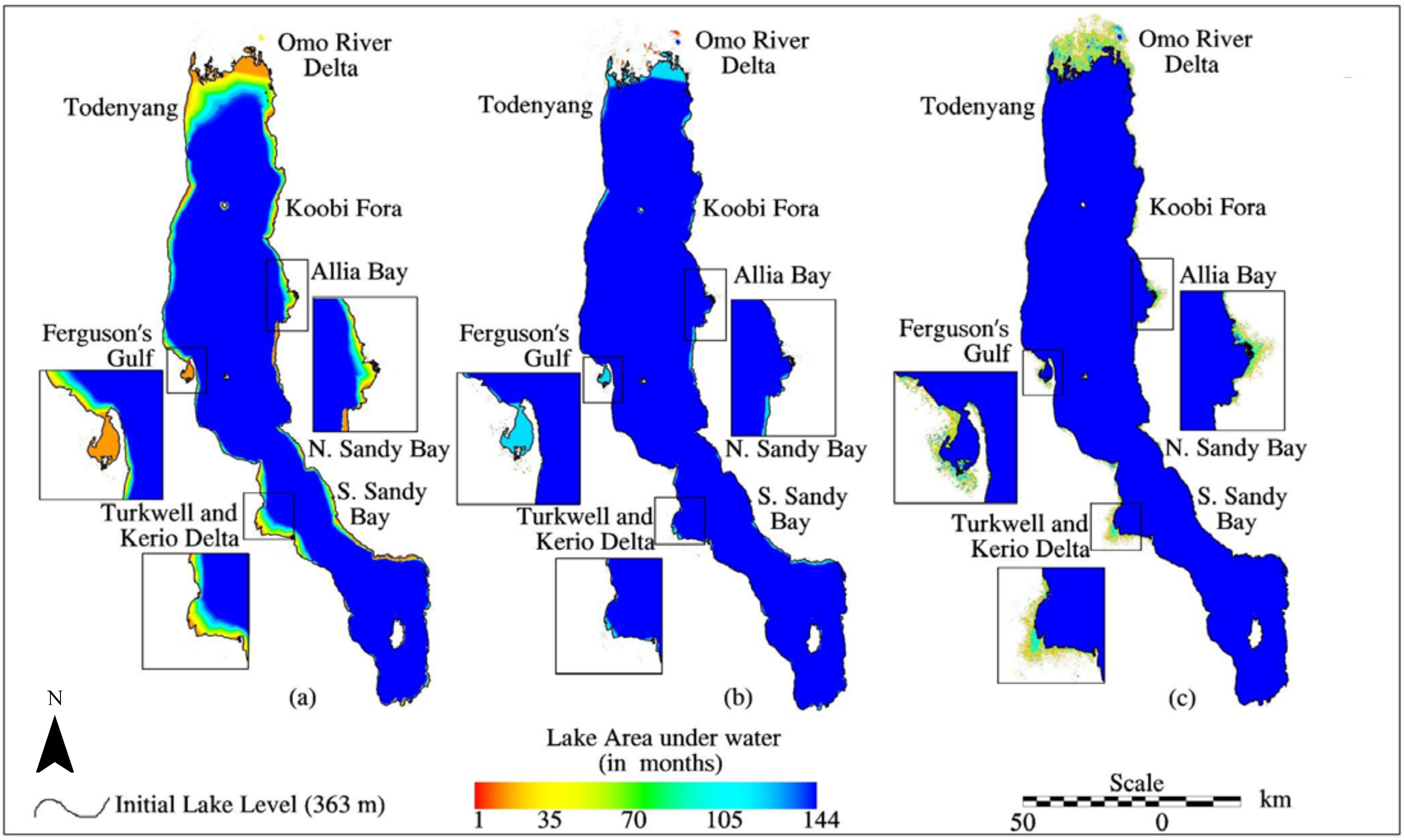


Figure 31: Impact of the Gibe III dam on Lake Turkana's shoreline simulated under three potential scenarios.

