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UNEP-DHI CENTRE

Support to Sustainable Development in Lake Turkana and its River Basins

Results of Modelling of Future Scenarios of Lake Turkana and its River Basins

Technical report

February, 2021

EXECUTIVE SUMMARY

Introduction

As part of the tripartite project, including the Federal Democratic Republic of Ethiopia, the Republic of Kenya and the United Nations Environment Programme (UNEP), on ‘Support to Sustainable Development in Lake Turkana and its River Basins’ which is being carried out by the UNEP-DHI Centre on Water and Environment.

The project is co-funded by the European Union Emergency Trust Fund for Africa, through its project on "Support for Effective Cooperation and Coordination of Cross-border Initiatives in Southwest Ethiopia-Northwest Kenya, Marsabit-Borana & Dawa, and Kenya-Somalia-Ethiopia (SECCCI)”. The overall SECCCI objective is to ensure the effective cooperation and coordination of cross border initiatives. The specific objectives of the project ‘Support to Sustainable Development in Lake Turkana and its River Basins’ are the following:

- Establishing a common scientific understanding of the Lake and its River Basins
- Set up a monitoring system for Lake Turkana and its River Basins
- Capacity building in Transboundary Water Management (TWM) and transboundary dialogue activities to build trust, confidence, cooperation and a shared vision
- Implementing pilot demonstrations for ecosystems rehabilitation.

Conclusions

Simulations for the next 20 years predict that climate change may result in a marked increase in inflow to Lake Turkana, primarily from the Omo River, but also increased inflow from Kerio and Turkwel rivers. Such a possible increase in inflow will result in an increasing water level in Lake Turkana. Thus, the flooding which occurred in year 2020, which was considered a rare event, is likely to be become more regular in the future without any adaptation measures. The new evidence of continuing rising lake water levels is partially based on climate change scenarios and a predicted change in rainfall patterns due to climate change. These climate change projections, however, are associated with a degree of uncertainty.

Mutual gains for both basin countries can be achieved if the basin countries develop an arrangement for water cooperation. Possible transboundary mutual gains between Climate Change (CC), Water Resources Developments (WRD) and Rehabilitation and Adaption Measures (RAM) have been identified:

- Increased irrigation and other abstractions within the basin may help to counterbalance increasing water levels in Lake Turkana due to climate change. Impacts of irrigation on water quality have not been factored in the model. Irrigation will need to be properly managed to avoid negative effects on water quality, such as agricultural nonpoint source pollution.
- Likewise, reforestation and soil and water conservation measures may also help to counterbalance the impact of climate change. However, the effect of

increasing water use will be relatively stronger, due to increased evaporation and less runoff from steep headwater catchments.

- It will be possible to partly reproduce the seasonality in inflow to Lake Turkana to maintain fish production and at the same time maintain the same Total Hydropower Production in the Ethiopian part of the basin.

- A cooperation framework should be established to guide planning and development efforts at the basin scale. The project deliverable “Draft Framework on Transboundary Water Management” addresses this.

- Soil and water conservation and reforestation measures will significantly help reducing the risk of landslides and mudflows as experienced in West Pokot County, Kenya. It is considered that both countries will benefit from when implementing these measures. The benefits will mainly be onsite benefits and will particularly ensure a more efficient and, not least, more sustainable crop production and conversion from other land uses to cultivation.

- From a global perspective reforestation and agroforestry may also help fighting global warming and help restoring habitat loss.

- Agroforestry will have two additional advantages: Intercropping crops with leguminous N_2-fixing agroforestry species e.g. Acacia and Caleandra, can help replenish nitrogen harvested with crops and thereby maintain the N-balance and reduce the need for artificial fertilizers. Fodder trees can also be an important feed source for livestock and reduce livestock pressure on grassland.

Indicator Framework

An attempt was made to establish a framework that covered all relevant sectors namely: Agriculture, Economy, Energy, Environment, Fishery, Social Welfare, Water Resources and Water Supply & Sanitation. Efforts to collect field data were carried out in the Kenyan part of the basin, to enable the conceptualization and calculation of indicators specific to the project scope and area. These efforts resulted in the calculation of the following indicators:

- Annual lake water level fluctuations
- Fish production indicators
- Households with farm holdings
- Labour division indicator
- Net Present Value for hydropower
- Net Present Value for irrigation
- Percent of years where water levels result in severe inundation
- Salinity indicator
- Settlements affected by inundation

This framework was used in the Planning application to facilitate the evaluation of each scenario as well as comparison of impacts across scenarios and the prioritization exercise using the MCDA method.

Scenario Modelling

The impacts of each scenario are presented and discussed in detail. The indicator framework is used for this purpose primarily. Additional model results are used as well to complement the discussion. For each scenario, the discussion of impacts is organized per relevant sector. A summary of the key results is presented next.

Scenario WRD 1 – Baseline by 2025

WRD 1 is the baseline scenario including hydropower and irrigation developments that are expected to be developed by the year 2025.

Ethiopia has the largest energy production from hydropower accounting for 98 percent of the total hydropower production in the basin. The effect of the reservoirs on low flows into lake Turkana will be less pronounced than immediately downstream of Gibe III due to catchment flow entering the Omo river from tributaries further downstream, but they will nevertheless have an impact on the seasonal variation of the lake water level.

Water use from irrigation has a significant impact on average and minimum stream flows downstream of the irrigated areas. The sugar cane plantation at Kuraz accounts for most of the water use due to its size. Here annual average water use is estimated to be 21.9 m^3/s corresponding to 3.9 percent of the stream flow upstream of Kuraz. During dry periods this increases to around 12 percent for minimum flows (Q98). For comparison: annual average water use at the second largest irrigation scheme Gibe Valley is 0.02 m^3/s.

Scenario WRD 2 – Full Development by 2040

WRD 2 contains planned investments in hydropower, irrigation and domestic water supply before 2040, according to the current national strategies consulted during this project.

The planned investments in the two new hydropower plants will lead to an increase in total annual average hydropower production of 2442 GWh corresponding to a percentage increase of 16.6 compared to the baseline. Most of the increase is from the Gibe V hydropower plant in Ethiopia, which accounts for 94 percent of the total increase.

The reservoir and hydropower plant operation will affect the stream flow hydrology downstream of the dams. In general, the total flow volumes are not affected or only affected to a small degree. However, reservoir operation has an impact on the flow regime by increasing low flows and reducing peak flows. Minimum flow defined as the 98th flow percentile increases from 236 m^3/s to 272 m^3/s downstream of Gibe V, an increase of 14 percent. Average flows are reduced slightly both downstream of Gibe V, and downstream of Arror in the Kerio river, not due to the hydropower plants, but due to an increase in domestic water use in WRD 2.

Water use due to increased irrigation results in a significant impact on average and minimum stream flows, particularly downstream of Kuraz reservoir. Average stream flow will reduce by 5.3 percent from 509 to 482 m^3/s. The irrigation scheme at Arror in Kenya will only have a minimal impact on flows with a reduction in average flows downstream in the upper Kerio catchment of 0.4 percent. This reduction also includes the effect of urban supply upstream in the Kerio catchment.

Lake water inflows and water levels will be impacted by the planned investments, mainly by the increased irrigation at Kuraz and by Gibe V. The increases in domestic water supply and the hydropower plant scheme at Arror, which includes irrigation, will only have a minimal impact on inflows to the Lake. Water levels in the lake are reduced by around 1 meter at the end of the model period compared to the baseline.

Based on water level alone fish catch per boat will be reduced from 10 tonnes in WRD 1 to 7 tonnes. However, higher annual water level fluctuations result in longer periods of optimal conditions for fishing which could be beneficial for fish production.

The scenario results of RAM2 are associated with a substantial margin of error.

Scenario RAM 1 – Natural Flow Conditions

The purpose of this scenario is to regenerate some of the mechanisms of natural inflow to Lake Turkana while still maintaining sufficient hydropower production upstream. The natural flow data available and the flow in WRD 1 were analysed to create an inflow requirement which partly mimics the natural flow variations.

The mean annual water levels of Lake Turkana for WRD 1, RAM 2 and natural flow conditions are shown in Figure 0.1. The water level of 362 m.a.s.l is a critical water level for the lake as Ferguson's Gulf dries out below this level. This is one of the major breeding grounds for fish and thus has a great importance for fish production in the lake. The average annual water level is below this value only in 3 instances for the natural flow, while this number is 10 for both WRD 1 and RAM 1.

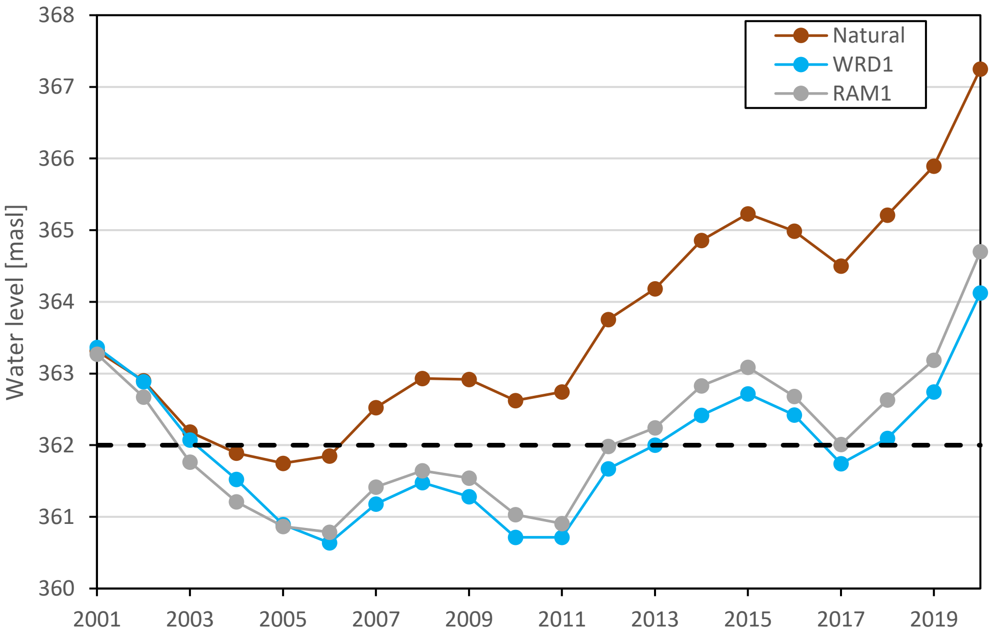

Figure 0.1 Mean annual water level in Lake Turkana. The black line indicates the water level 362 m.a.s.l. which is a critical water level for fish production in the lake.

RAM1 generally causes larger water level fluctuations than WRD 1 although they are not as high in the natural flow. There are several years where the natural water level fluctuations are within the 1-1.5 m range that is optimal for fish production, but RAM1 is rarely in this range. However, there is a clear improvement over WRD 1. The fish catch per boat, calculated based on water levels, has increased by 1 tonne on average.

Total hydropower production from Gibe III and Koysha increases by 2% from WRD1 to RAM1. However, while WRD1 has a continuous production over the year and higher production in the wet months, RAM 1 has a more gradual variation over the year. Even though the total production for RAM1 is slightly higher than in WRD1, there would be requirements for alternative power sources in Ethiopia during the dry months while it should be ensured that power is not wasted in the wet season.

To improve these results, stronger measures would be necessary. Increasing the water level would be challenging as this requires less water to be taken out of the system. This could primarily be accomplished by reducing the area of the Kuraz Sugar Plantation. It is possible that more optimal fluctuations could be achieved with the current system, but that would come at the cost of a further reduction of hydropower in the dry season and thus of firm power production. Depending on the size of the flows in the wet season, it is possible that these would exceed capacity, leading to spilling without production.

Scenario RAM 2 – Reforestation, Soil and Water Conservation

The purpose of this scenario is to assess how reforestation, agroforestry, and soil and water conservation measures may reduce flooding, soil erosion, and landslides.

The likely effect of the simulated soil conservation measures is a considerable reduction in overland flow. This along with reforestation will increase evaporation which is why groundwater recharge is not proportionally higher in the middle plot in Figure 4.26, only slightly. In turn, total runoff is reduced due to increased evaporation.

This scenario aims at alleviating landslide issues, with reforestation and soil and water conservation. Absolute values for indicators, will depend on the given conditions in the catchment such as: slopes, rainfall regime, soil types, etc. A better land cover and better root network will reduce soil erosion and stabilize the slopes to reduce the risks of landslides.

Scenario RAM 3 – Enforcing Land and Riparian Legislation

The purpose of this scenario is to reduce the risk of damage due to Lake Turkana water level rise by enforcing riparian land legislation which prohibits building of permanent structures and waste disposal within 30m horizontal distance or 2m vertical height of the highest recorded water level.

The maximum water level in Lake Turkana from the model output (in WRD1) is 364 m.a.s.l which is well below the demarcation of riparian land defined as below 368.8 m.a.s.l. In RAM 3, construction of buildings is prohibited below 368.8 m.a.s.l.. Therefore in RAM 3 no settlements are inundated by the rising water levels of Lake Turkana compared to eight settlements inundated in WRD1 on the west side of the lake around the Gulf of Ferguson and on the shoreline near Kerio and Eliye springs.

The maximum water level in Lake Turkana across all scenarios is in scenario CC 2 (extreme radiation forcing scenario RCP 8.5) where the water level reaches 367 m.a.s.l.. This maximum water level is still below the riparian land demarcation level of 368.8 m.a.s.l... Therefore, if the riparian land enforcement rehabilitation measure from RAM3 is applied, there would be no inundated settlements across all future scenarios.

Scenario RAM 4 – Transfer to Lake Logipi

This scenario is based on WRD1 and includes construction of an outlet from Lake Turkana to nearby Lake Logipi to make it possible to discharge water from Lake Turkana to Lake Logipi in years with high water levels. Water is discharged from Lake Turkana when the water level is 364 m.a.s.l. or above and transferred to Lake Logipi.

The purpose of this scenario is to control flooding due to rising lake water levels by constructing an outlet from Lake Turkana to nearby Lake Logipi when the water level is 364 m.a.s.l.. In the indicators and results we have only looked at the impact of this rehabilitation measure on Lake Turkana and the surrounding settlements. We have not assessed the impact on Lake Logipi which could be significant given the ecological importance of the lake, for example to Flamingoes that frequently inhabit the saline waters feeding on cyanobacteria and other plankton (Mathea, 2009). An assessment of the construction, operation and maintenance costs of building the infrastructure to deliver water from Lake Turkana to Lake Logipi has not been included.

In RAM 4 only 4 settlements are inundated on the west side of the lake in the Gulf of Ferguson and on the lake shoreline near Kerio. In contrast, in WRD1 8 settlements are inundated with lake water levels reaching over 364 m.a.s.l.. These settlements are on the west side of the lake around the Ferguson's Gulf and on the shoreline near Kerio and Eliye Springs. In CC2 28 settlements are inundated (with lake water levels reaching over 367 m.a.s.l) mostly on the west side of the Lake. In WRD1 water levels exceed 364 m.a.s.l. only in the last two years of simulation, therefore the percentage of years with water levels above 364 m.a.s.l. resulting in severe inundation is 10% in WRD1 but 0% in RAM4. In contrast, in CC2 the percentage of years with severe inundation is 40% but this would be reduced to 0% if the rehabilitation measures from RAM4 were applied.

Scenarios CC 1 & CC 2 – Climate Change RCPs 4.5 and 8.5

The two climate change scenarios are based on RAM1, but with all evaporation and rainfall time series replaced with ones that are adjusted to fit the climate change projections RCP 4.5 (CC1) and RCP 8.5 (CC2).

The inflow from the Omo River to Lake Turkana increases with climate change, by 7% in CC 1 and 11% in CC 2. Climate change clearly has a significant impact on the water levels, which rise in both scenarios. At the end of the modelling period, the water level in CC 1 is 2.1 m higher than in RAM 1, and the difference is 2.7 m for CC2. The change in inundated settlements is dramatic, rising from 8 inundated settlements in RAM 1 to 20 in CC 1 and 28 in CC 2. This clearly shows that significant negative impacts due to flooding can be expected in the future and that the events seen in 2020 may become more common.

Fish production as a function of water level increases from an average of 11 tonnes/boat/year to 14 tonnes in CC 1 and 15 tonnes in CC 2. The percentage of the period where the fluctuations are too low with respect to fish production decreases from 80% in RAM1 to 70% in CC 1 and further to 65% in CC 2. The percentage of years with optimal fluctuations increases accordingly. The largest fluctuation in the modelling period is just below 2.5 m, which is still much lower than fluctuations of 4 m which are assessed to be detrimental.

Power production falls in all the Ethiopian hydropower plants, while it increases for Turkwel in Kenya. The largest relative reduction happens for Gibe II, where production decreases by 13.1% and 18.1% in CC1 and CC2, respectively. The smallest decrease happens for Koysha, where it is only around 1%. In all cases, the effects of climate change (increase/decrease) are largest in CC2, with the exception of Koysha where the difference between the two is very small. The total power production in the basin drops by 5.1% and 7.2% in CC1 and CC2, respectively.

It seems counterintuitive that the lake inflow from the Omo River increases while power production in Ethiopia decreases. The explanation can be found in the distribution of the climate change factors for rainfall. While rainfall is set to increase in most of the basin, there are decreases in the northern parts which is where most of the water in the upstream part of the Omo River is generated. Major increases in rainfall happen downstream of Gibe III and especially Koysha, thus explaining the increased inflow to the lake.

Modelling of Key Basin Issues

The impact of the different scenarios on selected key issues are compared and discussed with focus on rehabilitation measures and climate change. To this end the Key Result and Trade-off plots from the Planning App were used.

Impact on Lake Turkana Water Level

For RAM 2, RAM 3 and RAM 4 the mean annual water level is almost identical to WRD1. Although the main focus for RAM1 is to increase the annual fluctuations in the lake, it also results in a slight accumulated increase in the water level of 0.58 m as compared to WRD1. WRD 2 scenario, results in a substantial decrease in the lake water level as the accumulated difference over the simulation period is about 1.16 m compared to WRD1. As a result, the mean annual water level is below the critical 362 m.a.s.l. for all simulation years except three. On the other hand, the water level does not exceed 364 m.a.s.l. during the simulation period.

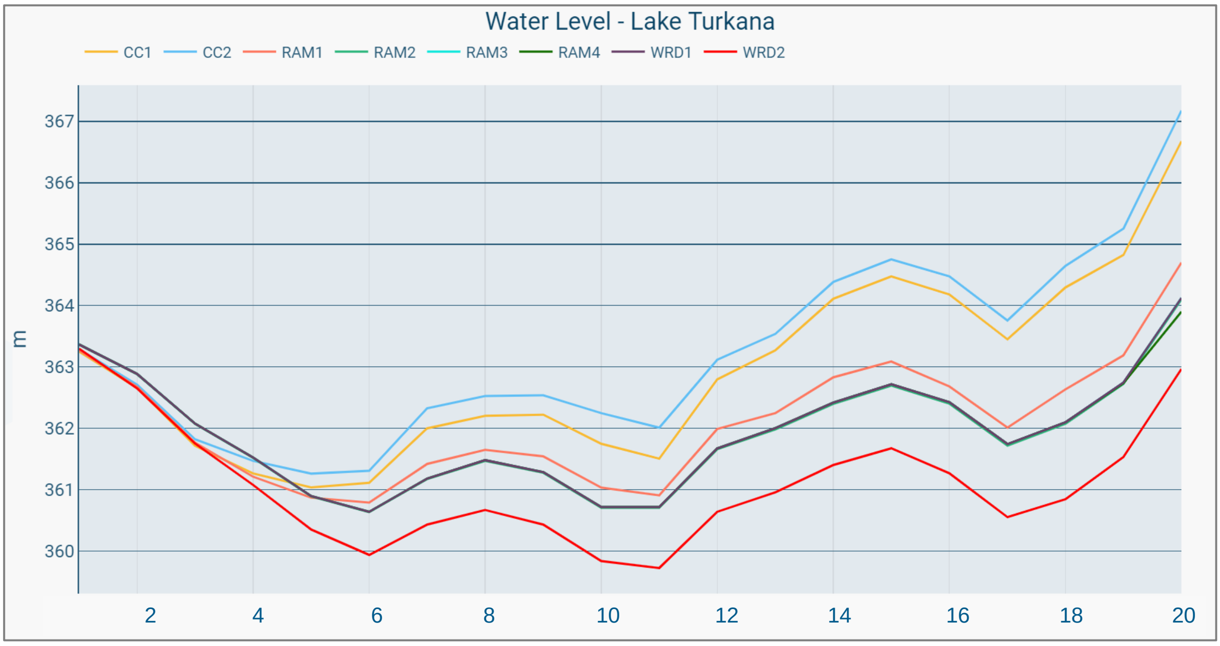

Figure 0.2 Variation in mean annual water level (m.a.s.l.) in Lake Turkana for all scenarios during the whole modelling period. Note that results for WRD1, RAM2, RAM3 and RAM4 overlap.

Both climate change scenarios result in a marked increase in the water levels in Lake Turkana. The accumulated water level difference over the simulation period is 1.98 and 2.48 m higher for CC 1 and CC 2, respectively, than for RAM 1 used as baseline. Thus, the mean annual water level is above 362 m.a.s.l. for most of the years. On the other hand, there is a substantial number of years where the water level is above 364 m.a.s.l., where severe flooding of settlements will start to occur.

Impact on Annual Water Level Fluctuations of Lake Turkana

It has been shown in scenario RAM 1 that it is possible to increase the annual water level fluctuations from 0.72 to 0.89 m as illustrated in the figure below. Though not optimal (1-1.5 m) it is a considerable improvement. It has also been shown that at the same time it has been possible to maintain and even slightly increase the total hydropower production. The firm power[1] production logically has decreased due to the introduced seasonality, so a larger part of the total hydropower production is secondary power[2].

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[1] Mean annual firm energy production from hydropower plants, corresponding to energy production, which can be delivered 90% of the time.

[2] Mean annual firm energy production from hydropower plants, corresponding to energy production, which can be delivered 90% of the time.