Source: Velpuri and Senay (2012)

Note: The scenarios are: (a) below-normal rainfall scenario (LCI)—the lake's shoreline shrinks inwards from the initial lake level and reaches up to 6 m; (b) average rainfall scenario (Median)—the lake's shoreline exhibits little variability from the initial lake level; and (c) above-normal rainfall scenario (UCI)—the lake's shoreline grows outwards from the initial lake level, flooding several regions along the shoreline. The colour denotes the time in months that the lake is under water.

6. CONCLUSIONS

Africa's biggest dam (by height) is under construction on the Omo River. The river contributes more than 80 per cent of inflows to Lake Turkana. However, the impact of regulated inflows to the lake and potential interactions between the Gibe III dam and Lake Turkana are not well understood due to its remote location and the dearth of reliable ground-truth datasets. The overarching goal of this study was to assess the potential hydrological impact of the Gibe III dam on Lake Turkana water levels using a calibrated water-balance model driven by satellite data for Lake Turkana. In this study, we analyzed existing data and presented a hydrologic modeling approach that uses multi-source satellite data to study the potential hydrological interactions between the Gibe III dam and Lake Turkana water levels using topo-bathymetry data, satellite-based rainfall estimates, modelled evapotranspiration (ET), runoff, and satellite altimetry data using different approaches.

Historical data indicate that there were wide fluctuations in Lake Turkana's water levels in the past. During the late 19th century, the lake's water level was about 20 m higher than the present day lake level (363 m), followed by a general decline during the first half of the 20th century. Lake levels declined to a minimum in the 1950s. There was a rapid increase in the 1960s through the 1970s and it reached a height of 366 m during late 1970s and 1980s. Most recent fluctuations show the lake has been expanding. Lake Turkana's level has seasonal variations of 1–1.5 m over a year, with a long-term natural variability of 5–10 m. The rainfall patterns over East Africa during the last few decades suggest there has been no considerable change (Cheung and others 2008). MODIS satellite land-cover data for 2001–2009 indicate that the percentage area under each class has remained almost unchanged, except for areas under grasslands, shrublands and woody savannah, which have undergone minor changes of less than 5 per cent.

We assessed the impact of the Gibe III dam on the lake's water levels with three different approaches that use existing satellite data and various future rainfall scenarios. The first approach uses the past climatic data for the period 1998–2009 and the assumption that the rainfall pattern would be same after the dam is commissioned. The results indicate that during the initial period of reservoir filling, the lake level would drop up to 2 m (95 per cent confidence interval). This result is similar to that reported by Avery (2010). We further found that the Gibe III dam would moderate water releases into the lake: inflows decrease from over 1 500 m^3/s to around 1 000 m^3/s in wet seasons, but base flow would increase in dry seasons with an all-time average flow rising to nearly 500 m^3/s.

It is not possible to predict the future climate in the lake's basin. To understand the potential climate, we used a second approach to build future rainfall scenarios based on knowledge and understanding of the frequency and distribution of rainfall over the Lake Turkana basin. The past variability in the climate provides the context under which we combined different below-normal (drier) and above-normal (wetter) rainfall years to generate 20 likely rainfall scenarios and to then assess the impacts of the dam on the lake's water levels. Based on the results from this approach, we found that the Gibe III reservoir would reach Minimum Operation Level (MOL) in 8–16 months, depending on the occurrence of rainfall under different scenarios. When compared to the lake level modeled without the dam, lake levels will remain unchanged or decline by up to 4.3 m in the below-normal rainfall scenario after the dam is commissioned. The variability in the lake levels due to regulated inflows after the dam is commissioned is found to be within the lake's natural variability.

We employed the nonparametric resampling technique using the most recent 12 years of satellite data to generate several future scenarios of climate data and to evaluate the impact of Gibe III. Results indicate that the time required for the Gibe III reservoir to reach MOL is about 10 months for the median scenario. Furthermore, results indicate that the average loss in lake levels as a result of the dam would range from 1.5 to 2.3 m Upper Confidence Interval (UCI), 1.2 to 2.2 m (median); and 0.6 to 1.8 m Lower Confidence Interval (LCI) under the three respective rainfall scenarios (Table 10). The impact of the dam would be greater when the basin receives above-normal rainfall, and the impact would be smaller when the basin receives below-normal rainfall.

In this study, we also identified hot spots along the Lake Turkana shoreline due to fluctuations in lake levels. Our shoreline-change analysis revealed that regions of the Omo River Delta in the north, Ferguson's Gulf and the Turkwel-Kerio River Delta regions in the west and Allia Bay and the Koobi Fora regions in the east are more susceptible to change. Furthermore, we found that under the below-normal rainfall scenario, the lake would shrink up to 5 m and the lake shoreline would show periodic wetting and drying in up to 20 per cent of the lake-surface area. Under the near-normal scenario, up to 9 per cent of the total lake

surface area would experience shrinking and expansion. Under the above-normal rainfall scenario, the lake would not shrink at all but would expand by up to 10 per cent of the surface area. Further analysis is needed to assess the impact of regulated Omo River flows due to the dam and potential irrigation projects on the lake's ecology and fisheries.

The use of satellite-based data for estimating runoff and evapotranspiration modeling makes the approaches used in this study consistent and robust, especially for a basin in which there is a dearth of long-term historical runoff and climate data. Results obtained from this study are thus based on observed remotely sensed data and results under different scenarios will be of great use to planners and others involved in the hydrological and environmental assessment of the dam's impacts under future climatic uncertainty.

7. REFERENCES

ARWG. (2008). Environmental and Social Impacts of the Proposed Gibe III Hydroelectric Project in Ethiopia's Lower Omo River Basin, A commentary by the African Resources Working Group.

ARWG. (2009). A Commentary on the Environmental, Socioeconomic and Human Rights Impacts of the Proposed Gibe III Dam in the Lower Omo River Basin of Southwest Ethiopia, ARWG-GIBE.org. African Resources Working Group.

Asante, K. (2000). Approaches to continental scale river flow routing, Ph.D., dissertation, University of Texas at Austin, 281.

Avery S. (2009). Assessment of hydrological impacts of Ethiopia's Omo Basin on Kenya's Lake Turkana water levels. Draft Report commissioned by the African Development Bank as part of mediation with Friends of Lake Turkana, November 2009.

Avery S. (2010). Hydrological impacts of Ethiopia's Omo basin on Kenya's Lake Turkana water levels and Fisheries, The Africa Development Bank, Tunis.

Bartle, A. (2002). Hydropower potential and development activities, Energy Policy, Volume 30, Number 14, November 2002 , pp. 1231-1239(9).

Behera, S., Luo, J., Masson, S., Delecluse, P., Gualdi, S., Navarra, A. and Yamagata, T. (2005). Paramount impact of the Indian Ocean dipole on the east African short rains: A CGCM study, Journal of Climate, 18, 4514-4530, 2005.

Birkett, C. and Mason, I. (1995). A new global lakes database for a remote sensing program studying climatically sensitive large lakes, Journal of Great Lakes Research, 21, 307-318.

Butzer, K. (1971). Recent history of an Ethiopian delta - The Omo River and the level of Lake Rudolf, Department of Geography, Research Paper No. 136, Chicago, USA: The University of Chicago Press.

Camberlin, P., Janicot, S., Poccard, I. (2001). Seasonality and atmospheric dynamics of the teleconnection between African rainfall and Tropical Ocean surface temperature: Atlantic vs. ENSO, International Journal of Climatology, 21:973–1005.

Cerling, T. (1986). A mass-balance approach to basin sedimentation: Constraints on the recent history of the Turkana basin, Palaeogeography, Palaeoclimatology, Palaeoecology, 43, 129-151.