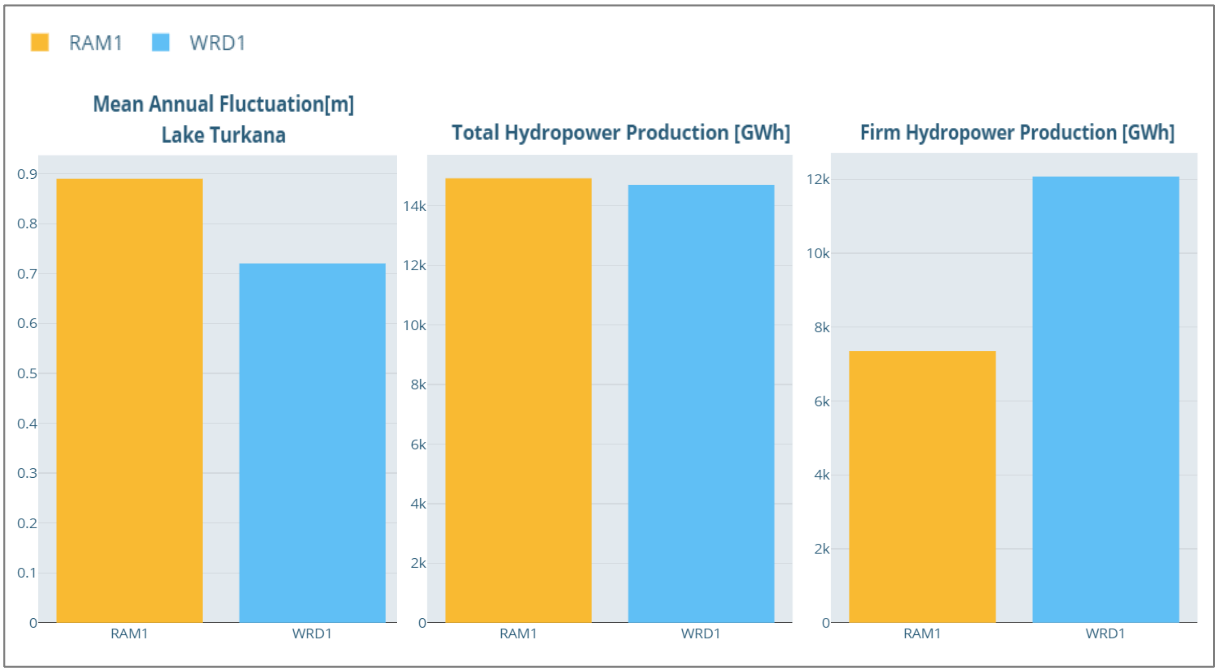

Figure 0.3 Impact of RAM1 on Mean Annual water level Fluctuations in Lake Turkana, Total and Firm Hydropower Production in the basin. It has been possible to increase fluctuations and maintain the total hydropower production.

Hydropower Production

The impact of the different scenarios on the hydropower production is summarized in Table 0.1. RAM2, RAM3, and RAM4 are all unchanged from WRD1 as no changes have been made to affect the reservoirs in these scenarios. A significant increase in hydropower production happens from WRD1 to WRD2 due to the introduction of two new reservoirs / hydropower plants, namely Gibe V in Ethiopia and Arror in Kenya.

Table 0.1 Total, firm, and secondary hydropower production (GWh/year) in the basin for all eight scenarios.

	WRD1	**WRD2**	**RAM1**	**RAM2**	**RAM3**	**RAM4**	**CC1**	**CC2**
Total Hydropower Production	14,702	17,144	14,925	14,702	14,702	14,702	14,165	13,844
Firm Hydropower Production	12,076	13,848	7,353	12,076	12,076	12,076	7,011	6,914
Secondary Hydropower Production	2,626	3,296	7,573	2,626	2,626	2,626	7,154	6,930

For RAM1, the total hydropower production is nearly unchanged and in fact slightly increased compared to WRD1. The introduced seasonality in the hydropower production inevitably has resulted in a decrease in firm power, so a larger portion of the total power production is secondary power. However, if connected to an energy grid with other energy sources, the hydropower production may be supplemented by the other sources during the dry season when less hydropower is produced. In this case the decrease in firm power may not be critical and this provides an opportunity for restoring some fluctuations in the lake while still meeting Ethiopia's energy needs.

For the climate change scenarios, the total hydropower production in the basin decreases by 3.7% for CC1 and 5.8% for CC2 when comparing to WRD1. There is an increase in production in Kenya, and reduction solely happens in Ethiopia, due to reduced runoff from the northern parts of the basin. Although climate change projections are uncertain, it is a potential issue of concern for Ethiopia that their hydropower schemes may generate less output in the future.

Fishery

The values of the fishery indicators are summarized in Table 0.2. RAM2, RAM3, and RAM4 are all unchanged from WRD1. WRD2 has a small positive impact on the water level fluctuations, with one year (5% of the simulation period) moving from too small to optimal. However, the falling water levels have a negative impact on fishery and the water level-based indicator decreases from WRD1 to WRD2.

The climate change scenarios both have an apparent positive impact on the two types of fish production indicators. A conflict exists because as the increasing water levels and fluctuations present better conditions for fishery, flood risk also increases. It is likely that the people dependent on a high fish production are the same people who have settled close to the lake and are therefore affected by flooding.

Table 0.2 Fishery indicators for all scenarios. Small fluctuations are below 1 m, optimal are 1-1.5 m, neutral are above 1.5 m and below 4 m, and too large are 4 m and above.

	WRD1 (RAM2, RAM3, RAM4)	**WRD2**	**RAM1**	**CC1**	**CC2**
Years with too small fluctuations [%]	85	80	80	70	65
Years with optimal fluctuations [%]	10	15	10	20	25
Years with neutral fluctuations [%]	5	5	10	10	10
Years with too large fluctuations [%]	0	0	0	0	0
Fish catch from water level [tons/boat]	10	7	11	14	15

Crop Production

The yearly production of maize and sugar cane production per country is shown in Table 0.3 for all scenarios. WRD2 shows the largest change due to a new irrigation scheme, Arror in Kenya, growing maize and an expansion of the Kuraz Sugar Cane Plantation. RAM1 result in a marginal decrease of maize in Ethiopia but is otherwise unchanged. RAM2 show a small reduction of maize in Kenya. Maize in both countries decreases slightly for the climate change scenarios. None of these changes, with the exception of WRD2, are significant.

Table 0.3 Production of maize and sugar cane (tonnes) in Kenya and Ethiopia in all scenarios.

	WRD1 (RAM3, RAM4)	**WRD2**	**RAM1**	**RAM2**	**CC1**	**CC2**
Maize - Ethiopia	50,872	50,872	50,767	50,872	50,779	50,758
Maize - Kenya	46,858	48,500	46,858	46,828	46,831	46,772
Sugar cane - Kuraz (Ethiopia)	3,953,191	5,847,916	3,953,191	3,953,191	3,953,191	3,953,191

Lake Turkana Flooding and Possible Adaptation Measures

WRD 1, RAM 1, RAM 2 and RAM 3 all experience severe water levels (i.e., larger than 364 m.a.s.l.) 10% of years, the number of settlements which may be inundated at least once during the entire simulation period is 8, expect for RAM 3 which is 0. For both WRD 2 and RAM 4 the percentage of years with severe water levels is zero, yet for different reasons. In WRD 2 the increased abstraction results in a considerable reduction of the water level in the lake. In RAM 4 water is discharge to Lake Logipi when reaching 364 m.a.s.l., therefore, the water level does not exceed 364 m.a.s.l..

Climate change will likely have a negative impact on the same population due to the significant increase in ‘Percentage of years with Severe Water Levels’ indicator. As a result, there will be a considerably increased risk of flooding with more settlements around the lake being inundated if no adaptation measures are implemented. Severe abrupt flooding like the one in 2020, has been relatively rare, yet climate change projections foresee that this may become a more regular, if no adaptation measures are put in place.

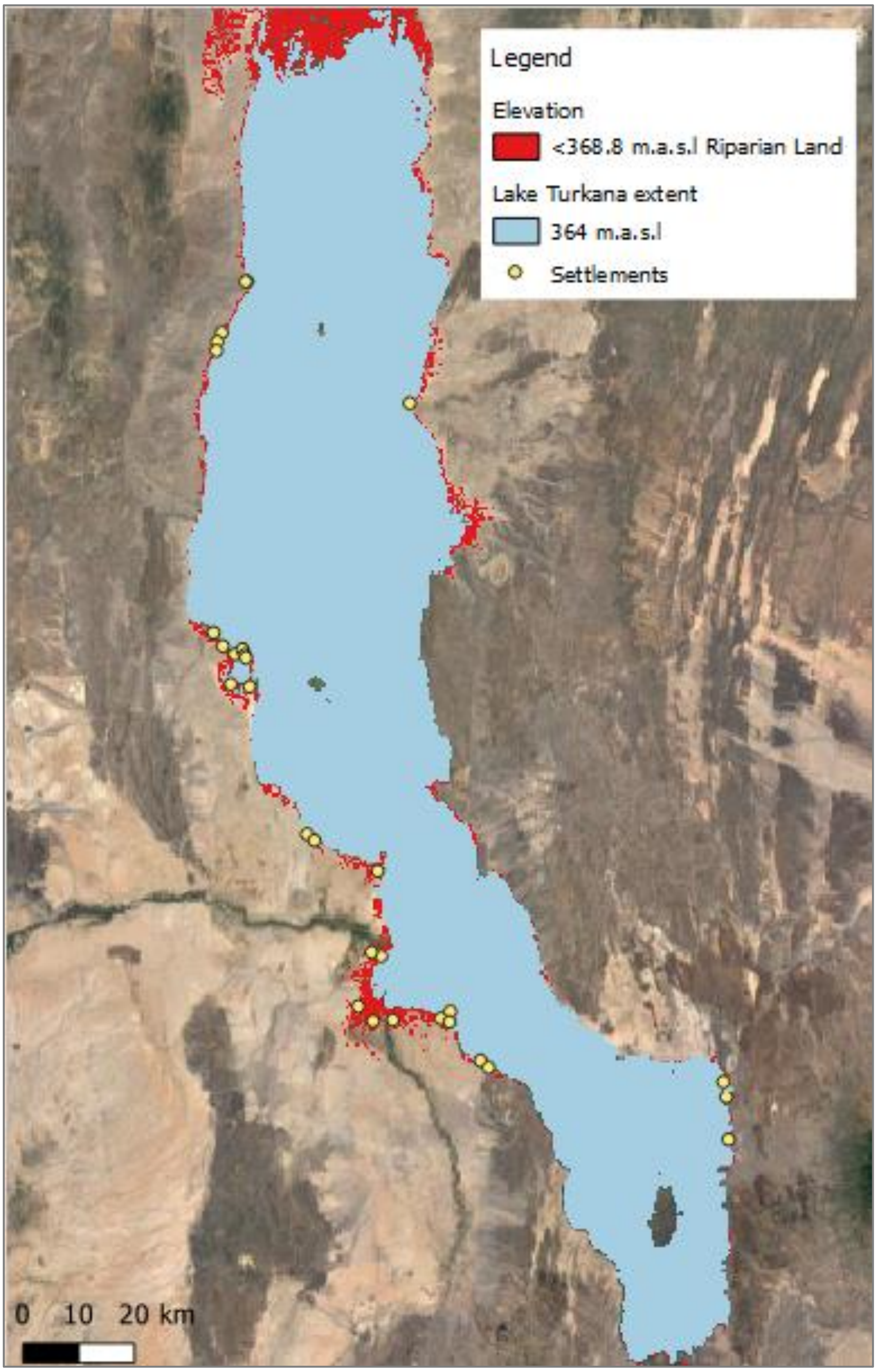

Figure 0.4 Riparian land demarcation (red) and Lake Turkana water level 364 m.a.s.l. (blue) with existing location of settlements.

An alternative solution to the flood adaptation measures of RAM 3 and RAM 4 to address the projected increased inflow to the lake, could be to abstract more water in the upstream catchments, both the Kenyan as well as the Ethiopian parts of the basin. This situation has potential mutual gains whereby Ethiopia could abstract more water to increase their agricultural production and at the same time help avoid flooding in Kenya around Lake Turkana.

Limitations and uncertainties

It is important to note that the models used for this study, while checked and calibrated to the best extent possible, have some limitations and uncertainties. Most importantly, there has been a lack of data for e.g. river discharge, reservoir management, properties of current and planned investments, fish production, etc. The climate change scenarios are also based on assumptions about future global greenhouse gas emissions and their impact on regional climatic patterns, known as the cascade of uncertainty in climate change projections.

For this reason, as comprehensive as the study has been at the basin and transboundary level, the conclusions presented should be taken as an indication of the impact of different measures. In future studies, exact values of hydropower production or lake water level should be used to illustrate the order of magnitude of values and trends. More accurate data on irrigation and livestock water use can also reduce uncertainty. Future work on climate change projections work should focus on clustering a large number of climate change scenarios with statistical analysis of likelihood of and confidence in the different scenarios.

CONTENTS

FIGURES

TABLES

UNITS

GWh	Gigawatt hours
m	Metres
m^3/s	Cubic metres per second
MAM	March – April – May
m.a.s.l.	Metres above sea level
Mm^3	Million Cubic metres
MW	Megawatts
USD	United States Dollar

ACRONYMS

CC	Climate Change
CORDEX	Coordinated Regional Climate Downscaling Experiment
DEM	Digital Elevation Model
DJF	December – January – February
DS	Downstream
ESS	Ecosystem Services
EEPCo	Ethiopian Electric Power Corporation
Eo	Evaporation from open water
EU	European Union
FAO	Food and Agriculture Organization
GIS	Geographic Information System
HH	Households
IWMI	International Water Management Institute
JJA	June – July – August
KSDP	Kuraz Sugar Development Project
KMFRI	Kenya Marine and Fisheries Research Institute
LAV	Level Area Volume
MCDA	Multi-Criteria Decision Analysis
NAM	Rainfall-Runoff Modelling
NPV	Net Present Value
P	Precipitation
PET	Potential Evapotranspiration
Q_{ET}	Lake inflow from Ethiopia
Q_{KE}	Lake inflow from Kenya
RAM	Rehabilitation and Adaptation Measures
RCP	Representative Concentration Pathway
S	Storage
SECCCI	Support for Effective Cooperation and Coordination of Cross-Border Initiatives
SON	September – October – November
TWM	Transboundary Water Management
TMO	Transboundary Monitoring Observatory

UNECE	United Nations Economic Commission
UNEP	United Nations Environment Programme
US	Upstream
USGS	United States Geological Survey
WL	Water Level
WLF	Water Level Fluctuations
WRD	Water Resources Development

1 Introduction

1.1 Project Background

As part of the tripartite project, between the Federal Democratic Republic of Ethiopia, the Republic of Kenya and the United Nations Environment Programme (UNEP), on ‘Support to Sustainable Development in Lake Turkana and its River Basins’ is being carried out by the UNEP-DHI Centre on Water and Environment. The project is co-funded by the European Union Emergency Trust Fund for Africa, through its project on "Support for Effective Cooperation and Coordination of Cross-border Initiatives in Southwest Ethiopia-Northwest Kenya, Marsabit-Borana & Dawa, and Kenya-Somalia-Ethiopia (SECCCI)”. The overall SECCCI objective is to ensure the effective cooperation and coordination of cross border initiatives.

The specific objectives of the project ‘Support to Sustainable Development in Lake Turkana and its River Basins’ are the following:

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Set up a monitoring system for Lake Turkana and its River Basins

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Implementing pilot demonstrations for ecosystems rehabilitation.

1.2 Purpose of this Report

This report is the final deliverable of ‘Activity 3B – Planning pilot rehabilitation projects’, generated under ‘Sub activity 3B.4 Reporting’. This report builds on the identification of environmental degradation hotspots areas documented in ‘ESS Hotspot Identification and Baseline Model report’ (UNEP-DHI, 2020c) and the conceptualization and detailed description of the scenarios documented in ‘Scenarios, Rehabilitation Measures and Indicator Framework report’ (UNEP-DHI, 2020d). The latter consisted in the selection of possible rehabilitation measures, the establishment of scenarios to be modelled as well as an indicator framework and the setup of the Planning application of the Transboundary Monitoring Observatory portal.

Hence, this report documents the work carried out under Activity 3B, where the Planning application of the Transboundary Monitoring Observatory is applied to support planning decisions with regards to rehabilitation and adaptation measures.

The remainder of this report is structured in the following way:

- Chapter 2 – description of the methodology applied
- Chapter 3 – description of the indicator framework
- Chapter 4 – results from scenario modelling
- Chapter 5 –comparison of the scenarios for Lake Turkana and its River Basins
- Chapter 6 – conclusions
- Chapter 8 – list of references.

2 Methodology

Support to planning decisions with regards to rehabilitation measures is based on providing stakeholders with means to analyze the trade-offs between the selected project scenarios, and the application of the Multi-Criteria Decision Analysis method.

The project scenarios, described in detail in the ‘Scenarios, Rehabilitation Measures and Indicator Framework’ report, consist of a combination of Water Resources Developments (WRD), Climate Change projections (CC) and Rehabilitation and Adaptation Measures (RAM). The interdependencies between scenarios are summarized in Table 2.1.

The Planning application of the TMO[3] is at the core of the methodology consisting of four main steps:

1. Extraction of the results, calculation of indicators and upload to the Planning app
2. Comparison of indicators across scenarios using tables and maps to analyse the impacts
3. Use of the MCDA method to explore the trade-offs between scenarios and possibly reveal conditions where mutual gains for the basin countries could be achieved
4. Workshop where stakeholders apply the Planning app to understand the scenarios, the indicators and discuss which are the most preferred alternatives

Table 2.1 Summary of the project scenarios consisting of a combination of water resources development (WRD), rehabilitation and adaption measures (RAM) and climate change projections (CC).

ID		S0	S1	S2	S3	S4	S5	S6	S7	S8
	Water Resources Development									
WRD 0	Present situation	X								
WRD 1	Planned Development by 2025		X		X	X	X	X		
WRD 2	Full development of Planned Hydropower and Irrigation in the Basin by 2040			X						
	Rehabilitation and Adaptation Measures									
RAM 1	Creating natural flow conditions				X				X	X
RAM 2	Reforestation and soil and water conservation					X				
RAM 3	Enforcing Riparian Land Legislation						X			
RAM 4	Transfer to Lake Logipi flood retention basin							X		
	Climate Change Projections									
CC 1	Near Future (2030-2050), RCP 4.5								X	

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[3] The planning application can be accessed at www.omoturkana-tmo.org

ID		S0	S1	S2	S3	S4	S5	S6	S7	S8
CC 2	Near Future (2030-2050), RCP 8.5									X

2.1 Calculation and Upload of Indicators

To evaluate the impacts of the scenarios an indicator framework was proposed by the project team and discussed with the stakeholders.

An attempt was made to establish a framework that covered all relevant sectors namely: Agriculture, Economy, Energy, Environment, Fishery, Social Welfare, Water Resources and Water Supply & Sanitation.

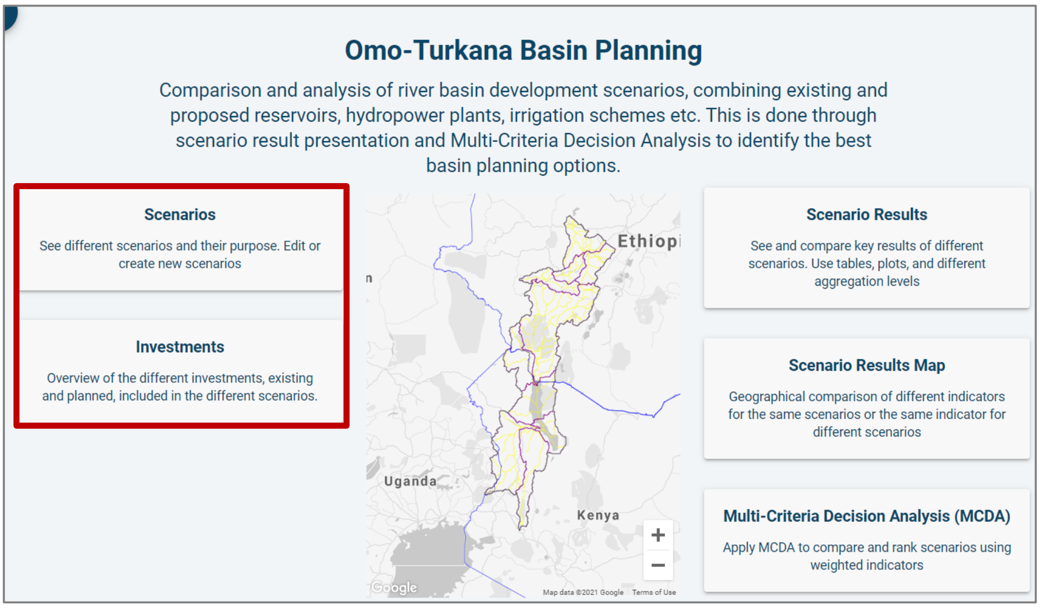
Efforts to collect field data were carried out, mainly in the Kenyan part of the basin, to enable the conceptualization and calculation of relevant indicators. These efforts resulted in the calculation of the following:

- Annual lake water level fluctuations
- Fish production indicators
- Households with farm holdings
- Labour division indicator
- Net Present Value for hydropower
- Net Present Value for irrigation
- Percent of years where water levels result in severe inundation
- Salinity indicator
- Settlements affected by inundation

Chapter 3 presents in detail all indicators used and how they are calculated, whereas chapter 4 presents the results from the scenario modelling providing a detailed description of the scenarios themselves and the indicators their results inform.

2.2 Comparison of Scenarios in the Planning Application

The Planning application of the TMO portal (landing page shown in Figure 2.1) was set up to include all project scenarios, existing and planned investments (shown in Figure 2.2), aggregation levels and the indicator results for each scenario uploaded.



Omo-Turkana Basin Planning

Comparison and analysis of river basin development scenarios, combining existing and proposed reservoirs, hydropower plants, irrigation schemes etc. This is done through scenario result presentation and Multi-Criteria Decision Analysis to identify the best basin planning options.

Scenarios

See different scenarios and their purpose. Edit or create new scenarios

Investments

Overview of the different investments, existing and planned, included in the different scenarios.

Scenario Results

See and compare key results of different scenarios. Use tables, plots, and different aggregation levels

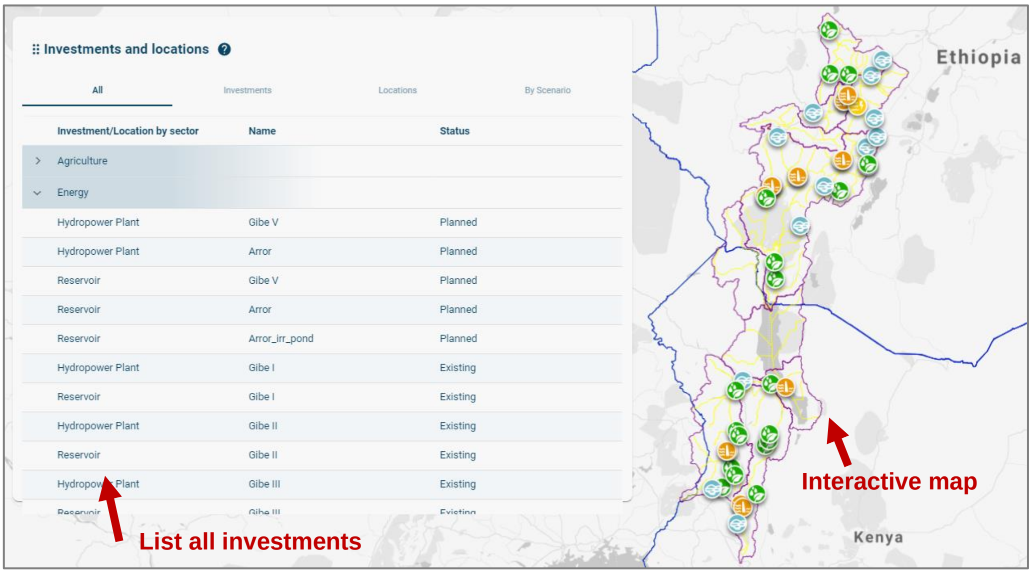
Scenario Results Map

Geographical comparison of different indicators for the same scenarios or the same indicator for different scenarios

Multi-Criteria Decision Analysis (MCDA)

Apply MCDA to compare and rank scenarios using weighted indicators

Figure 2.1 Landing page of the Planning application and functionality for setup of scenarios and investments highlighted in red.



Investments and locations

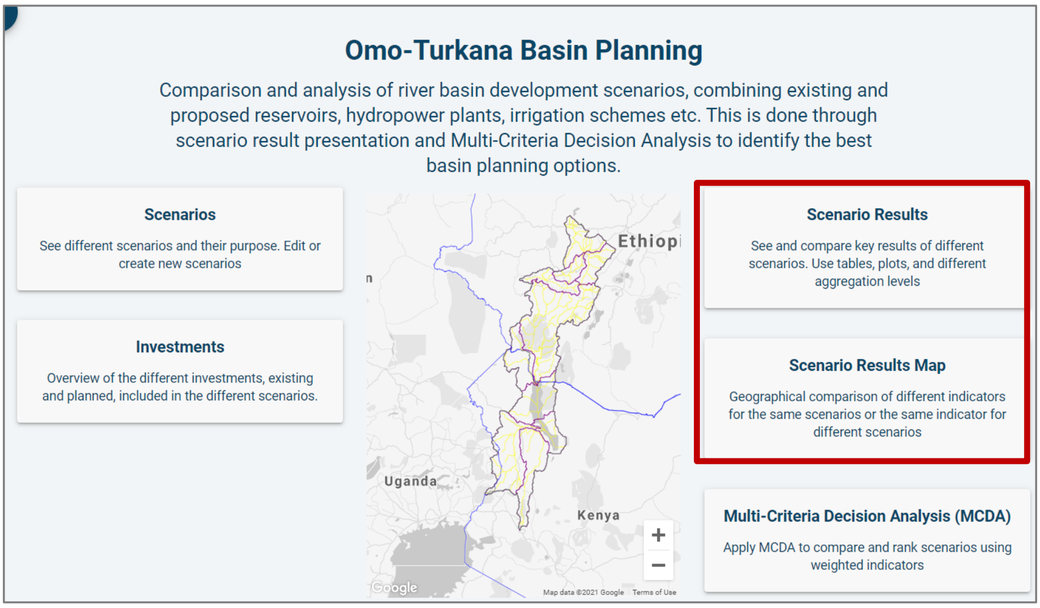
Investment/Location by sector	Name	Status
Agriculture		
Energy		
Hydropower Plant	Gibe V	Planned
Hydropower Plant	Arror	Planned
Reservoir	Gibe V	Planned
Reservoir	Arror	Planned
Reservoir	Arror_irr_pond	Planned
Hydropower Plant	Gibe I	Existing
Reservoir	Gibe I	Existing
Hydropower Plant	Gibe II	Existing
Reservoir	Gibe II	Existing
Hydropower Plant	Gibe III	Existing
Reservoir	Gibe III	Existing

Interactive map

List all investments

Figure 2.2 ‘Existing’ and ‘Planned’ investments in the Planning application.

To understand the indicators and compare the performance of the scenarios, individually and collectively, the Planning app provides the ‘Scenario Results’ functionality, a table where the decision-maker can view all indicator results for all sectors. In addition, there is also the ‘Scenario Results Map’ functionality, a graphical tool that allows the user to compare all possible combinations of scenarios, indicators, and aggregation levels (see Figure 2.3).



Omo-Turkana Basin Planning

Comparison and analysis of river basin development scenarios, combining existing and proposed reservoirs, hydropower plants, irrigation schemes etc. This is done through scenario result presentation and Multi-Criteria Decision Analysis to identify the best basin planning options.

Scenarios

See different scenarios and their purpose. Edit or create new scenarios

Investments

Overview of the different investments, existing and planned, included in the different scenarios.

Scenario Results

See and compare key results of different scenarios. Use tables, plots, and different aggregation levels

Scenario Results Map

Geographical comparison of different indicators for the same scenarios or the same indicator for different scenarios

Multi-Criteria Decision Analysis (MCDA)

Apply MCDA to compare and rank scenarios using weighted indicators

Figure 2.3 Scenario results comparison functionality within the Planning application.

These functionalities allow the decision-maker to visualize and analyze the results. This means that it is possible for example, to investigate the effects of building new hydropower sites and reservoirs in the basin, namely Arror in Kenya and Gibe V in Ethiopia, by assessing the indicators for scenario WRD 2. In parallel, by adding the baseline scenario WRD1, it is possible to investigate across scenarios the impact of these measures. As illustrated in Figure 2.4, the two maps show the Total Hydropower Production (GWh/year) at hydropower sites. WRD 1 scenario includes 5 hydropower stations, while WRD 2 scenario includes an additional 2. Another example of an energy sector indicator is shown in Figure 2.5.

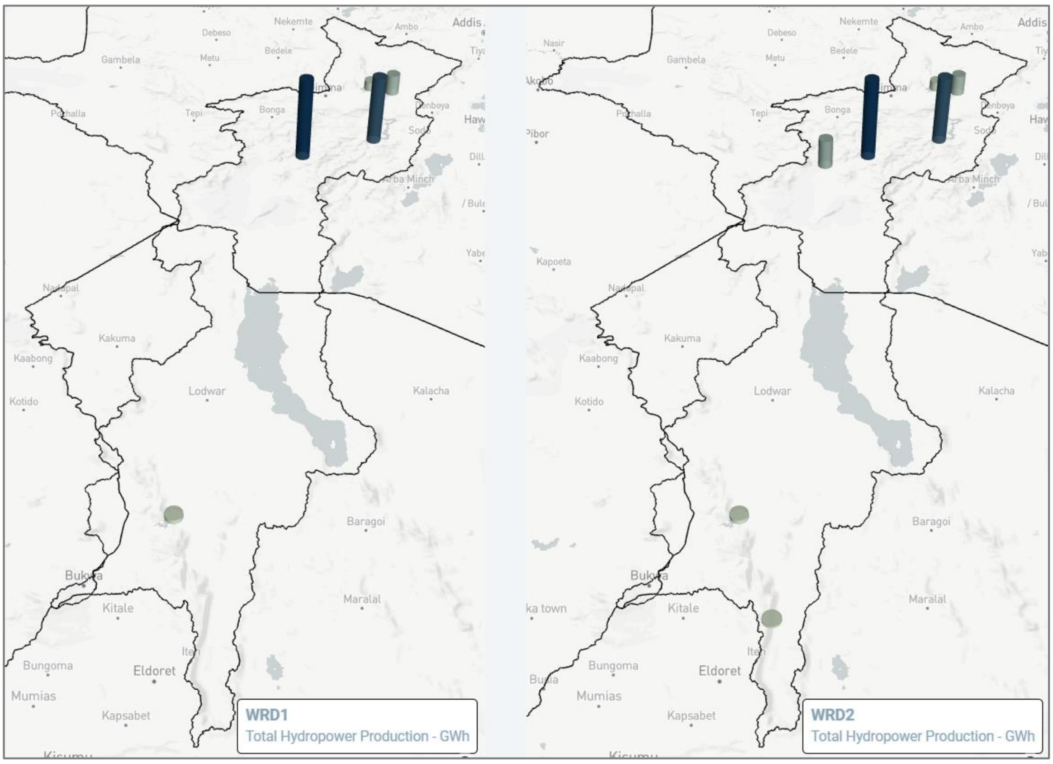
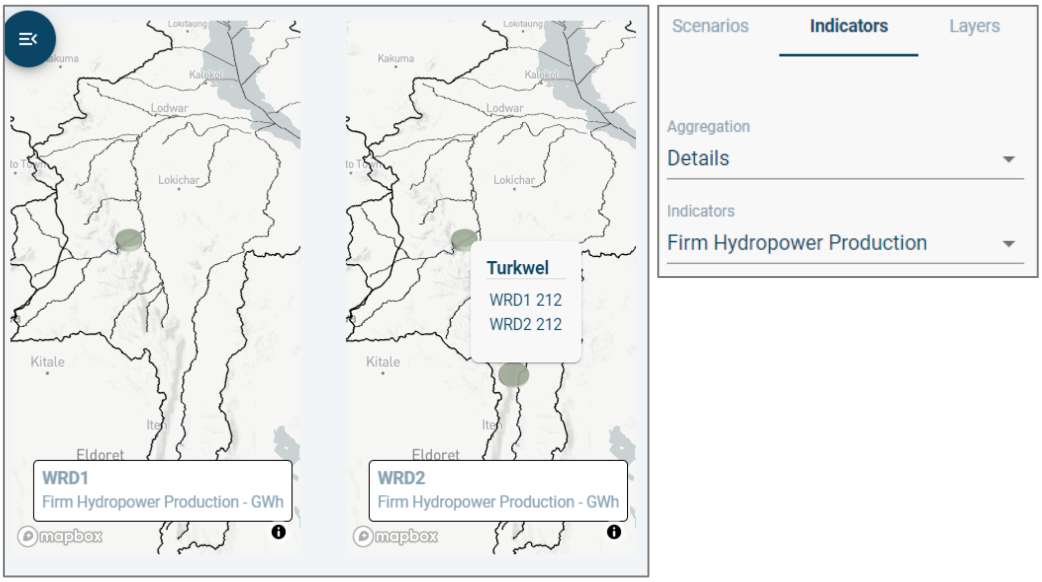


Figure 2.4 Comparison of scenarios WRD 1 (baseline) and WRD 2 (full development) using the Total Hydropower Production (GWh per year) indicator using the ‘Scenario Results Map’ functionality.



Turkwel
WRD1 212
WRD2 212

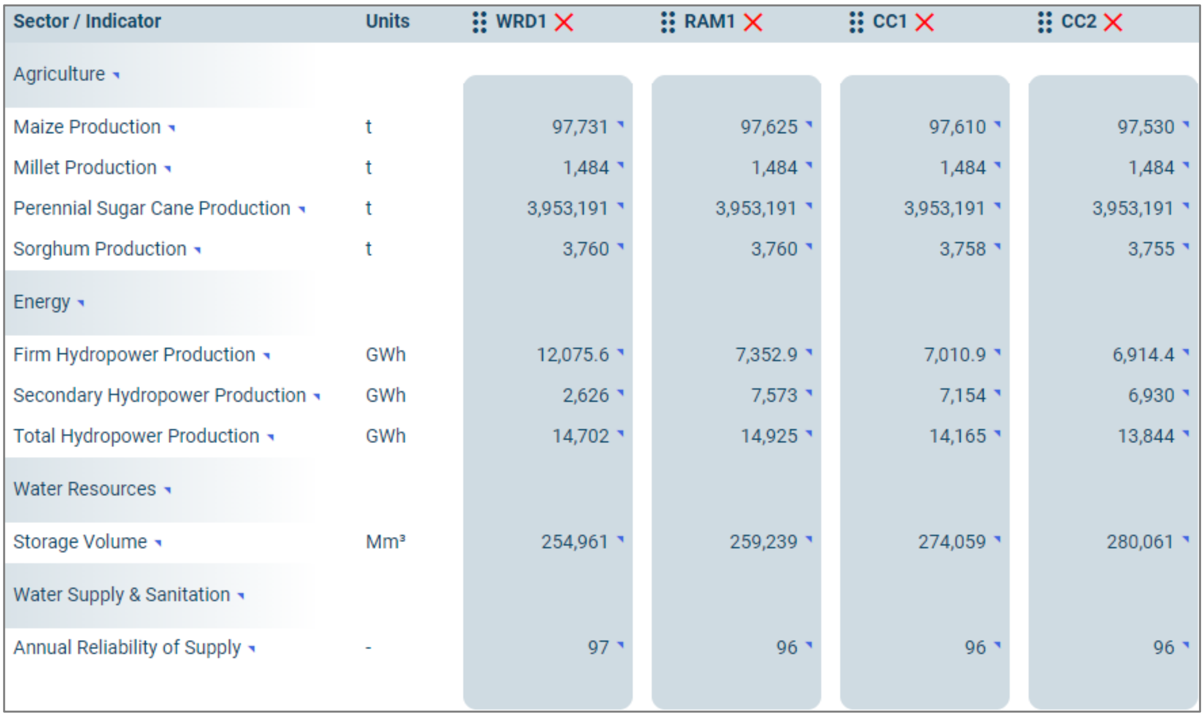
Aggregation
Details

Indicators
Firm Hydropower Production

Figure 2.5 Comparison of scenarios WRD 1 (baseline) and WRD 2 (full development) using the Firm Hydropower Production (GWh per year) indicator, when hovering over the location of the Turkwel hydropower plant the label displays the indicator result for both scenarios.

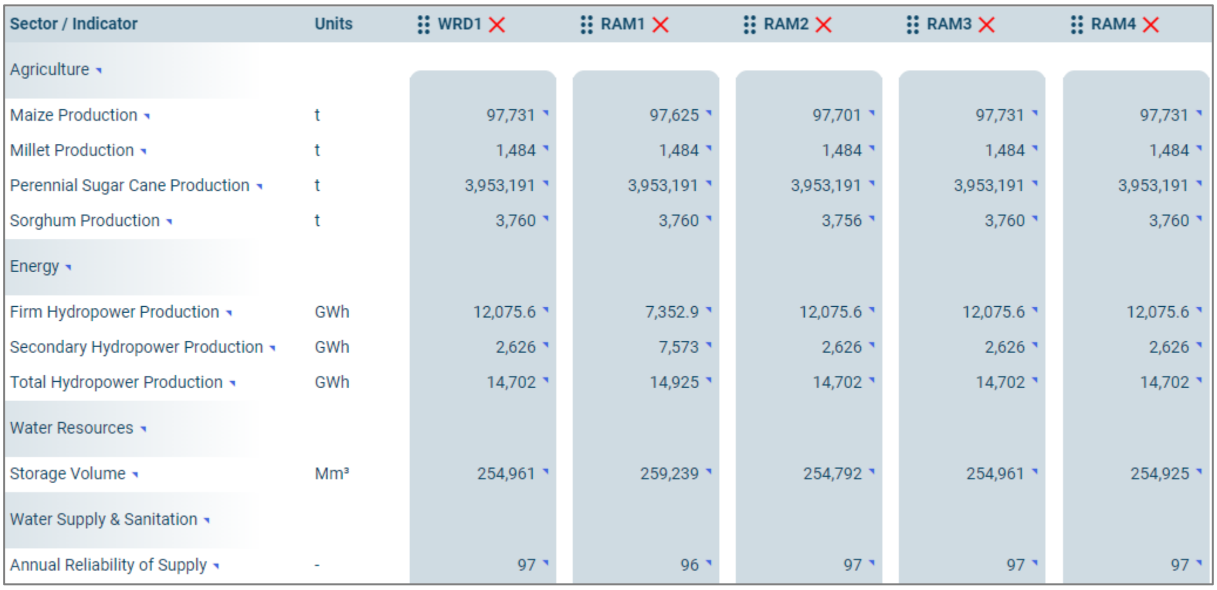
All indicators can also be displayed for different levels of aggregation, by changing the Aggregation of the Indicators. This can help to assess the effects of an investment in a basin or a region.

The ‘Scenario Results’ table was used to display indicator results grouped by sector - Agriculture, Economy, Energy, Environment, Fishery, Social Welfare, Water Resources and Water Supply & Sanitation, for each individual investment (see Figure 2.6 and Figure 2.7).



Sector / Indicator	Units	WRD1	RAM1	CC1	CC2
Agriculture					
Maize Production	t	97,731	97,625	97,610	97,530
Millet Production	t	1,484	1,484	1,484	1,484
Perennial Sugar Cane Production	t	3,953,191	3,953,191	3,953,191	3,953,191
Sorghum Production	t	3,760	3,760	3,758	3,755
Energy					
Firm Hydropower Production	GWh	12,075.6	7,352.9	7,010.9	6,914.4
Secondary Hydropower Production	GWh	2,626	7,573	7,154	6,930
Total Hydropower Production	GWh	14,702	14,925	14,165	13,844
Water Resources					
Storage Volume	Mm³	254,961	259,239	274,059	280,061
Water Supply & Sanitation					
Annual Reliability of Supply	-	97	96	96	96

Figure 2.6 Comparison of baseline scenario WRD 1, RAM 1 (partly regenerating natural flow conditions), CC 1 and CC 2 (climate change), using the ‘Scenario Results’ functionality, the table showing indicators aggregated at the basin level.



Sector / Indicator	Units	WRD1	RAM1	RAM2	RAM3	RAM4
Agriculture						
Maize Production	t	97,731	97,625	97,701	97,731	97,731
Millet Production	t	1,484	1,484	1,484	1,484	1,484
Perennial Sugar Cane Production	t	3,953,191	3,953,191	3,953,191	3,953,191	3,953,191
Sorghum Production	t	3,760	3,760	3,756	3,760	3,760
Energy						
Firm Hydropower Production	GWh	12,075.6	7,352.9	12,075.6	12,075.6	12,075.6
Secondary Hydropower Production	GWh	2,626	7,573	2,626	2,626	2,626
Total Hydropower Production	GWh	14,702	14,925	14,702	14,702	14,702
Water Resources						
Storage Volume	Mm³	254,961	259,239	254,792	254,961	254,925
Water Supply & Sanitation						
Annual Reliability of Supply	-	97	96	97	97	97

Figure 2.7 Comparison of baseline scenario WRD 1 and the rehabilitation and adaptation scenarios RAM 1 to 4 at the basin level. Indicators appear grouped per sector.

In this step of the methodology, the project team and the stakeholders, apply the Planning application to obtain a deep understanding of the differences between scenarios, and conclude on what are the most important indicators to carry over into the next step.

3 Indicator Framework

To evaluate the impacts of the scenarios an indicator framework was proposed by the project team and discussed with the stakeholders. Table 3.1 summarizes the framework presenting the name, unit and description of each indicator used in this project.

Table 3.1 List and description of the indicators to evaluate the scenarios.

Category/ Indicator	**Units**	**Description / Calculation method**
Agriculture		
Maize production	tonnes/year	The mean annual maize production from irrigation in the basin.
Millet production	tonnes/year	The mean annual millet production from irrigation in the basin.
Perennial sugar cane production	tonnes/year	The mean annual sugar cane production from irrigation in the basin (Kuraz Sugar Plantation).
Sorghum production	tonnes/year	The mean annual sorghum production from irrigation in the basin.
Economic		
Net Present Value (NPV) Formal irrigation	USD	This is the net present value for formal irrigation schemes. Costs includes both investment costs and operation and maintenance (O&M) costs while the benefits are the net benefits of the crops produced.
Net Present Value (NPV) Hydropower	USD	This is the net present value for hydropower plants. Costs includes both construction costs and O&M costs while the benefits are the value of the energy produced.
Energy		
Firm Hydropower Production	GWh/year	This is the mean annual firm energy production from hydropower plants, corresponding to energy production, which can be delivered 90% of the time.
Secondary Hydropower Production	GWh/year	This is the mean annual secondary energy production from hydropower plants, which corresponds to the difference between total and firm energy production.

Category/ Indicator	**Units**	**Description / Calculation method**
Total Hydropower Production	GWh/year	This is the mean annual energy production from hydropower plants.
Environment		
Critical river flow	m^3/s	Critical flow is the flow exceeded 80 percent of the time (Q80).
Environmental flow	m^3/s	Environmental flow is the flow exceeded 95 percent of the time (Q95).
Minimum flow	m^3/s	Minimum flow is the flow exceeded 98 percent of the time (Q98).
Fishery		
Fish production vs. water level	tonnes wet weight per boat	This indicator calculates fish production based on an equation developed by Kolding (1989), which relates fish catch to water level the previous year.
Fish production vs. water level fluctuations	% of years with too Low, Neutral, Optimal, or too High water level fluctuations	This indicator describes the water level fluctuations and their impact on fish production with a relative scale based on local knowledge.
Social welfare		
Households with farm holdings within formal irrigation schemes	Number of HH	This indicator calculates the number of households within formal irrigation schemes.
Inundated settlements	Number of settlements	How many settlements are inundated at least once during the simulation period.
Labour division	minutes/individual /month	This indicator calculates the time spent to fulfil water demands that are not met by the supply connection from the nearby river. It is segregated by gender.
Water resources		
Groundwater recharge index	%	This is an index describing the groundwater recharge as a percentage of the recharge in WRD1.

Category/ Indicator	**Units**	**Description / Calculation method**
Maximum storage volume	Mm^3	This is the maximum mean annual storage that occurs in the simulation period.
Mean annual lake level fluctuations	m	This describes the differences between the maximum and minimum water level within each year of the simulation period.
Mean river flow	m^3/s	This indicator represents the mean annual flow at selected important locations.
Minimum storage volume	Mm^3	This is the minimum mean annual storage that occurs in the simulation period.
Overland flow index	%	This is an index describing the overland flow as a percentage of the overland flow in WRD1. The overland flow is the part of the excess rainfall that does not infiltrate.
Percentage of years with severe water level	%	This indicates the percentage of years where the water level in Lake Turkana exceeds the critical water level 364 m.a.s.l which causes severe inundation. The indicator does not take into account whether this happens more than once in a given year.
Salinity in the lake	% of years under Highly saline, Moderately saline, Slightly saline, Low salinity conditions	This indicates the mean annual salinity in the lake during the simulation period. It is based on a simplified dilution approach, whereby the change in lake water level and corresponding change in lake volume is proportional to the change in conductivity/salinity obtained from observations. The indicator expresses the percentage of years salinity in the lake is falling under each category.
Storage volume	Mm^3	This the mean annual stored volume in the reservoirs.
Total runoff index	%	This is an index describing the total runoff as a percentage of the total runoff in WRD1.
Water level	m.a.s.l.	This is the water level in lakes and reservoirs.
Water supply and sanitation		
Reliability of Supply	%	This expresses the extent to which the water demands for a given water user has been fulfilled. It is calculated as (Total amount of water supplied)/(Total amount of water demanded)*100

The sections that follow describe in detail the indicators that have been developed specifically for the purpose of this project supported by literature, observations and field data collection carried out in Kenya during the project implementation period.

Fish Production Indicators

There are two indicators for fish production: one related to the water level fluctuations and one related to the absolute water level.

It is known that the annual lake level fluctuations are important for fish production. According to local knowledge, fluctuations of 1-1.5 m are optimal, while fluctuations of 4 m or more are detrimental. Since it is known that fluctuations are necessary, it has been assumed the fluctuations of less than 1 m are also detrimental, leading to the relative scale in Table 3.2.

Table 3.2 Relative scale for fish production related to lake water level fluctuations.