Cheung, W, Senay G., Singh A. (2008). Trends and spatial distribution of annual and seasonal rainfall in Ethiopia, International Journal of Climatology, 28, 13, 1723-1734.

Christensen, J., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R., Kwon, W., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C., Räisänen, J., Rinke, A., Sarr, A., Whetton, P. (2007). Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Conway, D., Hanson, C., Doherty, R., Persechino, A. (2007). GCM simulations of the Indian Ocean dipole influence on East African rainfall: Present and future. Geophysical Research Letters 34, L03705.

Cretaux, J., Jelinski, W., Calmant, S., Kouraev, A., Vuglinski, V., Berge-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., Maisongrante, P.(2011). SOLS: A lake database to monitor in the Near Real Time water level and storage variations from remote sensing data, Adv. Space Res., 47, 1497–1507, 2011.

Dinku, T., Chidzambwa, S., Ceccato, P., Connor, S., Ropelewski C. (2008). Validation of high resolution satellite rainfall products over complex terrain, International Journal of Remote Sensing, 29: 14, 4097 – 4110.

EEPCo. (1995). Gilgel Gibe Hydroelectric Project, Hydrological Report, undertaken for the Ministry of Mines and Energy - Ethiopian Electric Light and Power Authority. Ethiopian Electric Power Corporation.

EEPCo. (2004). Gilgel Gibe Hydroelectric power plant Information booklet, pp. 28, 2004. Ethiopian Electric Power Corporation.

EEPCo. (2007) Gibe III reservoir seepage risk analysis, SDP07-22-2-RGL3. Ethiopian Electric Power Corporation.

EEPCo. (2008). Maps of Lower Omo River Basin, 500-ENVDAG001A. Ethiopian Electric Power Corporation.

EEPCo. (2009a). CESI S.p.A and Mid-Day International, Gibe III Hydroelectric Project, Environmental and Social Impact Assessment, 300 ENV RC 002C. Ethiopian Electric Power Corporation.

EEPCo. (2009b). Agriconsulting S.p.A and Mid-Day International, 2009b. Gibe III Environmental Impact Assessment, Additional Study of Downstream Impacts, 300 ENV R AG 003B. Ethiopian Electric Power Corporation.

Efron, B., and Tibshirani, R. (1993). An Introduction to the bootstrap, Chapman and Hill, New York.

FAO (1995). Digital Soil Map of the World Version 3.5 (CD-ROM), Food and Agriculture Organization of the United Nations, Rome.

Farr, T. and Kobrick, M. (2000). Shuttle Radar Topography Mission produces a wealth of data, EOS Transactions. AGU, 81, 583-585.

FoLT. (2009). Comments of Draft Hydrological Report on Lake Turkana prepared by Dr. Sean Avery on behalf of AfDB. Friends of Lake Turkana.

Friedl, M., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X. (2010). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sensing of Environment, 114, 168_182.

Funk, C., Dettinger, M., Michealsen, J., Verdin, J., Brown, M., Barlow, M., Hoell, A. (2008). Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development, PNAS, 105, 32, 11081-11086.

Gilgel Gibe Affair. (2008). An Analysis of the Gilgel Gibe hydroelectric projects in Ethiopia, Counterbalance. Challenging the EIB, CEE Bankwatch Network, Online publication: http://www.crbm.org/modules.php?name=downloadandf=visitandlid=216.

Hansen, M., Defries, R., Townshend, J., Carrol, M., Dimiceli, C., Sohlberg, A. (2003). Global percent tree cover at a spatial resolution of 500 meters: first results of the MODIS VCF algorithm, Earth Interactions, 7, 1-15.

Hathaway, T. (2010). Fighting for Lake Turkana, Why Kenyan communities are resisting Gibe III Dam? International Rivers, Accessede online on January 24, 2012 at www.internationalrivers.org/files/LakeTurkanaTripReport0610.pdf

Herman, A., Kumar, V. , Arkin, P., Kousky, J. (1997). Objectively Determined 10-Day African Rainfall Estimates Created for Famine Early Warning Systems, International Journal of Remote Sensing, Vol. 18, 2147-2159.

ICOLD. (1998). World Register of Dams 1998. Paris, France: International Commission on Large Dams.

Kallqvist, T., Lien, L., Liti, D. (1998). Lake Turkana Limnological Study 1985 – 1988. Norwegian Institute of Water Resources, Report no. 0-85313, 98 p.

Kolding, J. (1992). A summary of Lake Turkana: an ever-changing mixed environment, Mitt. Int. Verein. Limnol. 23 25-35.

Lahiri, S. (2003). Resampling methods for dependent data, Springer series in Statistics, Springer-Verlag, New York.

Moges, S., Alemu, Y., Mcfeeters, S. (2010). Flooding in Ethiopia: Recent history and 2006 flood: Implications for the Nile Basin, Eds. Kloos, H.,Legesse, W., Cambria Press, NY, 285-305, 2010.

Olivera, F., Flamiglietti, J., Asante, K. (2000). Global scale flow routing using a source-to-sink algorithm, Water Resources Research, 36, 8, 2197-2207.

Rajagopalan, B., Lall, U., Tarboton, D., Bowles, D. (1997). Multivariate non-parametric resampling scheme for generation of daily weather variables. Stoch. Hydrol. Hydraul., 11, 65–93.

Ricketts, R. and Johnson, T. (1996). Climate change in the Turkana basin as deduced from a 4000 year long δO18 record. Earth and Planetary Science Letters, Vol. 142, 7-17.

Rodriguez, E., Morris, C., Belz, J., Chapin, E., Martin, J., Daffer, W., Hensley, S. (2005). An Assessment of the SRTM Topographic Products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 p.

Salini Constructions. (2010). Gibe III impact on Turkana lake levels, EEPCo Gibe III Hydroelectric project presentation, Luxembourg, 10th March 2010.

Senay, G. and Verdin, J. (2003). Characterization of yield reduction in Ethiopia using a GIS-based crop water balance model, Canadian Journal of Remote Sensing, 6, 687-692.

Senay, G. , Budde, M., Verdin, J., and Melesse, A. (2007). A coupled remote sensing and SSEB approach to estimate actual evapotranspiration from irrigated fields, Sensors, 7, 979-1000.

Senay, G., Verdin, J., Lietzow, R., Melesse, M. (2008). Global daily reference evapotranspiration modeling and evaluation, Journal of American Water Resources Association, 44, 969-979.

Senay, G. (2008). Modeling landscape evapotranspiration by integrating land surface phenology and water balance algorithm, Algorithms, 1, 52-68.

Senay, G., Asante, K., Artan, G. (2009). Water balance dynamics in the Nile basin, Hydrological Processes, 23, 3675-3681, 2009.

Sharma, A. and Lall, U. (1997). A nearest neighbour conditional bootstrap for resampling daily rainfall. 24th Hydrology and Water Resources Symposium, The Institution of Engineers, Australia, 439–444.

Shongwe, M., Van Oldenborgh, G., Van Den Hurk, J. (2009). Projected Changes in Mean and Extreme Precipitation in Africa under Global Warming, Part I: Southern Africa, J. Climate, 22, 3819–3837.

Srikanthan, R. and McMohan, T. (2001). Stochastic generation of annual, monthly and daily climate data: A review, Hydrology and Earth System Sciences, 5(4), 653-670.

The Gilgel Gibe Affair. (2008). An independent study about the Gilgel Gibe hydroelectric projects in Ethiopia – How states and corporations make business using the international public money, Publication of European Union.

The Economist. (2010). Tap that water- controversy surrounds the argument for dam-building in Africa. Online resource: http://www.economist.com/node/16068950/ (last accessed Feb 07, 2012).