Fluctuation	**Category**
Less than 1 m	Detrimental (low)
1-1.5 m, both included	Optimal
Above 1.5 m and below 4 m	Neutral
4 m and above	Detrimental (high)

For the correlation to mean water levels, an equation developed by Kolding (1989) is used. Using data from 1962-1988, he has developed a regression correlating fish catch per boat to mean water level the year before in the following way:

$$y = 22.15 + 3.87x$$

Here *y* is the yield per boat in tonnes wet weight, and *x* is the mean water level in metres the previous year. The water level values have the datum 365 m.a.s.l., where $x = 0$. The yield reaches 0 at a water level of approximately 359.5 m.a.s.l., so it is assumed that water levels below this value result in no fish production.

Local knowledge tells us that at water levels below 362 m.a.s.l led to Ferguson’s Gulf drying out which has significant negative impact on the fish breeding. This is not explicitly included in the in the indicator, but it is assumed that the impact of this will be reflected in the lower yields calculated by the formula at this water level.

Households with Farm Holdings

This indicator calculates the number of households that are within formal irrigation schemes. According to local knowledge of Turkana County, irrigation schemes of 61,000 ha correspond to 25,000 households, giving approximately 2.5 ha per household. It is assumed that this value can be used throughout the basin. This indicator is then calculated by dividing the area of the irrigation schemes included by 2.5 ha to get the number of households in each.

Labour Division Indicator

According to local knowledge, 79% of water fetchers are women or girls. This has been translated into that 79% of the deficit is fetched by women.

According to Sorenson, et al., (2011) a typical estimate is that a water carrier walks 0.62 miles (1 km) to fetch 5 gallons (19 L) of water and then walks 0.62 miles back. It has been assumed that the outward walking speed is 4 km/h and the homebound walking speed 3 km/h. This corresponds to 35 minutes for fetching 19 L of water.

According to local knowledge, men in Turkana typically use animals or pull carts for fetching water. It is assumed that they use donkeys which walk at a speed of 6 km/h (Thornton-O'Connell, n.d.). It is assumed they carry 40 L of water. According Ellis (2019) a standard donkey can carry around 125 pounds, corresponding to approximately 55 kg. Putting the weight lower in the calculations is to make up for the fact that some men will be walking with pull carts or carrying water themselves. With these assumptions, men spend 20 minutes fetching 40 L of water.

Additionally, 3 minutes are added for filling containers for women and 6 minutes for men. This is based on the assumption that filling a 20 L container will take 1 minute (International Federation of Red Cross and Red Crescent Societies, 2020) and that there will be some queuing for the pump.

The indicator is focused on the 13 towns that are included in the model. Each is connected to a river branch, and it is assumed that the water coming from here is distributed to the households without significant labour for the inhabitants. Thus, only the time needed to collect the deficit (the difference between water demand and supplied water) is taken into account in this indicator.

The time consumption is then calculated by dividing the monthly deficit in m^3 between men and women (79% for women and 21% for men). It is then calculated how many rounds are needed to fulfil the deficit, assuming 19 L are fetched per round for women and 40 L for men. The number of rounds is then multiplied by the time one round takes (38 minutes for women and 26 minutes for men). The time is then divided by the number of men and women, respectively, in the given town to get the time per individual, and an average is taken to get the time per individual per month.

Net Present Value for Hydropower

The Net Present Value (NPV) calculates the present worth of investments. It requires the initial investment costs, operation and maintenance costs, and the benefits of the project. For hydropower the benefits are calculated from the energy production, which is calculated by the model, and the energy price. Based on local knowledge, the energy price in Kenya is estimated at 0.0236 USD/kWh and in Ethiopia at 0.05 USD/kWh. The discount rate is set to 0.08, based on local knowledge.

The costs are the construction costs and the operation and maintenance costs. The latter are estimated as 2% of the construction costs per year (Energy Technology Network, 2010) (Houston, 2015). The construction costs and maintenance costs for all included hydropower plants and reservoirs are thus as shown in Table 3.3. For Gibe V and Arror construction costs could not be found but based on the other HPPs it seemed that there was a correlation between construction costs and installed capacity. This was used to estimate the construction costs for these two reservoirs.

Table 3.3 The construction costs and operation and maintenance costs for the HPPs included in the study. The operation and maintenance costs are estimated as 2% of the construction costs.

Hydropower plant	**Construction costs (million USD)**	**Operation and maintenance costs (million USD)**	**Source for construction costs**
Gibe I	331.4	6.628	(Hathaway, 2008)
Gibe II	600	12	(Hathaway, 2008)
Gibe III	1,700	34	(Hathaway, 2008)
Koysha	2,800	56	(Seifu, 2016)

Hydropower plant	Construction costs (million USD)	Operation and maintenance costs (million USD)	Source for construction costs
Turkwel	165.7	3.314	(Kenya Kroll Report, n.d.)
Gibe V	740	14.8	Estimated based on correlation between cost and installed capacity in other HPPs
Arror	140	2.8	Estimated based on correlation between cost and installed capacity in other HPPs

The net present value is then calculated for each year as

$$NPV = \frac{benefits - costs}{(1+r)^t}$$

where *r* is the discount rate and *t* is the number of years since year 0. The yearly NPVs are summed over the simulation period with the construction costs included as a negative cash flow in year 0, and the final value is presented as the NPV indicator. The indicator is in USD.

Net Present Value for Irrigation

The Net Present Value (NPV) calculates the present value of investments. It requires the initial investment costs, operation and maintenance costs, and the benefits of the project. For irrigation the benefits are calculated from the crop production, which is calculated by the model, and the crop price.

The crop prices per kg for maize (0.33 USD), sorghum (0.58 USD) and millet (0.90 USD) are average retail market prices in Kenya (2018 humdata.org), and the crop price for pre-processed sugar (0.091 USD) is from local expert knowledge.

The costs are the construction costs and the operation and maintenance costs. The construction cost (3,796 USD per hectare) is estimated from a small-scale irrigation scheme in Ethiopia (FAO, 2003).

The operation and maintenance cost (25.88 USD per hectare) includes annual capital cost, maintenance cost and labour cost estimated from a traditional gravity irrigation scheme in Tanzania for maize (FAO, 1997).

For sugar, the additional construction cost of the Kuraz plantation factories was added. For all scenarios except WRD2 this additional construction cost is 460 million USD estimated from the cost of building Omo Kuraz II (170 million USD) (The Reporter, 2017) and Omo Kuraz III (290 million USD) (Nazret.com, 2018). For WRD2 scenario, the construction cost also included an estimate for the cost of building factory Omo Kuraz V (700 million USD) (Kamski, 2016).

The discount rate is set to 0.08, based on local knowledge.

Percent of Years Where Water Levels Result in Severe Inundation

This is the percent of years in the simulation period where the water levels are above 364 m.a.s.l. GIS investigations have shown that this water level results in severe inundation of a number of settlements around Lake Turkana (described in UNEP-DHI, 2020d).

The indicator calculates the maximum each year and finds the number of years in which the maximum exceeds 364 m.a.s.l. The indicator does not distinguish between whether severe inundation occurs only once a year or several times within a year.

Salinity Indicator

The salinity indicator estimates the change in Lake Turkana salinity level or conductivity level as a function of the lake water level. It is based on a simplified dilution assumption. The change in lake water level and corresponding change in lake volume is proportional to the change in conductivity/salinity.

Half the lake volume corresponds to double salinity (ppm). Field data from KMFRI reported in Avery 2012, and more recent data provided have been used to develop the indicator. The salinity varies horizontally and with depth for Lake Turkana and consequently data collected near the surface in the central part of the lake have been used as a measure of lake salinity.

USGS salinity classes (freshwater – hyper saline) have been used, see Table 3.4. The indicator expresses the percentage of years salinity in the lake is falling under each category. Lake Turkana water is currently described as brackish with main lake conductivity measurements in the range of 3000 – 4000 µS/cm.

Table 3.4 USGS salinity classes used in the indicator.

Salinity indicator	Range	Range, conduct
	ppm	µS/cm
Highly saline	> 10000	> 15000
Moderately saline	3000-10000	4500-15000
Slightly saline	1000 - 3000	1500-4500
Low salinity	< 1000	< 1500

Settlements Affected by Inundation

This indicates the number of settlements that are inundated at least once during the entire simulation period.

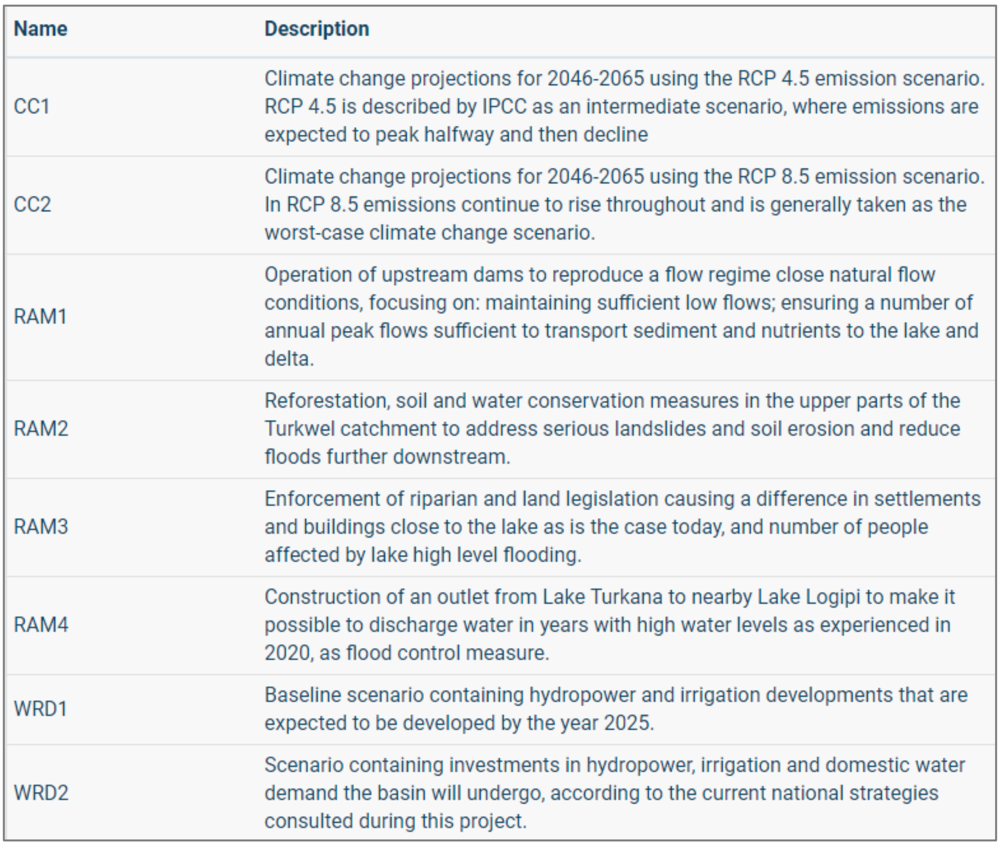
It has been investigated how many settlements are inundated at different water levels. Water levels in a range of 360-369 with 1 m intervals have been investigated. The indicator then calculates the maximum water level in the simulation period and checks the number of settlements that are inundated at this level (see Table 3.5). A settlement is defined as inundated when the water from Lake Turkana reaches at least one household or building in the settlement. The indicator does not show how frequently settlements are inundated.

Table 3.5 Number of settlements inundated at various Lake Turkana water level intervals

Lake Turkana water level (m.a.s.l)	Number of inundated settlements
360	0
361	0
362	0
363	4
364	8
365	14
366	20
367	28
368	29
369	29

4 Scenario Modelling

The following subchapters present the impacts of each scenario in detail when compared with the baseline scenario WRD 1. Figure 4.1 captures the name and a brief description of each scenario. The key results from the models are extracted and discussed to reveal their impacts. Also, to this end, the most important indicators are examined using the Planning application. For each scenario, the discussion of impacts is organized per relevant sector.



Name	Description
CC1	Climate change projections for 2046-2065 using the RCP 4.5 emission scenario. RCP 4.5 is described by IPCC as an intermediate scenario, where emissions are expected to peak halfway and then decline
CC2	Climate change projections for 2046-2065 using the RCP 8.5 emission scenario. In RCP 8.5 emissions continue to rise throughout and is generally taken as the worst-case climate change scenario.
RAM1	Operation of upstream dams to reproduce a flow regime close natural flow conditions, focusing on: maintaining sufficient low flows; ensuring a number of annual peak flows sufficient to transport sediment and nutrients to the lake and delta.
RAM2	Reforestation, soil and water conservation measures in the upper parts of the Turkwel catchment to address serious landslides and soil erosion and reduce floods further downstream.
RAM3	Enforcement of riparian and land legislation causing a difference in settlements and buildings close to the lake as is the case today, and number of people affected by lake high level flooding.
RAM4	Construction of an outlet from Lake Turkana to nearby Lake Logipi to make it possible to discharge water in years with high water levels as experienced in 2020, as flood control measure.
WRD1	Baseline scenario containing hydropower and irrigation developments that are expected to be developed by the year 2025.
WRD2	Scenario containing investments in hydropower, irrigation and domestic water demand the basin will undergo, according to the current national strategies consulted during this project.

Figure 4.1 Brief description of each scenario as set up in the Planning app.

4.1 WRD 1: Planned Development by 2025

4.1.1 Background

WRD 1 is the baseline scenario including hydropower and irrigation developments that are expected to be developed by the year 2025. The scenario is the point of departure for future development scenario WRD 2 and all the rehabilitation scenarios: RAM 1, 2, 3 and 4. The baseline model setup is described in detail in the previous report: Support to Sustainable Development in Lake Turkana and its River Basins - ESS Hotspots Identification and Baseline Model (UNEP-DHI, 2020c) including the main inputs, model calibration and some results.

The key results from the model in terms of hydropower production, crop production and irrigation, lake water levels and lake inflows as well as baseline fishing conditions are presented below.

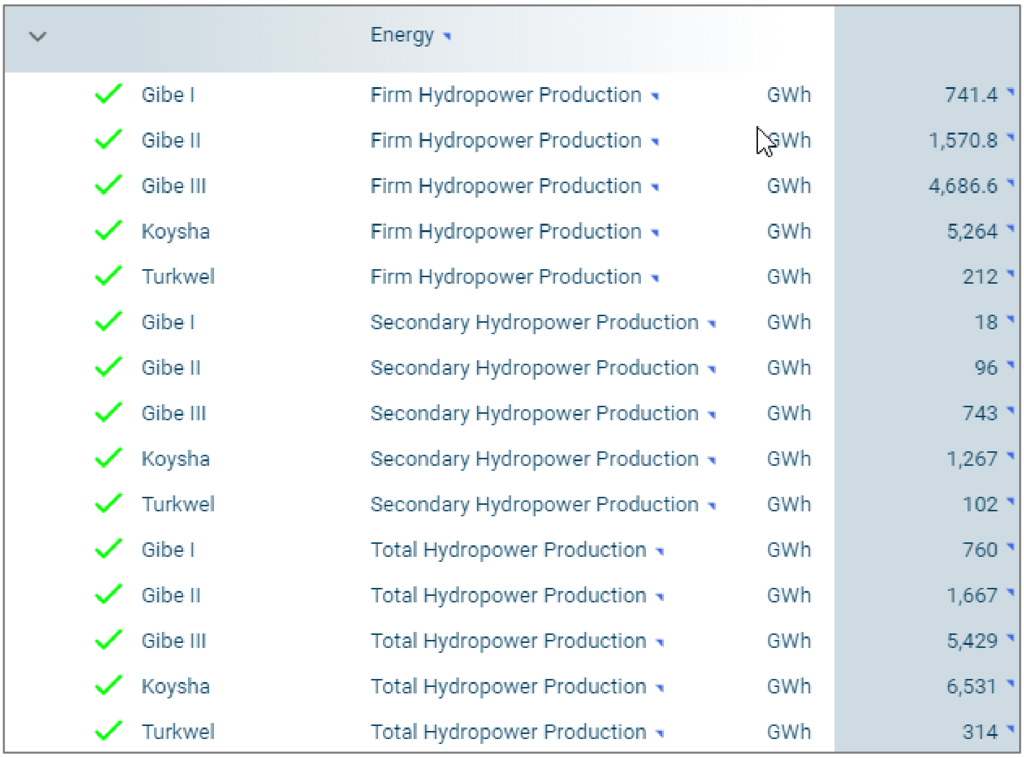
4.1.2 Results

Hydropower

Hydropower in the Omo-Turkana basin is produced from five hydropower power plants, of which the four largest are located in Ethiopia. The firm, secondary and total hydropower production from each station estimated using the water resources model are summarised in Figure 4.2. Ethiopia has the largest energy production from hydropower accounting for 98 percent of the total hydropower production in the basin.

The hydropower plants have a significant effect on the stream flow hydrology downstream of the dams and further downstream on the hydrology of Lake Turkana. As a rule, the average annual river flow volumes downstream of the reservoirs are only affected to a small degree due to evaporation and rainfall, unless the reservoirs are also used for irrigation and domestic water supply. However, reservoir operation has an impact on the flow regime by increasing low flows and reducing peak flows. This is illustrated for Gibe III in Figure 4.3 showing the inflows to the reservoir compared with the outflows downstream of the hydropower plant for the simulation period of 20 years. The plots show how the flows are smoothed out over time and increased during dry periods due to hydro power operation. The small difference in average in- and outflow is due to net precipitation and storage changes in the reservoir.

The effect of the reservoirs on low flows into Lake Turkana will be less pronounced than immediately downstream of Gibe III due to catchment flow entering the Omo River from tributaries further downstream but they will nevertheless have an impact on the seasonal variation of the lake water level.



		Energy		
✓	Gibe I	Firm Hydropower Production	GWh	741.4
✓	Gibe II	Firm Hydropower Production	GWh	1,570.8
✓	Gibe III	Firm Hydropower Production	GWh	4,686.6
✓	Koysha	Firm Hydropower Production	GWh	5,264
✓	Turkwel	Firm Hydropower Production	GWh	212
✓	Gibe I	Secondary Hydropower Production	GWh	18
✓	Gibe II	Secondary Hydropower Production	GWh	96
✓	Gibe III	Secondary Hydropower Production	GWh	743
✓	Koysha	Secondary Hydropower Production	GWh	1,267
✓	Turkwel	Secondary Hydropower Production	GWh	102
✓	Gibe I	Total Hydropower Production	GWh	760
✓	Gibe II	Total Hydropower Production	GWh	1,667
✓	Gibe III	Total Hydropower Production	GWh	5,429
✓	Koysha	Total Hydropower Production	GWh	6,531
✓	Turkwel	Total Hydropower Production	GWh	314

Figure 4.2 Total hydropower production from each hydropower plant in the Omo-Turkana basin, screenshot from the Planning Tool.

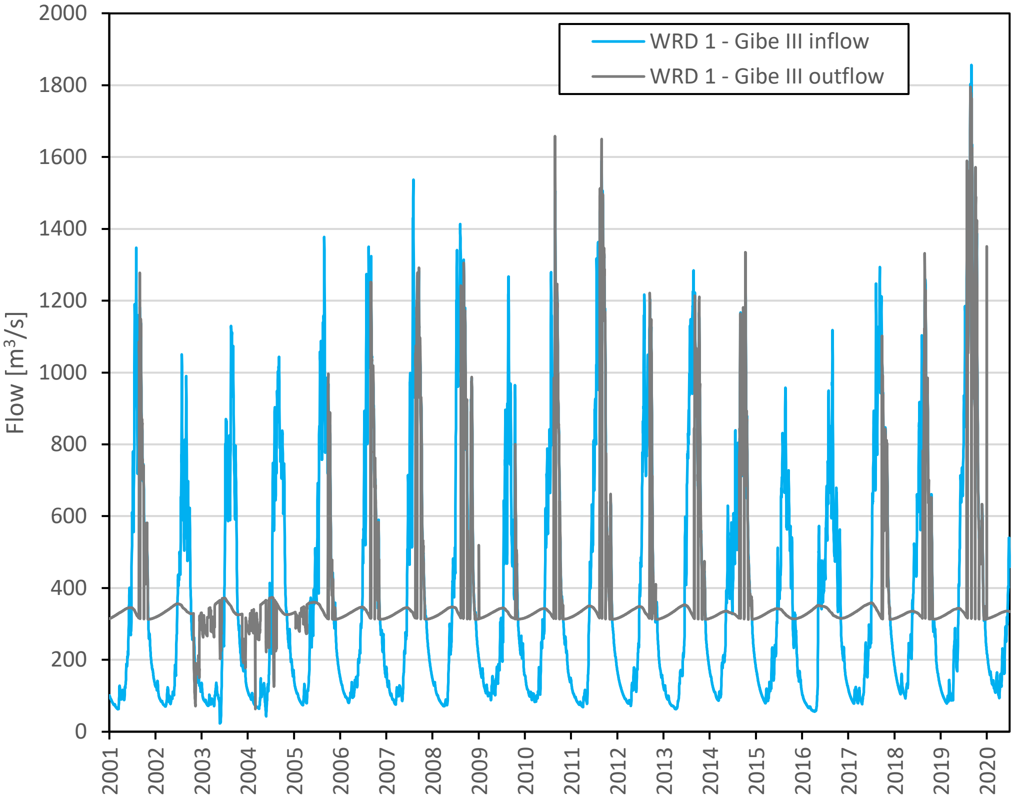


Figure 4.3 Modelled inflows and outflows for Gibe III. Average inflows and outflows are 388.7 m^3/s and 392.8 m^3/s.

Crop Production

Crop production in the basin includes many different types of crops with the most common being maize, millet, sugar cane and sorghum. An overview table of the crops included in the water resources model and the crop production by country is presented in Figure 4.4 below. The model only considered irrigated crops and not rainfed cultivation, and for simplicity only major crops were included.

The table shows the production from irrigated areas with the sugar plantation at Kuraz in Ethiopia accounting for 97.4 percent of the total crop production. Maize production is the second most frequent crop and production is relatively evenly distributed between Ethiopia and Kenya. Millet and sorghum are estimated to account for less than 0.15 percent of the total production or 5 percent ignoring the sugar cane production.

Water use from irrigation has a significant impact on average and minimum stream flows downstream of the irrigated areas. The sugar cane plantation at Kuraz accounts for most of the water use due to its size. Here annual average water use is estimated to be 21.9 m^3/s corresponding to 3.9 percent of the stream flow upstream of Kuraz. During dry periods this increases to around 12 percent for minimum flows (Q98). For comparison annual average water use at the second largest irrigation scheme Gibe Valley is 0.02 m^3/s.

		Agriculture		
✓	Ethiopia	Maize Production	t	50,872
✓	Kenya	Maize Production	t	46,858
✓	Kenya	Millet Production	t	1,484
✓	Ethiopia	Perennial Sugar Cane Production	t	3,953,191
✓	Kenya	Sorghum Production	t	3,760

Figure 4.4 Summary of crop production for each crop in the Omo-Turkana basin taken from the Planning Tool.

Lake Inflow and Water Levels

In terms of inflows to Lake Turkana the impact of Kuraz of around 3.7 percent of the total average flow is significant and will have an impact on water levels in Lake Turkana compared to natural conditions. The modelled water level in the lake is shown in Figure 4.5 below with critical levels in terms of fishing and flooding.