Tucker, C., Pinzon, J., Brown, M., Slayback, D., Pak, E., Mahoney, R., Vermont, E., Nazmi, El.-S. (2005). An Extended AVHRR 8-km NDVI Data Set Compatible with MODIS and SPOT Vegetation NDVI Data. Intl. Jour. of Remote Sensing 14: 4485–4498, 2005.

USGS. (2008). Opening the Landsat Archive, USGS Newsletter. US Geological Survey. Web publication: http://pubs.usgs.gov/fs/2008/3091/pdf/fs2008-3091.pdf (last accessed: Jan 20, 2012)

Velpuri, N., Senay G., Asante, K. (2012). A Multi-Source Satellite Data Approach for Modelling Lake Turkana Water Level: Calibration and Validation using Satellite Altimetry Data. Hydrology and Earth System Science (HESS), Vol. 16, 1-18.

Velpuri, N.M., and Senay, G.B. (2012). Assessing the potential hydrological impact of the Gibe III Dam on Lake Turkana water level using multi-source satellite data. Hydrology and Earth System Sciences, 16, 3561-3578.

WCD. (2000). Dams and Development – A new framework for decision making, the report of the World Commission on Dams, Earthscan Publication Ltd, London and Sterling, VA.

WEC. (2004). Survey of Energy Resources, Elsevier, Oxford, 2004. World Energy Council.

WFP. (2000). Kenya's drought: No sign of any let up, World Food Program, Rome, Italy. Accessed online on November 09 2011 at http://reliefweb.int/node/70268,

Xie, P. and Arkin, P. (1996). Analysis of Global Monthly Precipitation Using Gauge Observations, Satellite Estimates, and Numeric al Mod el Prediction, Journal of Climate, Vol. 9, 840-858.

Xu, H. (2006). Modification of normalized difference water index (NDWI) to enhance open water features in remotely sensed imagery. International Journal of Remote Sensing, 27:14, 3025 -3033.

Yuretich, R. (1979). Modern sediments and sedimentary processes in Lake Rudolf (Lake Turkana) eastern Rift Valley, Kenya. Sedimentology, Vol. 26, 313-331.

ACRONYMS

AfDB	Africa Development Bank
ARWG	Africa Resources Working Group
asl	above sea level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
DEM	Digital Elevation Model
EEPCo	Ethiopian Electric Power Corporation
ENSO	El Niño Southern Oscillation
ET	Evapotranspiration
Eta	Actual Evapotranspiration
Eto	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FEWS NET	Famine Early Warning Systems Network
FoLT	Friends of Lake Turkana
GCM	Global Climate Models
GDAS	Global Data Assimilation System
GDEM	Global Digital Elevation Map
GIS	Geographic Information System
GWh	Gigawatt Hour
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
KMFRI	Kenya Marine Fisheries Research Institute
kWh	Kilowatt Hour
LCI	Lower Confidence Interval
LLM	Lake Level Model
LSP	Land Surface Phenology
MMD	Multi-Model Data
MOL	Minimum Operation Level
MW	Mega Watt
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NOAA CPC	National Oceanic and Atmospheric Administration Climate Prediction Center
RFE	Rainfall Estimate
SRTM	Shuttle Radar Topography Mission
SST	Sea Surface Temperature
TOPEX	Topography Experiment
TWh	Total Watts hour
UCI	Upper Confidence Interval
UNEP	United Nations Environment Programme
USAID	United States Agency for International Development
USGS	United States Geological Survey
WCD	World Commission of Dams
WHC	Water Holding Capacity
w.r.t	with respect to

www.unep.org

United Nations Environment Programme
P.O. Box 30552 - 00100 Nairobi, Kenya
Tel.: +254 20 762 1234
Fax: +254 20 762 3927
e-mail: uneppub@unep.org
www.unep.org

UNEP