Water levels in the lake have ranged from a low of 360.5 m.a.s.l. to above 364 m.a.s.l. during the model period from 2001 to 2020. In 2020 water levels were above the critical flood level which caused widespread flooding of settlements around the lake.

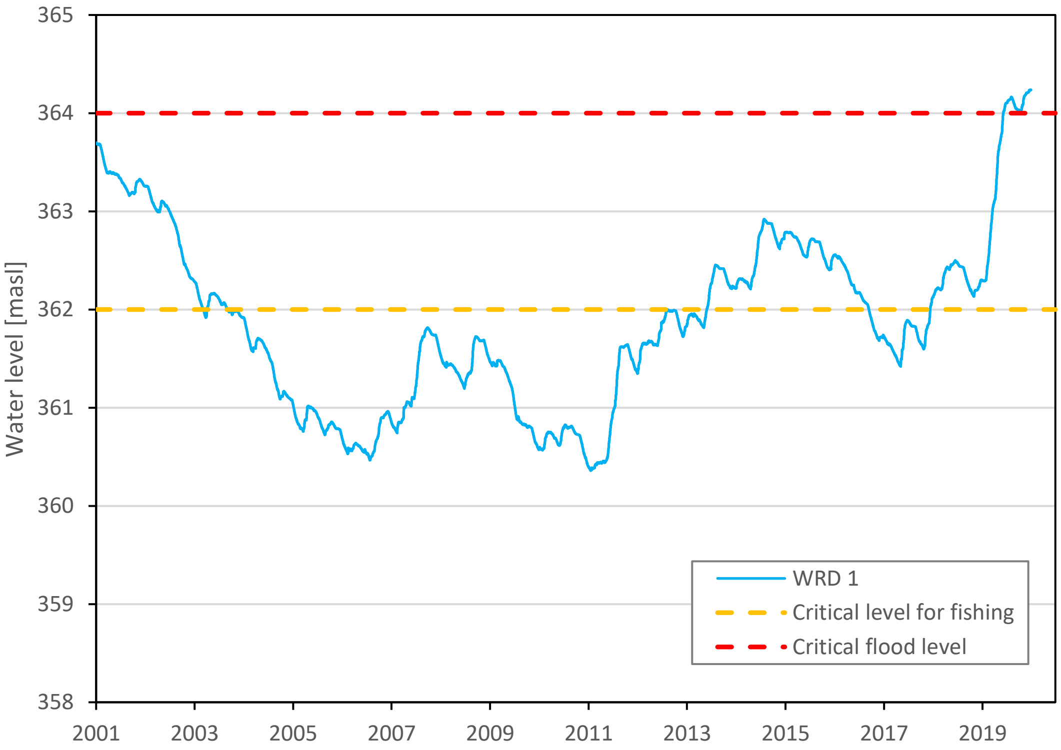


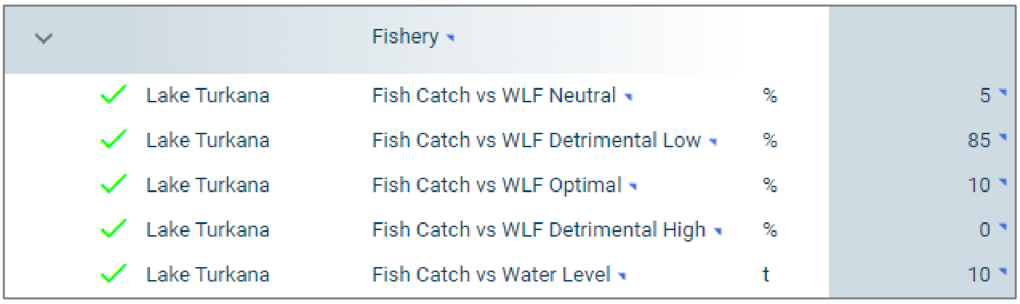
Figure 4.5 Modelled water level in Lake Turkana for WRD 1 including critical levels for fishing and flooding.

Fish Production

Fish production in Lake Turkana depends on several factors including the hydrology and water quality of the lake. A number of indicators, summarised in Figure 4.6, based on the water level of the lake provide a means of assessing current fishing conditions.

Unfortunately, at this time insufficient information is available for assessing the impact of water quality on fishing conditions in Lake Turkana.

Estimated fish catch per boat for the study period estimated from annual average water level from the previous year is 10 tonnes. This was calculated using an equation by Kolding (1989). Annual water level fluctuations on the other hand indicate sub-optimal conditions for fishing for most of the year (85%) (see table below). Optimal conditions only occur 10 percent of the time according to the indicator. It has not been possible to verify these results against current conditions, but the indicators provide a baseline for assessing any impacts on fishery in the scenarios presented below.



		Fishery		
✓	Lake Turkana	Fish Catch vs WLF Neutral	%	5
✓	Lake Turkana	Fish Catch vs WLF Detrimental Low	%	85
✓	Lake Turkana	Fish Catch vs WLF Optimal	%	10
✓	Lake Turkana	Fish Catch vs WLF Detrimental High	%	0
✓	Lake Turkana	Fish Catch vs Water Level	t	10

Figure 4.6 Summary of indicators for fishery from the Planning application.

4.2 WRD 2: Full Development by 2040

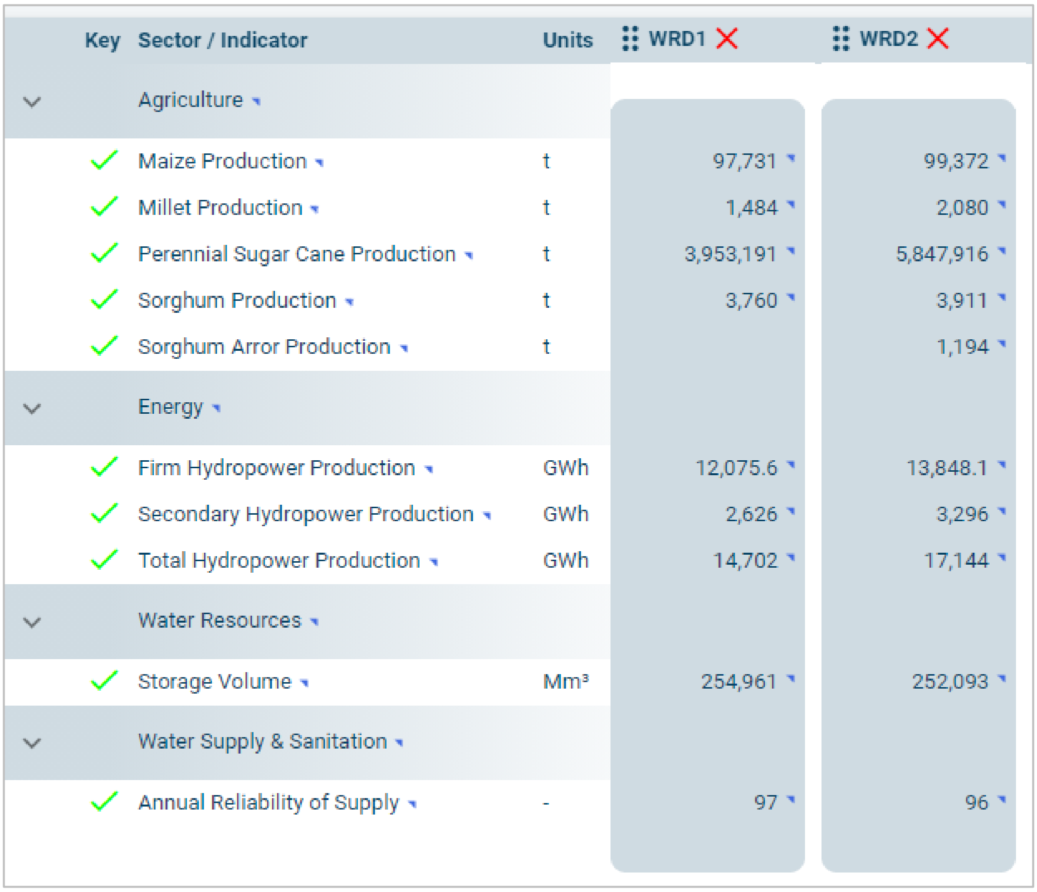
4.2.1 Background

WRD 2 contains planned investments in hydropower, irrigation and domestic water supply by 2040, according to the current national strategies consulted during this project.

Planned reservoir and hydropower plant projects in the Omo-Turkana Basin comprise three schemes in Ethiopia and two schemes in Kenya. However, some of the schemes are very uncertain and have limited information on location, design and operation. Consequently, only two of the reservoirs and hydropower schemes have been included in the model scenario, namely Gibe V located downstream of Koysha and a combined reservoir, hydropower and irrigation scheme at Arror in the Kerio catchment in Kenya. Originally it was also the intention to include the Halele-Werabesa cascade of reservoirs located in the upper part of the basin in Ethiopia as outlined in UNEP-DHI, 2020d but due to insufficient/inaccurate information about the locations and their operation this was not possible in the end. The reservoirs are to be located in the far northern part of the basin and this could have some impact on the flow regime further downstream, but the effects are expected to be limited.

In addition to the two hydropower schemes the scenario includes expansion of the irrigation areas at the sugar cane plantation at Kuraz and at Naipa in the Upper Turkwel, as well as increases in urban domestic water supply by 2040 for the 13 cities included in WRD 1.

The impacts of the planned investments on hydropower production, crop production and the hydrology compared with the baseline are presented and discussed below. A summary of the key indicators for the two scenarios from the water portal Planning application is presented in Figure 4.7.



Key	Sector / Indicator	Units	WRD1	WRD2
	Agriculture			
✓	Maize Production	t	97,731	99,372
✓	Millet Production	t	1,484	2,080
✓	Perennial Sugar Cane Production	t	3,953,191	5,847,916
✓	Sorghum Production	t	3,760	3,911
✓	Sorghum Arror Production	t		1,194
	Energy			
✓	Firm Hydropower Production	GWh	12,075.6	13,848.1
✓	Secondary Hydropower Production	GWh	2,626	3,296
✓	Total Hydropower Production	GWh	14,702	17,144
	Water Resources			
✓	Storage Volume	Mm³	254,961	252,093
	Water Supply & Sanitation			
✓	Annual Reliability of Supply	-	97	96

Figure 4.7 Summary of key indicators for WRD 1 and WRD 2 from the Planning application.

4.2.2 Results

Hydropower

The planned investments in the two new hydropower plants will lead to an increase in total annual average hydropower production of 2,442 GWh corresponding to a 16.6% increase compared to the baseline. Most of the increase is from the Gibe V hydropower plant in Ethiopia which accounts for 94 percent of the total increase. The total hydropower production in Ethiopia will increase by 16% from 14,387 GWh to 16,679 GWh and the hydropower production in Kenya will increase by 48% from 314 GWh to 465 GWh. In other words, the increase in hydropower production in the Kenyan part of the basin is limited but this is starting from a lower level.

Figure 4.8 below shows the increase in total monthly power production in Ethiopia and in Kenya, respectively. These figures are somewhat uncertain as the operation of the plants are not known at this stage but nevertheless provide a rough estimate of the increase.

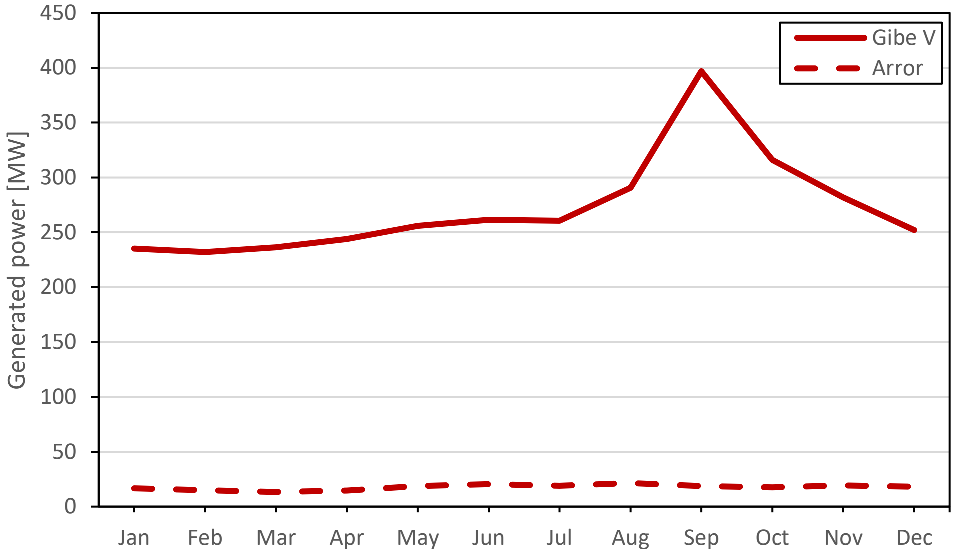


Figure 4.8 Monthly power production for Gibe V and Arror hydropower plants in WRD 2.

The reservoir and hydropower plant operation will affect the stream flow hydrology downstream of the dams. In general, the total flow volumes are not affected or only affected to a small degree. However, reservoir operation has an impact on the flow regime by increasing low flows and reducing peak flows.

The effect of the operation on Gibe V on river flows in the Omo river is illustrated in Figure 4.9 and Figure 4.10 showing the flow duration curves downstream of Gibe V and the average monthly flows for WRD 1 and WRD 2. Minimum flow defined as the 98th flow percentile increases from 236 m^3/s to 272 m^3/s downstream of the reservoir. This corresponds to an increase of 14 percent.

Average flows are reduced slightly both downstream of Gibe V, and also downstream of Arror in the Kerio river, not due to the hydropower plants but due to an increase in domestic water use in WRD 2.

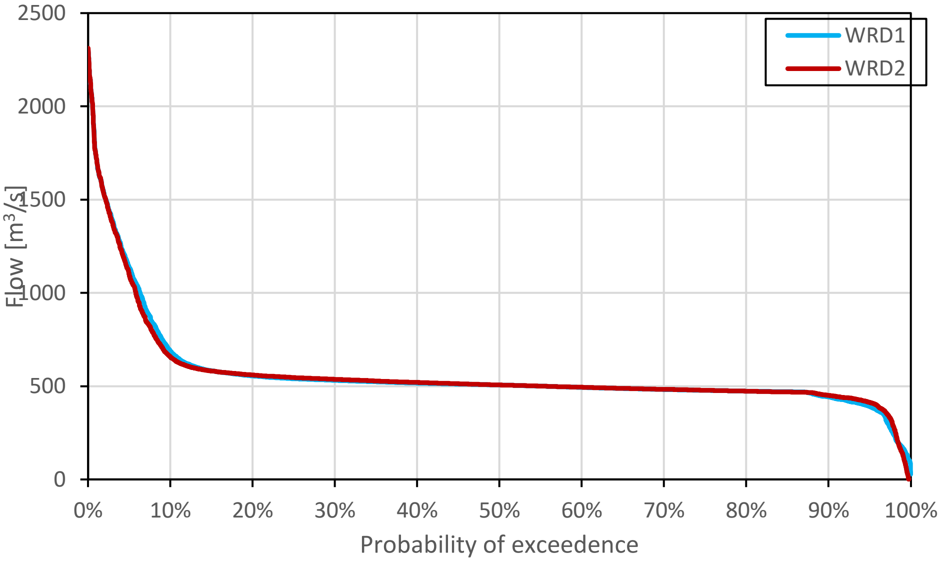


Figure 4.9 Flow duration curves for WRD 1 and WRD 2 downstream of Gibe V.

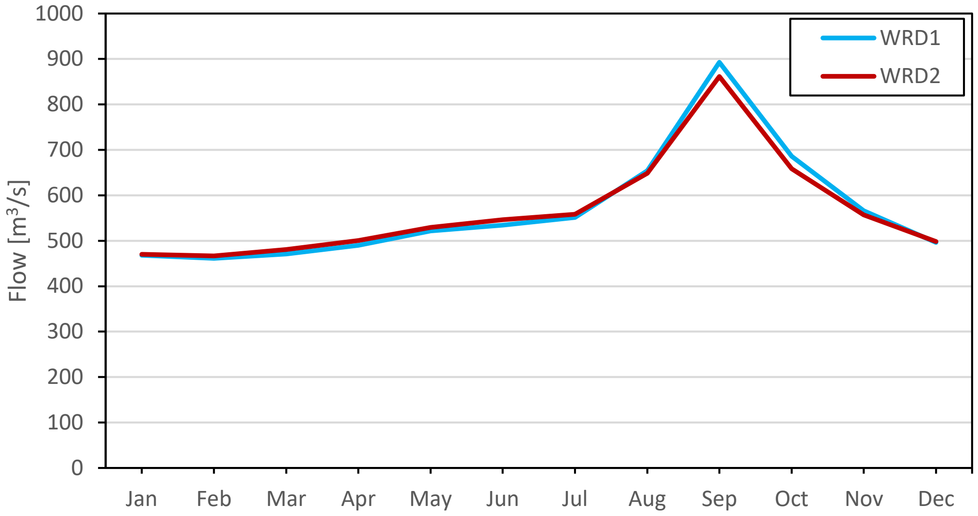


Figure 4.10 Monthly flows for WRD 1 and WRD 2 downstream of Gibe V.

Crop Production

The total crop production in the basin will increase due to the planned increases in the irrigated areas at Kuraz, Naipa and Arror. According to the model the sugar cane production at Kuraz will increase by 1.9 million tonnes corresponding to a percentage increase of 47.9. This model result is proportional with the planned increase in sugar cane area.

Smaller increases are seen for the other crops in Kenya at Naipa and Arror. The total crop production from irrigated areas (maize, sorghum and millet combined) is estimated to increase by 2.3 percent from 0.103 million tonnes to 0.105 million tonnes. The production of these crops and the resulting water use for irrigation is very small compared to the water used for sugar cane production in the basin. The irrigated crop production, not including sugar cane, is evenly distributed between Ethiopia and Kenya.

Water use due to increased irrigation results in a significant impact on average and minimum stream flows, particularly downstream of Kuraz reservoir. Average stream flow will reduce by 5.3 percent from 509 to 482 m^3/s. The irrigation scheme at Arror in Kenya will only have a minimal impact on flows with a reduction in average flows downstream in the upper Kerio catchment of 0.4 percent. This reduction also includes the effect of urban supply upstream in the Kerio. Minimum flows are increased slightly due to the reservoir operation at Arror.

Lake Inflow and Water Levels

Lake water inflows and water levels will be impacted by the planned investments, mainly by the increased irrigation at Kuraz and by Gibe V. The increases in domestic water supply and the hydropower plant scheme at Arror, which includes irrigation, will only have a minimal impact on inflows to the Lake. The flow duration curves in Figure 4.11 at the inlet to the delta show the impact on inflows with the largest reductions at low flows below the 80th percentile of flow. The average inflow will be reduced by 4.7 percent from irrigation and domestic supply compared to around 3.7 percent in WRD 1 (Kuraz only) and minimum flows are reduced by 74 percent from 156 m^3/s to 40 m^3/s.

Water levels in the lake are reduced by around 1 m at the end of the model period compared to the baseline (Figure 4.12). The annual variation on the other hand is increased as illustrated in Figure 4.13 showing the annual fluctuation for WRD 2 compared to WRD 1 and this is mainly caused by the increased irrigation at Kuraz which causes a reduction in inflows during dry periods.

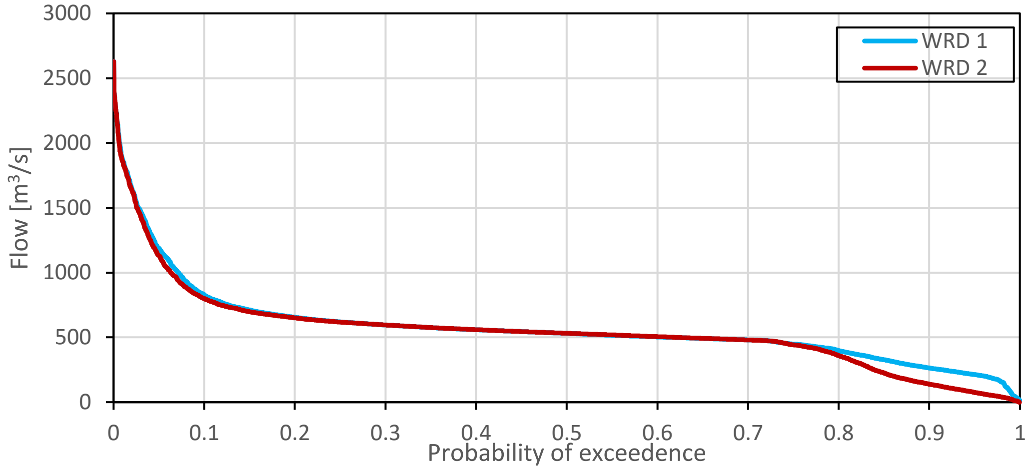


Figure 4.11 Flow duration curves for WRD 1 and WRD 2 at the inlet to the delta in Ethiopia.

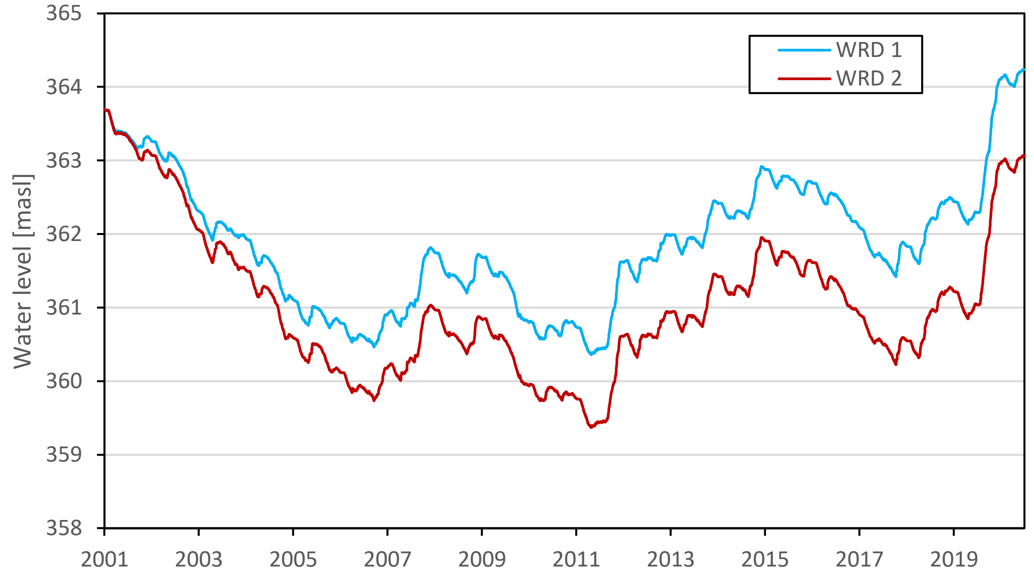


Figure 4.12 Modelled water level in Lake Turkana for WRD 1 and WRD 2.

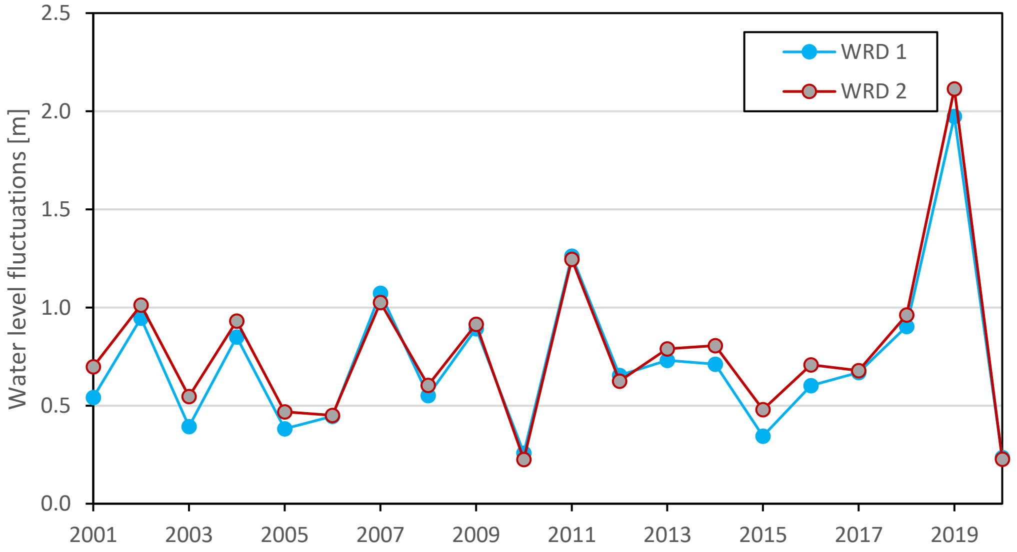


Figure 4.13 Estimates of annual fluctuation in Lake Turkana for WRD 1 and WRD 2.

Fish Production

According on the modelled impact on water levels in Lake Turkana fish production will be affected compared with WRD 1 but the effects are somewhat mixed. Based on water level alone fish catch per boat will be reduced from 10 tonnes to 7 tonnes. However, taking higher annual water level fluctuations into account results in longer periods of optimal conditions for fishing which could be beneficial for fish production.

4.3 RAM 1: Regenerating Natural Flow Conditions

4.3.1 Background

The purpose of this scenario is to regenerate some of the mechanisms of natural flow while still maintaining sufficient production of hydropower. It is not expected that the natural flow can be fully regenerated as this will come at a too high loss of power production, especially in the dry season where the natural flow levels are very low.

Figure 4.14 shows the lake water level in the WRD1 scenario compared to the water level under natural conditions. The developments in the basin clearly have two major effects:

1) The lake water levels drop, ending 3.0 m below the natural flow at the end of the modelling period and with a maximum difference between the two of 3.4 m.

2) The seasonal variations are significantly dampened, to the extent where many years in the WRD1 water levels do not show a seasonal variation at all.

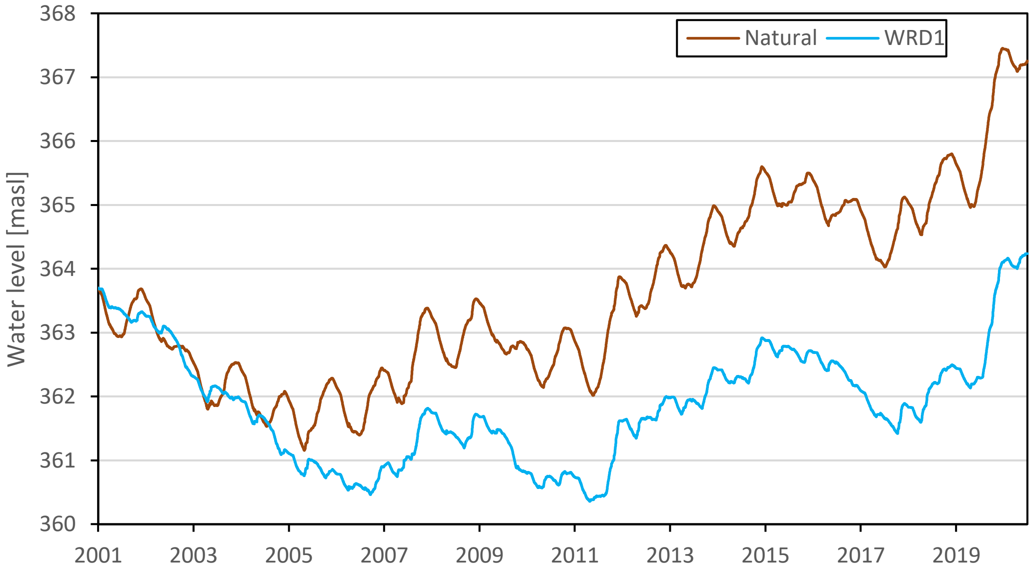


Figure 4.14 Lake water level in the WRD1 scenario compared with natural conditions

The falling water levels are most likely hard to remedy, since more water is removed from the system in WRD1 (and thus also in RAM1) than in the natural system. There are several irrigation users added, in particular the Kuraz Sugar Plantation, which has a large water consumption. Additionally, water will evaporate from the reservoir surfaces although this may in some cases be counterbalanced by rainfall on the water surface. For this reason, RAM1 is not expected to have a major impact on lake water level as this would force stored water from the reservoirs through the system which over time would no longer be possible. Instead, RAM1 focusses mainly on restoring some water level fluctuations.

This is done by creating a lake inflow requirement, which determines the minimum flow that should be upheld at the lake. By connecting the lake inflow node to the upstream reservoirs, the releases from the reservoirs fulfil this demand if possible. The inflow requirement is connected to the closest upstream reservoir, which in this case is the Kuraz1 reservoir. Since this reservoir has very little storage and since its inflow will be strongly affected by the operation of Koysha and Gibe III, these three reservoirs are connected in a series, so that Kuraz1 has a storage demand from Koysha, which in turn has a storage demand from Gibe III. A required water level is set in the downstream reservoir, which the upstream reservoir needs to release water to fulfil. The flow from the upstream reservoir to the downstream is in turn controlled by rule curve which specifies a minimum water level in the upstream reservoir. The target power for Gibe III and Koysha is set to 0, so the only water passing through the system, and the only power produced, is what is required to fulfil the flow demand at the lake and possibly spilling from the reservoirs. In order to maximise power production, the water levels in Gibe III and Koysha have been kept high, although it is necessary to allow space for storage for the dry period.

Determining Inflow Requirements

Determining the inflow requirement to the lake was challenging, as there was little information about the exact requirements. EEPCo (2009) suggest that a lake inflow of 1600 m^3/s for 10 days should be adequate to fulfil the environmental needs of the lake. However, since it is known that the water level fluctuations within the year are very important for fish production, it seemed likely that this suggestion cannot stand alone. This has been investigated with a model run which has an inflow requirement at the lake of 1600 m^3/s for 10 days in September as well as a few days' gradual increase and decrease on either side of the peak. Note that in this model run, all reservoir operations are as in WRD1, with the exception of the flow requirement and connection of the reservoirs.

Figure 4.15 shows that the seasonal variation in lake inflow is not recreated by this measure. There is a peak in September which is larger than for WRD1, but the rest of the year is very similar to WRD1. Additionally, there is almost no impact on the seasonal variation compared to WRD1, as seen in Figure 4.16. The lake water levels are also falling continuously. Based on this, it is assessed that EEPCo's suggested requirements do not fulfil the ecosystem needs.

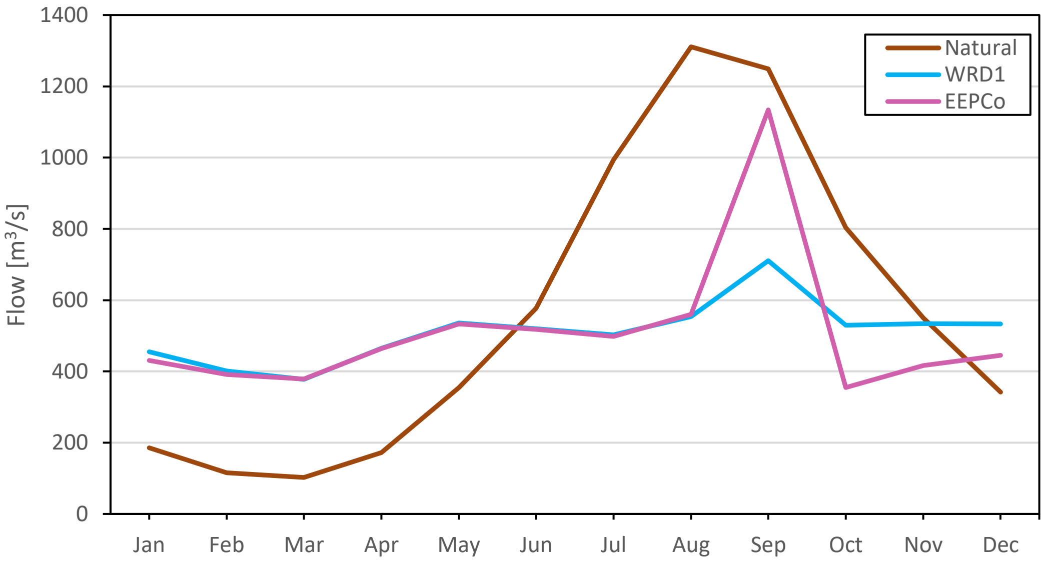


Figure 4.15 EEPCo model run with a peak of 1600 m^3/s in the second half of September compared with natural and WRD1 inflow to the lake. Monthly means of lake inflow for the period 2001-2010.

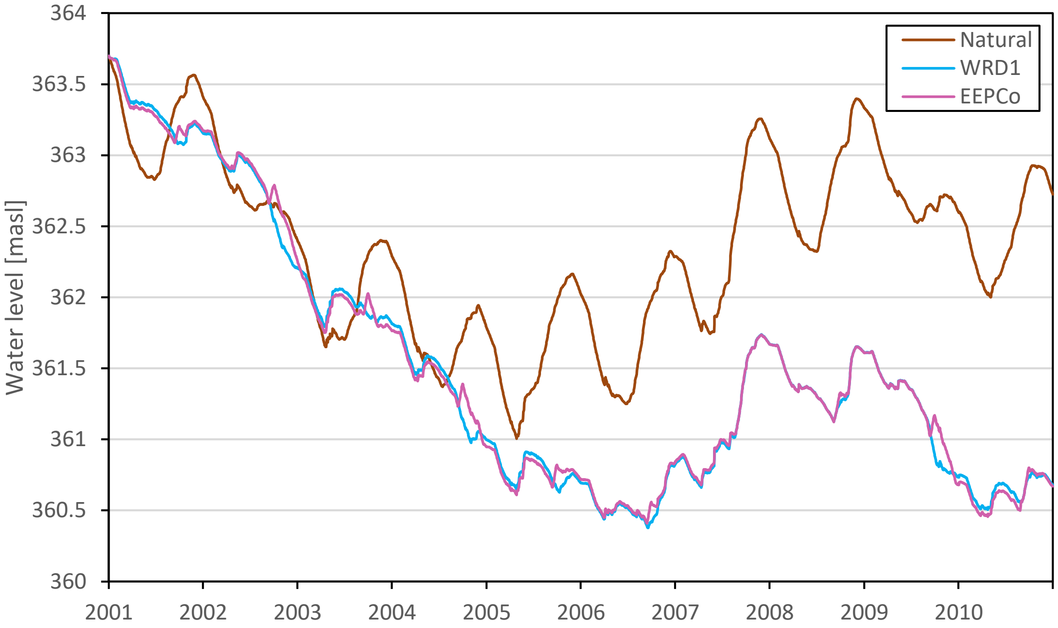


Figure 4.16 Water levels with EEPCo's requirement compared to WRD1 and the natural scenario

RAM 1 Inflow Requirement

Instead of using EEPCo's recommendations, the natural flow and the flow in WRD1 have been analysed to create another inflow requirement. Looking at the monthly means of lake inflow for WRD1 and the natural flow, a requirement has been developed which mimics the variations in the natural flow, but with a smaller difference between the lowest and highest flow, see Figure 4.17. The flow cannot be allowed to reach as low levels as in the natural flow as this would result is very little power production during this period. To compensate for higher flows in the dry period, there must be lower flows in the wet period. The requirement curve has been shaped so that is has approximately the same area under the curve as the WRD1 curve, thus having the same flow volume but rearranging it over the year.

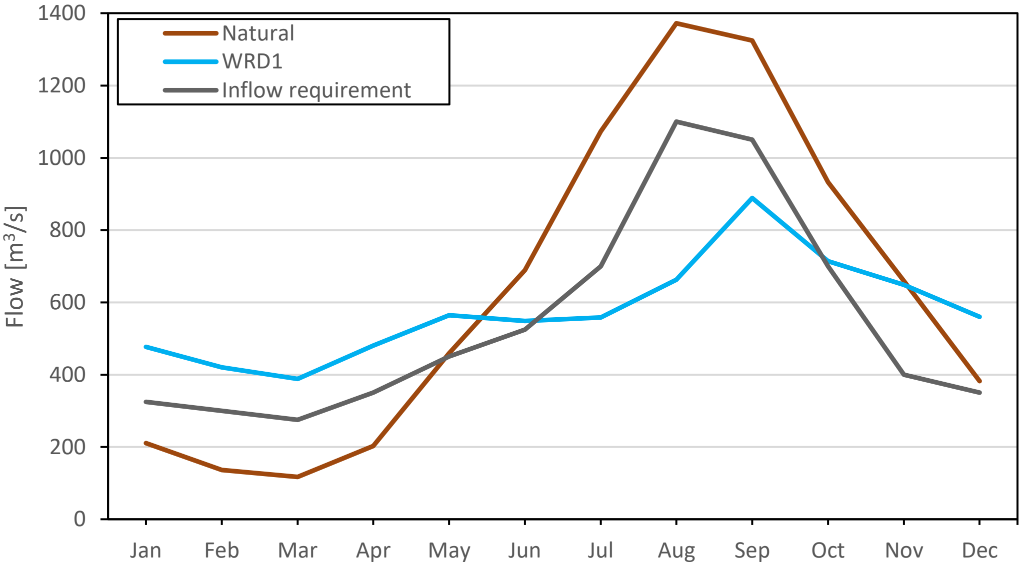


Figure 4.17 The monthly means of lake inflow for WRD1 and the natural scenario. A requirement is developed which has a seasonal variation while still allowing production in the dry season

The daily averages for the whole year are calculated for the natural flow, and a factor is calculated to resize the natural flow value each day to the flow dictated by the requirement curve in Figure 4.17. The natural flow for the entire modelling period is then adjusted with these factors. This gives a flow time series that varies as specified by the requirement curve but allows for variations from year to year. In this way, there is less flow in a dry year than in a wet year. The requirement therefore follows the hydrology, and the system is not forced to fulfil high flow requirements in years where there is little water. The values are adjusted to have the same mean as WRD1. This time series is then used as the requirement for inflow to the lake.

4.3.2 Results

Lake Inflow

Figure 4.18 shows duration curves for the actual inflow and the required inflows to RAM1. There is very good agreement between the curves, indicating that the model fulfils the inflow requirements. In fact, the inflow seems to be slightly higher than the requirement, probably due to extra spilling in the reservoirs.

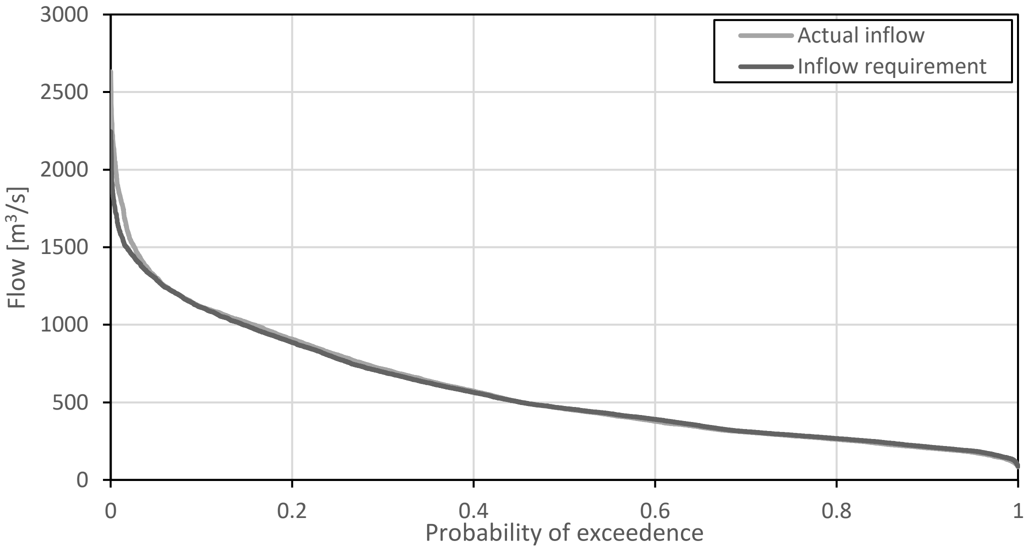


Figure 4.18 Duration curves for the actual inflow to the lake and the inflow requirement in RAM1

Figure 4.19 compares the duration curves of the lake inflow for RAM1, WRD1, and natural flow. For WRD1 the central part of the curve is relatively flat due to very constant flows for hydropower production. As would be expected from Figure 4.17, the duration curve for RAM1 is approximately in between WRD1 and natural flow. While the RAM1 curve is smoother than WRD1, it is clear that some concessions have been made to hydropower production. The natural flow reaches both higher and lower levels than the flow in RAM1 and has a smoother course.

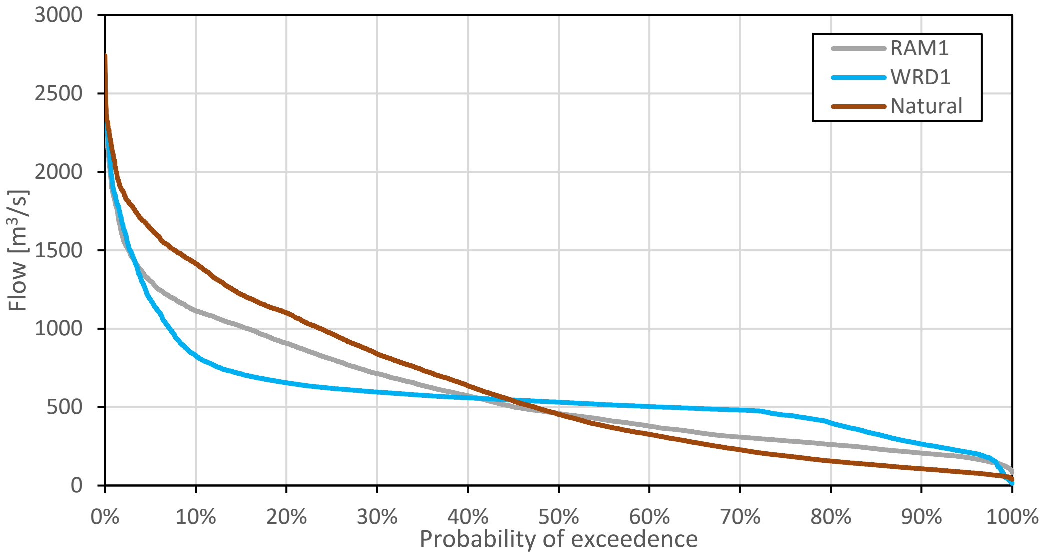


Figure 4.19 Duration curve for lake inflow in RAM1, WRD1 and the natural scenario

Lake Water Level

The water levels in the natural scenario, WRD1, and RAM1 are shown in Figure 4.20. Although the purpose of RAM1 was not to increase lake water levels, it can be seen that they have risen by approximately half a metre at the end of the simulation period. While the fluctuations are not as large as for the natural flow – since the variation in inflow in the inflow requirement is smaller – they are clearly improved in comparison with WRD1.

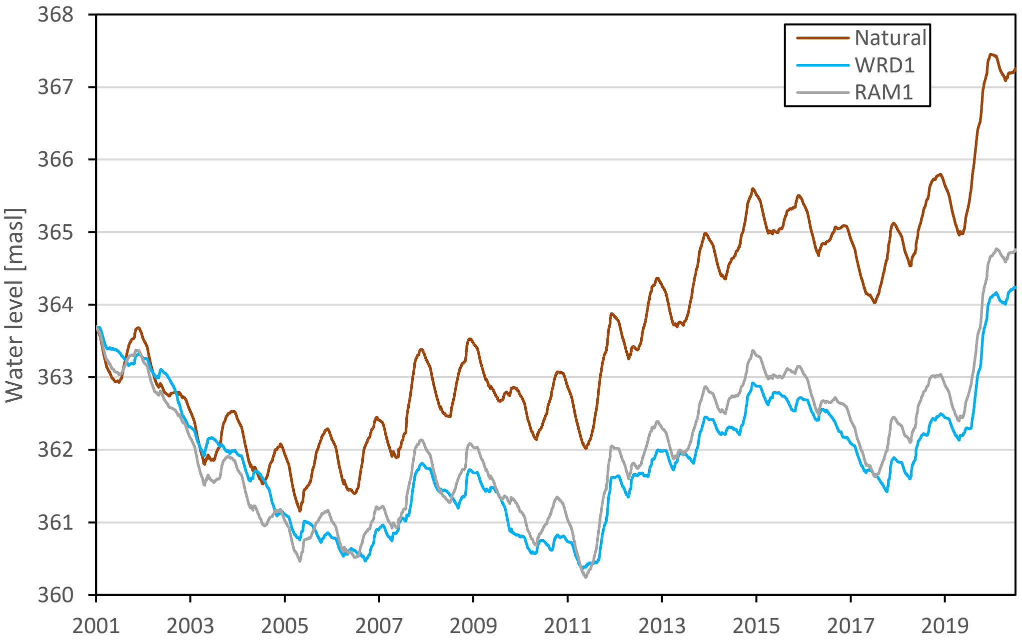


Figure 4.20 Lake Turkana water levels in the natural scenario, WRD1, and RAM1.

The mean annual water levels of the three scenarios are shown in Figure 4.21. The black line indicates the water level of 362 m.a.s.l which is a critical water level for the lake as Ferguson’s Gulf dries out below this level. This is one of the major breeding grounds for fish and thus has a large importance for fish production in the lake. The average annual water level is below this value only three times for the natural flow, while this number is 10 for both WRD1 and RAM1.

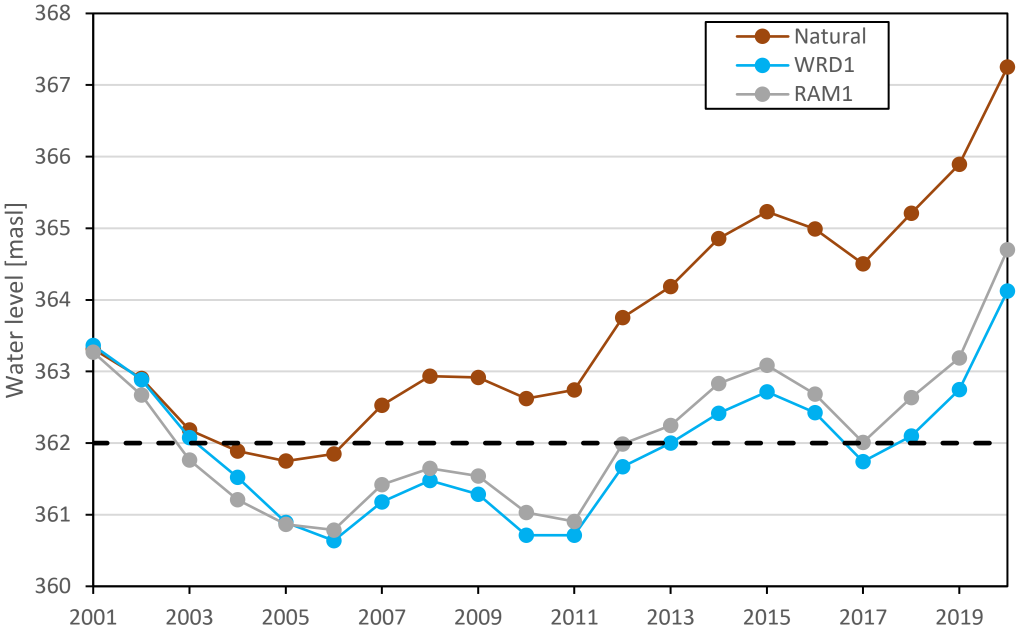


Figure 4.21 Mean annual water level in Lake Turkana. The black line indicates the water level 362 masl which is a critical water level with regard to fish production in the lake.

Figure 4.22 shows the annual fluctuations, that is, the difference between maximum water level and minimum water level each year. RAM1 generally causes larger variations than WRD1 although they are not as high in the natural flow. There are several years where the natural water level fluctuations are within the 1-1.5 m range that is optimal for fish production, but RAM1 is rarely in this range. However, there is a clear improvement over WRD1.

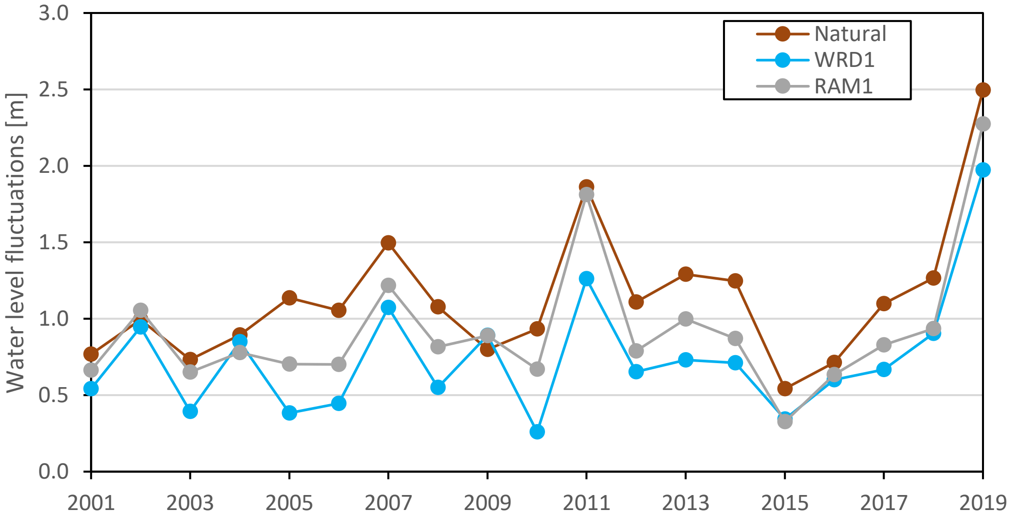


Figure 4.22 Water level fluctuations for natural flow, WRD1, and RAM1. Note that the plot only includes full years in the simulation period, i.e. until 2019

Hydropower Production

When looking at the total hydropower production from Gibe III and Koysha, this increases by 2% from WRD1 to RAM1. However, the distribution over the year changes significantly, as seen in Figure 4.23. Where WRD1 has a continuous production over the year and higher production in the wet months, RAM 1 has a more gradual variation over the year. The smaller peak in February-March coincides with months where the demands of the Kuraz Sugar Plantation are high, and water is discharged to meet these demands. This shows that even though the total production for RAM1 is slightly higher than in WRD1, there would be requirements for alternative power sources during the dry months while it should be ensured that power is not wasted in the wet season.

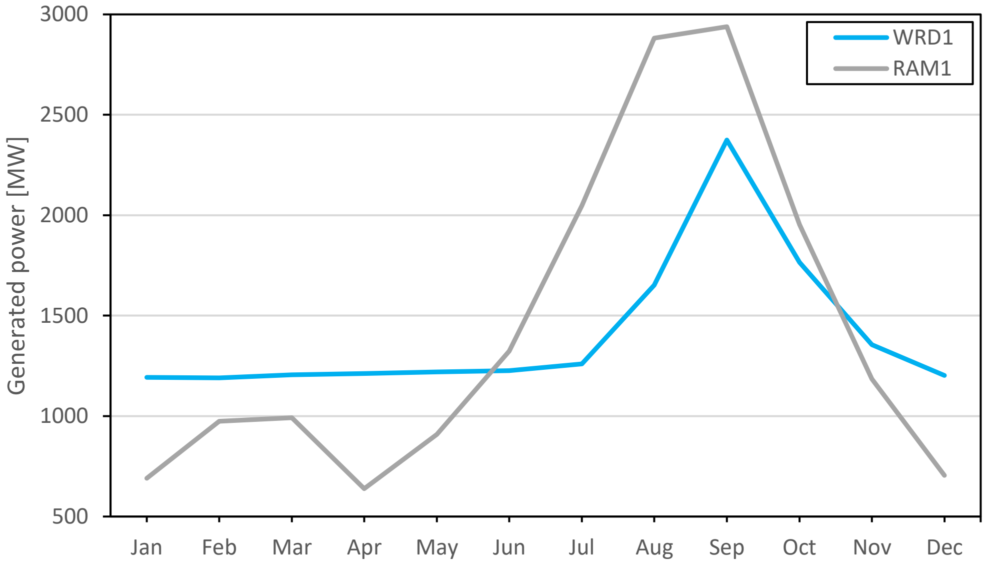


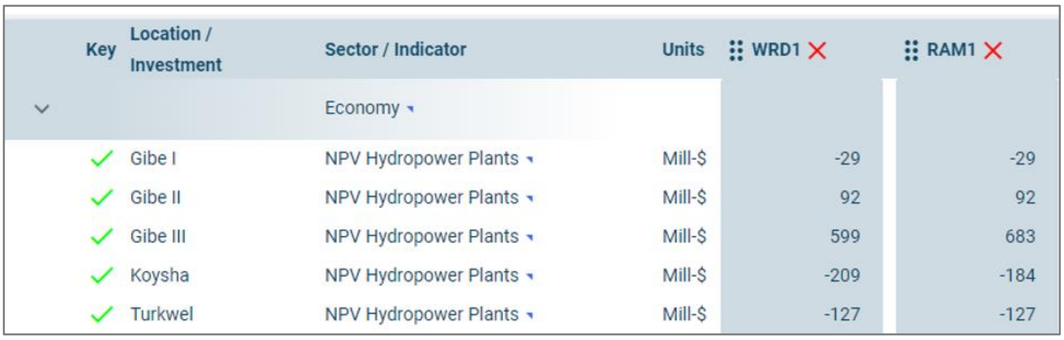
Figure 4.23 Generated power for Gibe III and Koysha in the scenarios WRD1 and RAM1

The changes in hydropower production are also reflected in Figure 4.24. While the total hydropower production is almost unchanged, and slightly increased, for RAM1, the firm hydropower has decreased significantly to be replaced with secondary hydropower.

Key	Sector / Indicator	Units	RAM1	WRD1
	Energy			
✓	Firm Hydropower Production	GWh	7.352,9	12.075,6
✓	Secondary Hydropower Production	GWh	7.573	2.626
✓	Total Hydropower Production	GWh	14.925	14.702

Figure 4.24 Hydropower production in the basin. Screenshot from the Planning Tool

Figure 4.25 shows the NPV for all hydropower plants in the basin. As expected from the previous results, RAM1 has a positive impact on the NPVs for Gibe III and Koysha.



Key	Location / Investment	Sector / Indicator	Units	WRD1	RAM1
		Economy			
✓	Gibe I	NPV Hydropower Plants	Mill-$	-29	-29
✓	Gibe II	NPV Hydropower Plants	Mill-$	92	92
✓	Gibe III	NPV Hydropower Plants	Mill-$	599	683
✓	Koysha	NPV Hydropower Plants	Mill-$	-209	-184
✓	Turkwel	NPV Hydropower Plants	Mill-$	-127	-127

Figure 4.25 NPV for hydropower plants in the basin. Screenshot from the Planning Tool

Fish Production

The results for water levels and water level fluctuations, which have impacts on fish production, have been discussed previously. The actual fish production indicators can be seen in Table 4.1. RAM1 has a positive impact, but not a significant one. The fish catch per boat, calculated based on water levels, has increased by 1 tonne on average. 5% of the simulation period, corresponding to one year, have moved from too low to neutral.

To improve these results, stronger measures would be necessary. Increasing the water level would be challenging as this requires less water to be taken out of the system. This could primarily be accomplished by reducing the area of the Kuraz Sugar Plantation. It is possible that more optimal fluctuations could be achieved with the current system, but that would come at the cost of a further reduction of hydropower in the dry season and thus of firm power production. Depending on the size of the flows in the wet season, it is possible that these would exceed capacity, leading to spilling without production.

Table 4.1 Fish production indicators for WRD 1 and RAM 1

		WRD 1	**RAM 1**
Average fish production as function of water level (tonnes/boat)		10	11
Water level fluctuations (% of simulation period)	Too low	85	80
	Optimal	10	10
	Neutral	5	10

4.4 RAM 2: Reforestation, Soil and Water Conservation

4.4.1 Background

The background for this scenario is described quite thoroughly in UNEP-DHI, 2020d, and this section primarily provides a summary of the most important points. The purpose of this scenario is to assess how reforestation, agroforestry, and soil and water conservation measures may reduce flooding, soil erosion, and landslides. The focus is on West Pokot in Kenya, which has experienced severe landslides, flooding and land degradation due to deforestation and cultivation on steep slopes. The changes are simulated by changing the model parameters in the rainfall-runoff models in the catchment.

Reforestation, agroforestry and soil and water will have an impact on the water balance, the path the water will take, as well as the soil and nutrient balances. The impact on soil and nutrients will be discussed briefly towards the end of this section.

The RAM 2 scenario is based on WRD 1 and the measures are only implemented in one model catchment in the West Pokot area, which is a headwater sub-catchment in the Turkwel catchments. The results from RAM 2 will therefore only be compared to the results from this catchment in WRD 1, and the focus will be on the following three indicators:

1) Overland Flow Index: This describes the overland flow as percentage of the overland flow in WRD 1. The overland flow is that part of the rainfall which is not intercepted and does not infiltrate into the soil.

2) Groundwater Recharge Index: This describes the groundwater recharge as percentage of the groundwater recharge in WRD 1.

3) Total Runoff Index: This describes the total runoff from the catchment as a percentage of the total runoff in WRD 1.

Several previous studies aiming at assessing the impact of land use changes have been carried out in Kenya. Jacobs et al. (2007) and Hunink et al. (2011) conducted studies in the Upper Tana River Basin using the modelling software Soil & Water Assessment Tool (SWAT).

In this project, the NAM[4] rainfall-runoff model generates catchment runoff based on a set of calibrated model parameters. The calibrated NAM model from WRD 1 was used, to assess how some of the model parameters are likely to change when the RAM 2 measures are fully implemented, then re-run the NAM model, compare the results and calculate the indicators described above for both scenarios.

There are a number of challenges and uncertainties related to the modelling of the effect of the RAM 2 measures:

It is well understood that trees and bushes provide better protection against rainfall and increase infiltration and evaporation losses, thereby reducing the total runoff. However, the magnitude of these effects is hard to quantify without thorough knowledge about other parameters such as slope steepness, soil type, etc.

The NAM rainfall-runoff model is a lumped model, meaning that it is not spatially distributed across the catchment.

The catchment is, like any other catchment, heterogenous in terms of slope, soils, existing land use practice, so it is not one well-defined land use practice the measures are applied to.

The NAM rainfall-runoff model is not a physically based model. Although the parameters are correlated to the physiography of the catchment, the parameters are not directly linked to e.g., the soil physics or depth of plant roots.

This means that when trying to simulate the RAM 2 measures, the selection of model parameters will rest on an “expert judgement” and experience built up from numerous studies in different environments. However, no matter how experienced the modeller is, the selection of representative model parameters will always have a certain degree of subjectivity and uncertainty. For the same reason, the scenario results will be associated with a substantial margin of error.

When assessing the modified NAM model parameters, it was assumed that the following measures were implemented in the catchment:

1. Planting of vetiver grass along the contours to stabilize slopes with their deep root system, reducing surface runoff and slowly build up small terraces,
2. Planting of agroforestry species with roots which are good at anchoring and binding soils (Hairiah et al., 2020) in those parts of the catchment most prone to erosion.

As mentioned above selection of modified NAM model parameters are based on an “expert judgement”. However, previous studies where the NAM model has been applied

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[4] The NAM model (MIKE by DHI) is a deterministic, lumped and conceptual rainfall-runoff model accounting for the water content in up to four different storages. NAM can be prepared in a number of different modes depending on the requirement. As default, NAM is prepared with nine parameters representing the surface zone, root zone and the groundwater storages.

to and calibrated for catchments similar to the land use practices in RAM 2 have been reviewed.

In the NAM model the following four key model parameters have been modified:

3. Umax / Maximum water content in the surface storage: This has been increased considerably in RAM 2 due to the fact that a substantial amount of water can be stored and later infiltrate behind the vetiver grass planted along the contours and increased interception losses due to the trees.
4. Lmax / Maximum water content in the root zone storage: This has been increased considerably in RAM 2 as the measures are able to maintain the existing soil and not least due to a deeper root net from especially the trees.
5. CQOF / Overland flow runoff coefficient: This parameter has been reduced very considerably due to the planting of vetiver grass along the contours and tree cover on the steepest slopes.
6. CK12 / Time constant for routing of overland flow: This one has been increased due to longer travelling for the overland flow which takes place.

The comparison of the RAM 2 results with the original WRD 1 result, presented and discussed below.

4.4.2 Results

Total Runoff Index

The total runoff index is shown in Figure 4.26. The runoff has decreased by approximately 15% in RAM 1 compared to WRD 1. This reduction is due to increased evapotranspiration caused by a better land cover but primarily due to reforestation, which creates a dense and deep root network able to extract additional soil moisture particularly during the dry season. Being a lumped model, it assumes that the measures are implemented in the whole catchment, which will not take place in reality. Thus, as the measures will only take place in part of the catchment, the decrease in total runoff is likely to be considerably less than 15%.

Overland Flow Index

As seen in Figure 4.26, the overland flow index, which expresses overland flow in the scenarios as a percentage of the overland flow in WRD 1 has decreased significantly in RAM 2, to approximately 45% of WRD 1. This reduction in overland flow shows a significant impact of land cover change and a possibility to reduce in the risk of floods and landslides by changing the land cover and land use. It should be noted that the magnitude of these results is quite uncertain due to lack of knowledge of other characteristics of the catchment. However, they clearly indicate that a reduction in overland flow and thereby a positive impact on soil erosion and flooding downstream can be expected from implementing the RAM 2 measures.

Groundwater Recharge

The groundwater recharge index is shown in Figure 4.26. The groundwater recharge increases by approximately 10% in RAM 2 when comparing with WRD 1. The reason that groundwater recharge does not rise proportionately with the fall in overland flow is due to the reduction of total flow caused by increased evapotranspiration as discussed earlier.

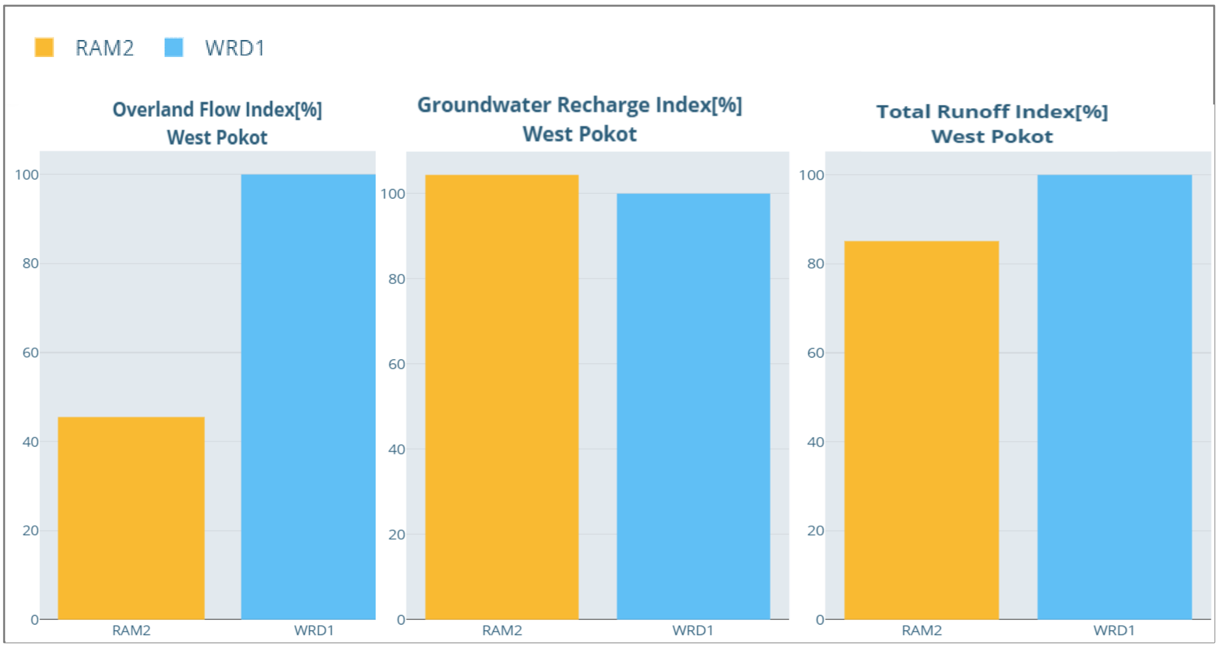


Figure 4.26 The Total Runoff Index, Overland Flow Index and Groundwater Recharge Index for RAM1 and WRD1. The index expresses a percentage of WRD1, which is the reason why values are 100 for WRD 1.

The likely effect of the simulated soil conservation measures is a considerable reduction in overland flow. This along with reforestation will increase evaporation which is why groundwater recharge is not proportionally higher in the middle plot in Figure 4.26, only slightly. In turn, total runoff is reduced due to increased evaporation.

The results are of a similar range as found by Hunink et al. (2011) although the reduction in overland flow is higher in this study. But the direction of impact is the same as in Hunink et al. (2011) for all indicators.

The RAM 2 measures should, however, not only be considered as re-active measures but also as pro-active measures. Re-active to remedy already existing problems as those in West Pokot, and pro-active as measures to be implemented in existing cultivated areas, as well as being integrated part of the conversion of other land uses to cultivated areas. The latter, to ensure a sustainable conversion to cultivation in terms of water, soil, and nutrients.

Also, geographically RAM 2 can be applied throughout the Omo-Turkana Basin, in both Kenya and Ethiopia, where the above-mentioned conditions apply.

The type of rehabilitation measures included in RAM 2 is overall considered to be beneficial wherever they are implemented.

Locally, it will have many advantages:

Soil and water conservation measures will increase infiltration, reduce surface runoff and therefore retain and conserve water, soil and nutrients, and help maintaining crop yields.

Reforestation will have a similar impact as the soil and water conservation measures. Added to that, their root network will help stabilizing the soils. Due to increased evapotranspiration, it will reduce the risk of saturated soils. Thereby reforestation will significantly help reducing the risk of landslides and mudflows as experienced in West Pokot.

Agroforestry will have two additional advantages: Intercropping crops with leguminous N_2-fixing agroforestry species, e.g. Acacia and Caleandra, can help replenish nitrogen harvested with crops and thereby maintain the N-balance and reduce the need for artificial fertilizers. Fodder trees can also be an important feed source for livestock and reduce livestock pressure on grassland.

Downstream, the impacts may be the following:

The risk of flash floods and flooding in general will be considerably reduced.

A clear improvement of the water quality in the rivers downstream, including less turbidity and less E coli.

A likely increase of total evapotranspiration locally and corresponding likely decrease of total annual runoff. The magnitude of the decrease in total runoff from a catchment will depend on the type and extent of measures implemented, but as they only are likely to be implemented in parts of the catchments, the reduction in annual runoff will in most cases be within 0-10%.

As the total annual runoff may be slightly reduced, the measures may slightly reduce inflow to Lake Turkana, but the impact is considered to be small compared to the impact of abstraction for irrigation. This may, however, add to the impact of irrigation and thereby be considered as a slightly negative impact on the water level in Lake Turkana. On the other hand, it may in the future counterbalance increased inflow due to climate change and thereby be a win-win situation.

From a global perspective reforestation and agroforestry may also help fighting global warming and help restoring habitat loss.

All in all, RAM 2 is considered a rehabilitation measure from which both countries will benefit. The benefits will mainly be onsite benefits and will particularly ensure a more efficient and not least more sustainable crop production and conversion from other land uses to cultivation.

4.5 RAM 3: Riparian Land Legislation

4.5.1 Background

The purpose of this scenario is to reduce the risk of damage due to Lake Turkana water level rise by enforcing riparian land legislation which prohibits building of permanent structures and waste disposal within 30m horizontal distance or 2m vertical height of the highest recorded water level.

In this scenario we enforce riparian land legislation and therefore it is assumed there are no permanent structures built within 2 m vertical height from the highest recorded water level of 366.8 m.a.s.l, therefore within 368.8 m.a.s.l. The highest recorded water level of 366.8 m.a.s.l. was taken from the Jason dataset in the portal recorded in November 2020 as shown in Figure 4.27.

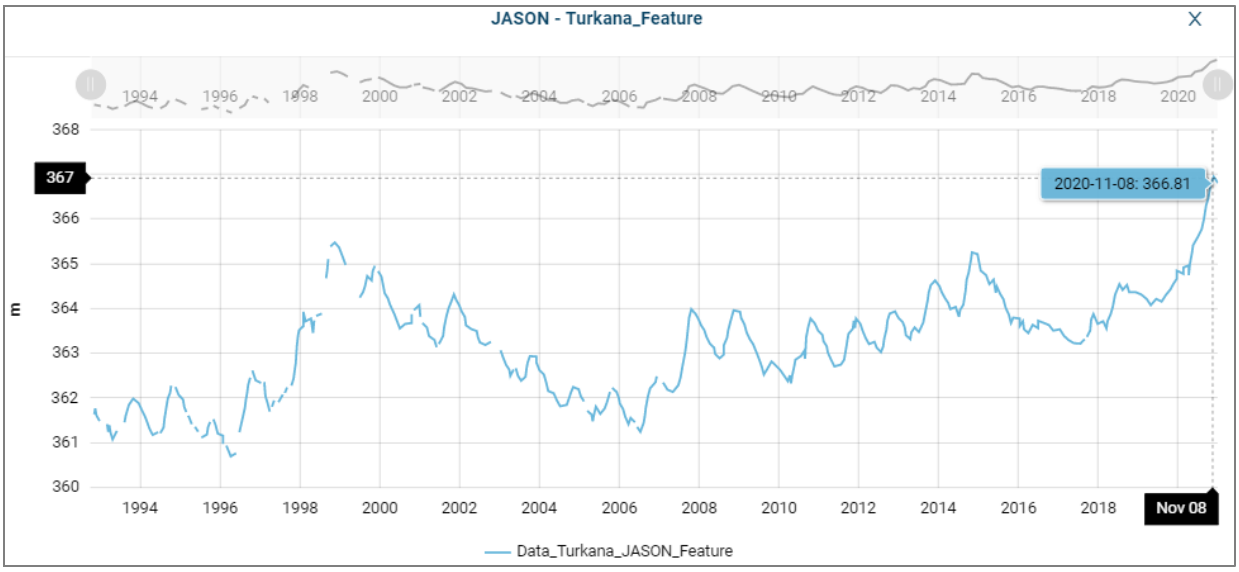


Figure 4.27 Water level of Lake Turkana with highest recorded level of 366.8 m.a.s.l in November 2020 (Jason dataset from the Portal)

4.5.2 Results

This scenario is based on WRD1 and there is no change to the model in this scenario, therefore the model outputs are the same as WRD1. The only difference in results between RAM3 and WRD1 is the number of settlements inundated indicator. Note that this scenario does not include any other potential impacts of building permanent structures further away from the lake, for example negative impacts of being a greater distance away from the lake and taking longer to access the lake.

Flooding

The maximum water level in Lake Turkana from the model output (in WRD1) is 364 m.a.s.l which is well below the demarcation of riparian land defined as below 368.8 m.a.s.l. In RAM3 construction is prohibited below 368.8 m.a.s.l., therefore in RAM3 no settlements are inundated by the rising water levels of Lake Turkana compared to eight settlements inundated in WRD1 on the west side of the lake around the Gulf of Ferguson and on the shoreline near Kerio and Eliye springs.

The riparian land demarcation is shown in red in Figure 4.28 where permanent structures are prohibited in RAM3, and the lake extent at its maximum water level in WRD1 (364 m.a.s.l) is shown in blue. The lake extent is calculated using DHI's Flood Screener based on the DEM and the water level of the lake. Existing settlements around Lake Turkana are shown in yellow.

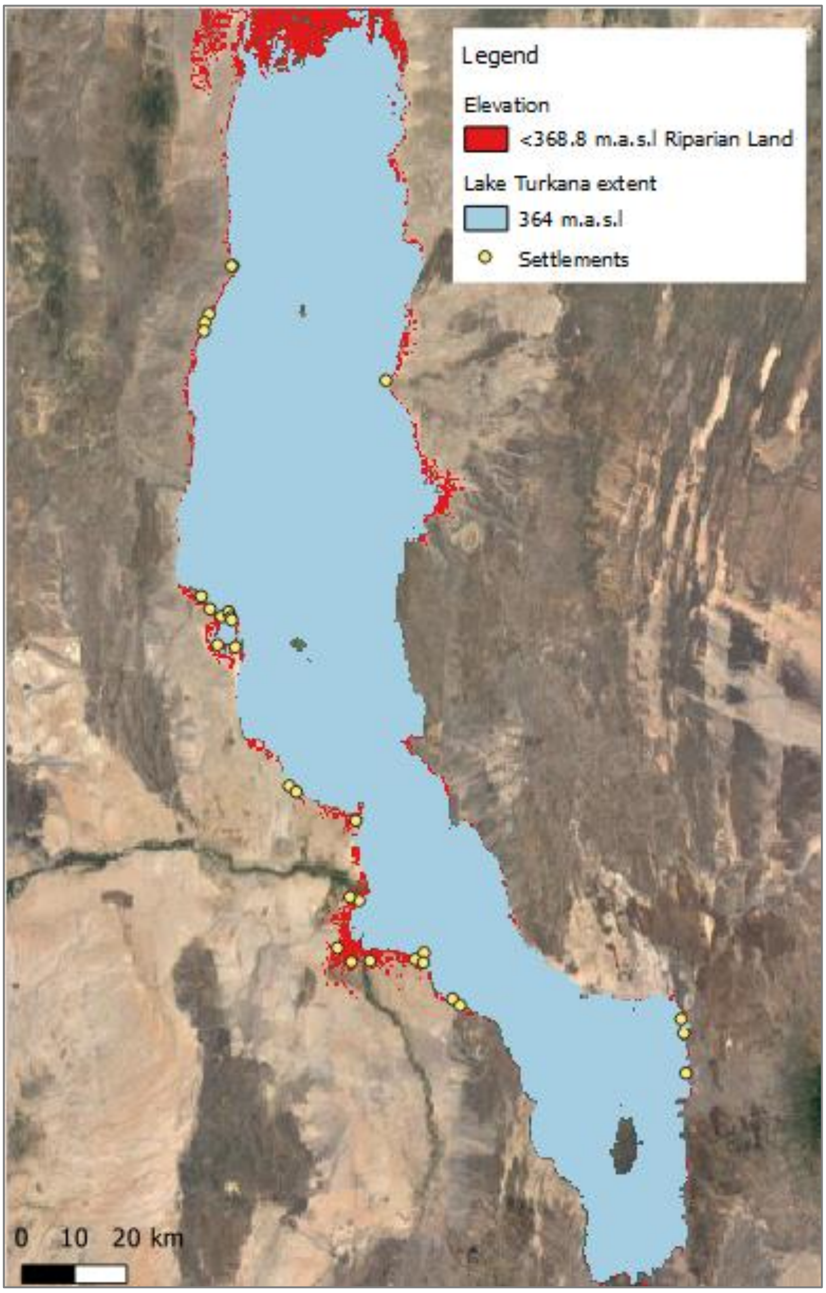


Figure 4.28 Riparian land demarcation (red) and Lake Turkana water level 364 m.a.s.l. (blue) with existing location of settlements.

In addition, it is interesting for this rehabilitation measure to look at the maximum water level of Lake Turkana across all scenarios. The maximum water level in Lake Turkana across all scenarios is in scenario CC2 (extreme radiation forcing scenario RCP 8.5) where the water level reaches 367.0 m.a.s.l.. This maximum water level is still below the riparian land demarcation level of 368.8 m.a.s.l.. Therefore, if the riparian land enforcement rehabilitation measure from RAM3 is applied, there would be no inundated settlements across all future scenarios, including climate change scenarios.

The settlements colour coded according to the water level when at least one structure or household in the settlement is inundated by rising water levels of Lake Turkana is shown in Figure 4.29.

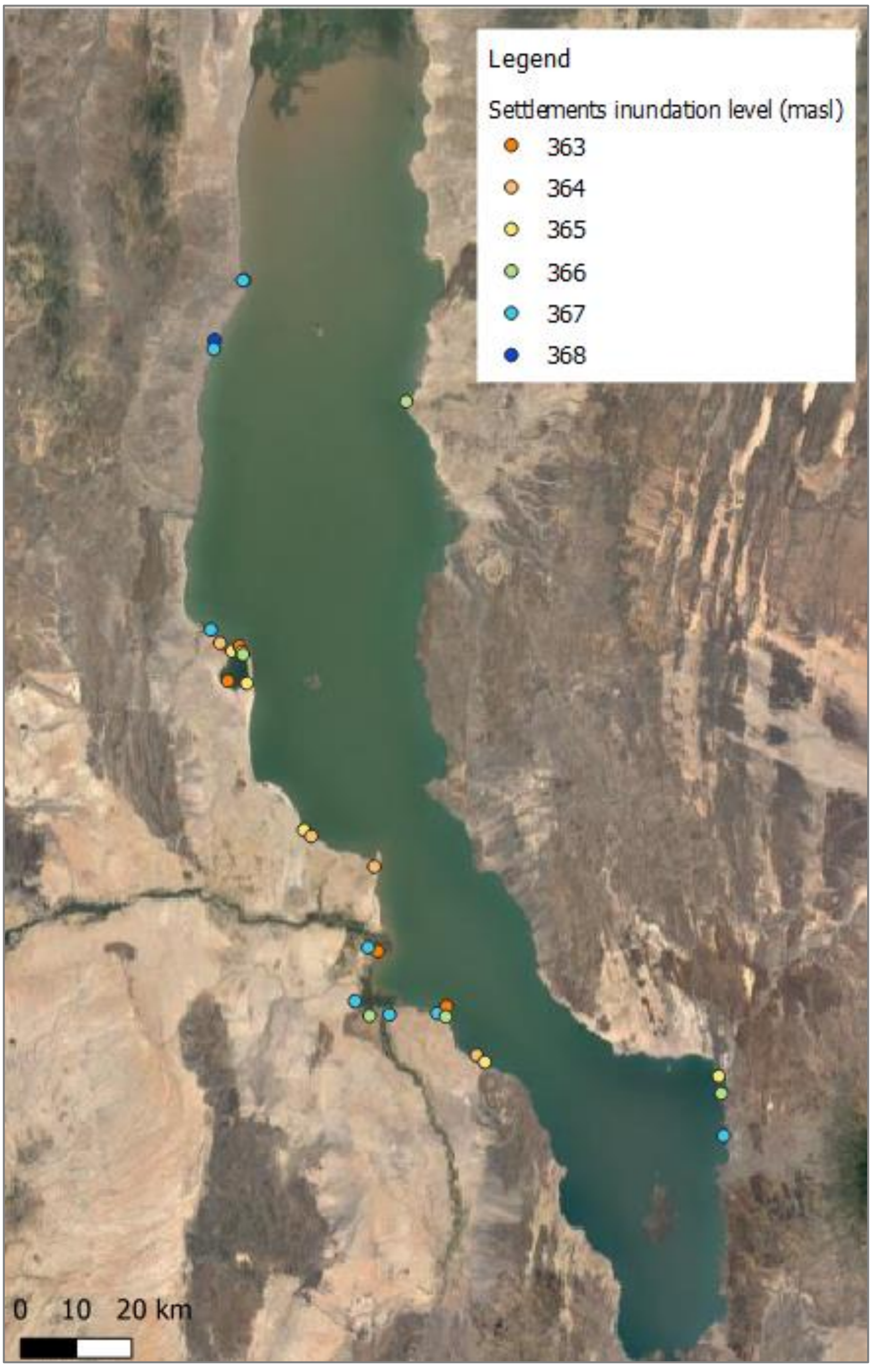


Figure 4.29 Settlements inundated at different water levels of Lake Turkana.

4.6 RAM 4: Transfer to Lake Logipi

4.6.1 Background

This scenario is based on WRD1 and includes construction of an outlet from Lake Turkana to nearby Lake Logipi (see Figure 4.32) to make it possible to discharge water from Lake Turkana to Lake Logipi in years with high water levels. Water is discharged from Lake Turkana when the water level is 364 m.a.s.l. or above and transferred to Lake Logipi.

In the indicators and results we have only looked at the impact of this rehabilitation measure on Lake Turkana and the surrounding settlements. We have not assessed the negative impact on the Lake Logipi ecosystem. This could be significant given the ecological importance of the lake, for example to Flamingoes that frequently inhabit the saline waters feeding on cyanobacteria and other plankton (Mathea, 2009). We have also not included assessment of the construction, operation and maintenance costs of building the infrastructure to deliver water from Lake Turkana to Lake Logipi.

4.6.2 Results

The results of this scenario only differ from WRD1 when the water level in Lake Turkana exceeds 364 m.a.s.l.. This only occurs in one year of the WRD1 scenario, in the last year of the simulation, as shown in Figure 4.30.

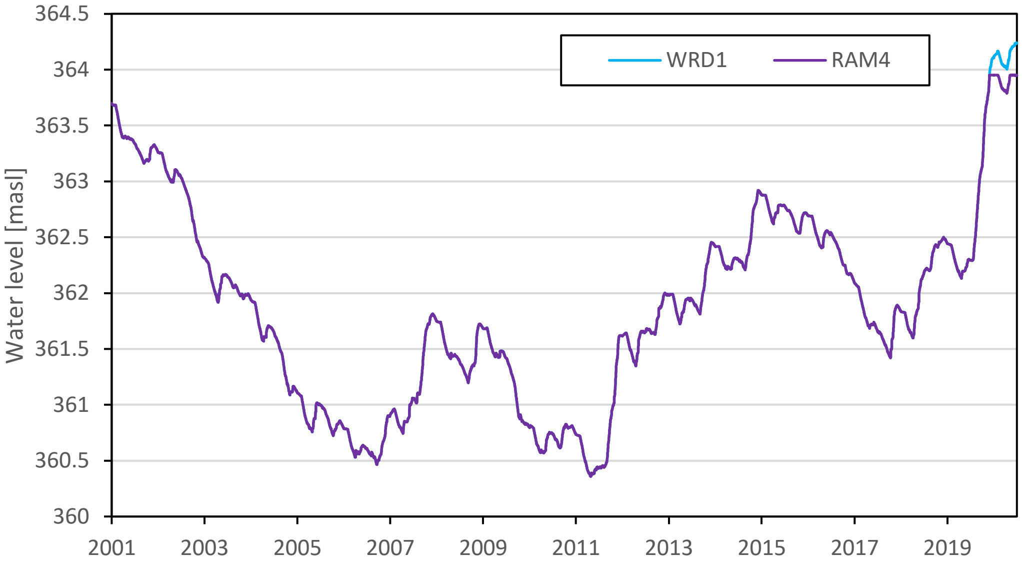


Figure 4.30 Water level in Lake Turkana in WRD1 and RAM4, showing the difference in the last year of simulation where the water level exceeds 364 m.a.s.l. in WRD1.

In RAM4, the water level in Lake Turkana remains below 364 m.a.s.l. because water above this level is discharged to Lake Logipi.

Flooding

In RAM4 only 4 settlements are inundated on the west side of the lake in Ferguson's Gulf and on the lake shoreline near Kerio. These are settlements that have at least one household or structure inundated when Lake Turkana water levels are at 363 m.a.s.l. Applying this rehabilitation measure of discharging water to Lake Logipi means that the water level in Lake Turkana will never exceed 364 m.a.s.l. and therefore no more than 4 settlements (based on their current location) will ever be inundated. In contrast, in WRD1 8 settlements are inundated with lake water levels reaching over 364 m.a.s.l.. These settlements are on the west side of the lake around the Ferguson's Gulf and on the shoreline near Kerio and Eliye Springs. In CC2 28 settlements are inundated (with lake water levels reaching over 367 m.a.s.l) mostly on the west side of the Lake.

In WRD1 water levels exceed 364 m.a.s.l. only in the last year of simulation, therefore the percentage of years with water levels above 364 m.a.s.l. resulting in severe inundation is 10% in WRD1 but 0% in RAM4. In contrast, in CC2 the percentage of years with severe inundation is 40% but this would be reduced to 0% if the rehabilitation measures from RAM4 were applied.

Lake Logipi

In WRD1 water would be transferred to Lake Logipi in only one year of the simulation period of 20 years. However in the CC2 scenario water would be transferred to Lake Logipi in 8 years of the simulation period so it is likely to have a much greater impact on Lake Logipi.

If we assume that the water level in Lake Logipi is 270 m.a.s.l. at the start of the RAM4 simulation period and that the only water input to Lake Logipi is the discharged water from Lake Turkana, then the water level in Lake Logipi at the end of the RAM4 simulation is 283.5 m.a.s.l. as shown in Figure 4.31.

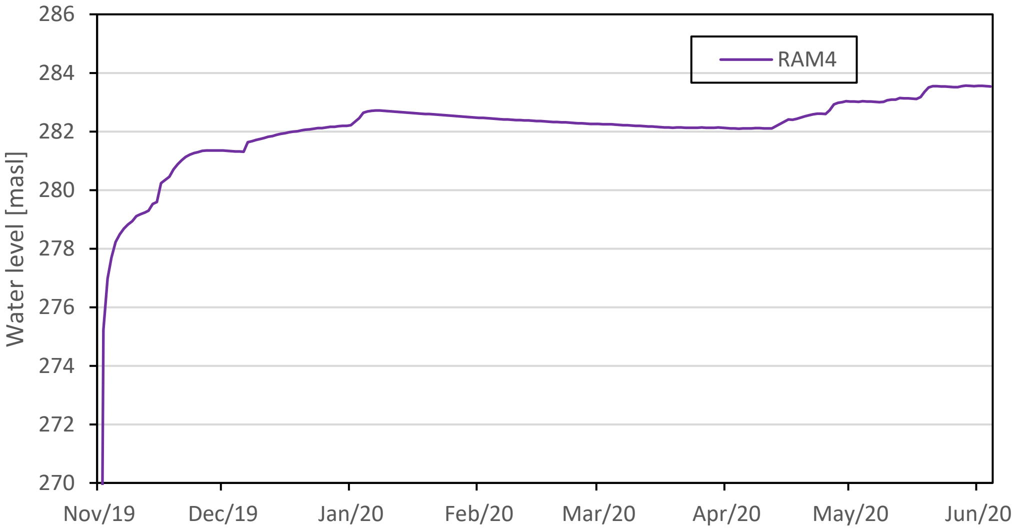


Figure 4.31 Lake Logipi water level in RAM4, assuming the water level is 270 m.a.s.l. at the start of the simulation and the only input is water discharge from Lake Turkana.

The area covered by Lake Logipi when the water level is 283.5 m.a.s.l. is shown in Figure 4.32.

Figure 4.32 Lake Logipi area when the water level is 283.5 m.a.s.l.

4.7 CC 1 & CC 2: Climate Change

4.7.1 Background

The two climate change scenarios are based on RAM1, but with all evaporation and rainfall time series replaced with ones that are adjusted to fit the climate change projections RCP 4.5 (CC1) and RCP 8.5 (CC2). All model objects, reservoir operations, inflow requirements etc. are unchanged.

Climate Change Projections

The two climate change scenarios CC1 and CC2 used in the analysis consist of monthly climate change factors from the World Climate Research Programme CORDEX Africa for two emission scenarios: the medium radiation forcing scenario RCP4.5 and the extreme radiation forcing scenario RCP8.5. The factors represent the ratio between the average in the control model run (1986-2005) and the projection model run (for 2046-2065) for each month. The analysis uses the median of the factors from ensembles generated from ten Regional Climate Models (RCMs). The climate data sets are available from the Data Monitor application in the Water Tools portal where a more detailed description can be found.

The monthly change factors for rainfall and potential evapotranspiration (PET) for the two emissions scenarios have been extracted for each sub-catchment (a total of 66) to reflect the seasonal differences across the Omo-Turkana basin and these have been used in the model scenarios. Figure 4.34-4.36 show maps of the rainfall and potential evapotranspiration factors by season for RCP4.5 and RCP8.5.

The climate change factors for rainfall vary considerably across the basin, both geographically and by season. Looking at scenario 4.5 large reductions in rainfall of 10-50% are seen in the northern part of the basin in Ethiopia in winter and spring whereas increases of 10-20% are observed in middle of the basin in Ethiopia and in the south in Kenya for the same period. The opposite is seen in the summer with large reductions in rainfall around Lake Turkana in the Kenyan part of the basin and in the south compared with increases or small reductions in Ethiopia. In the autumn season rainfall increases across the whole basin with the largest increases in Kenya around Turkwel and in the middle reaches of the Omo. In fact, rainfall consistently increases by 10-50% in the middle reaches of the Omo all year. A similar pattern is observed in scenario 8.5 with large increases in rainfall in the middle reaches of the Omo. Large increases are also seen around Turkwel in the southern part of the basin in the autumn and winter. With respect to evapotranspiration the increase in PET is more constant across the basin with increases of around 5-10% for RCP4.5 and 7-14% for RCP8.5 for all seasons.

In summary, the climate change scenarios indicate drier conditions in the northern part of the basin in winter, spring and summer. In contrast the middle reaches of the Omo basin north of Lake Turkana will be wetter during the same period. In the Kenyan part of the basin the climate scenarios indicate wetter conditions in spring, autumn and winter. This is particularly pronounced in the western part of the basin in the area around Turkwel. Due to differences in the rainfall patterns in the basin as previously reported in UNEP-DHI, 2020c the impact of changes in the climate on the hydrology will vary across the basin. The northern part receives strongly summer dominated precipitation (May-September, peaking in July-Aug) and the middle and southern part receives bi-modal precipitation with peaks in March to May (the ‘long rains season’) and October to December (the ‘short rains season’). Figure 4.33 below shows how the monthly rainfall varies at different locations in the basin in the catchments upstream of Gibe I, Koysha and Turkwel.

The seasonal variation in rainfall has implications for rainfall-runoff and stream flow with reductions in stream flows in the northern part of the basin, increases in the middle reaches of the Omo river as well as increases in the Turkwel area in Kenya. The impacts on the hydrology and implications for irrigation, hydropower production and lake water levels are discussed in more detail in the results section below.

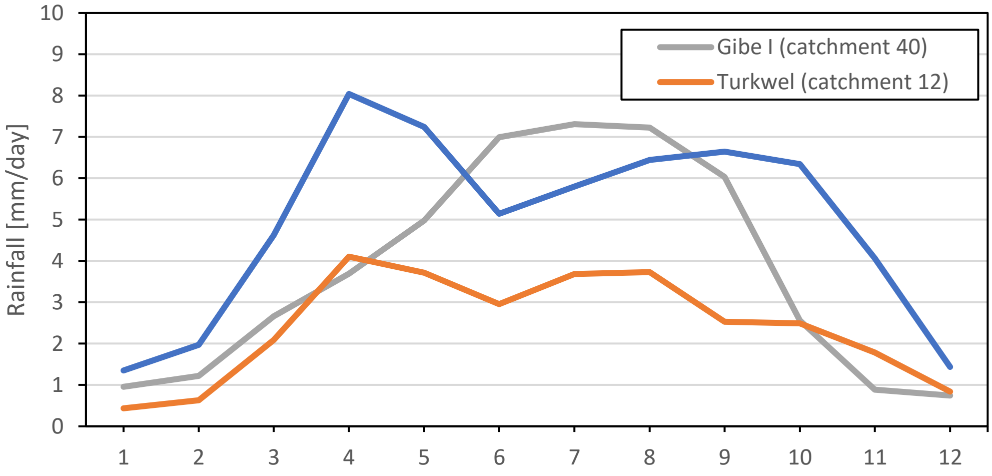


Figure 4.33 Historical average monthly rainfall upstream of Gibe I, Koysha and Turkwel.

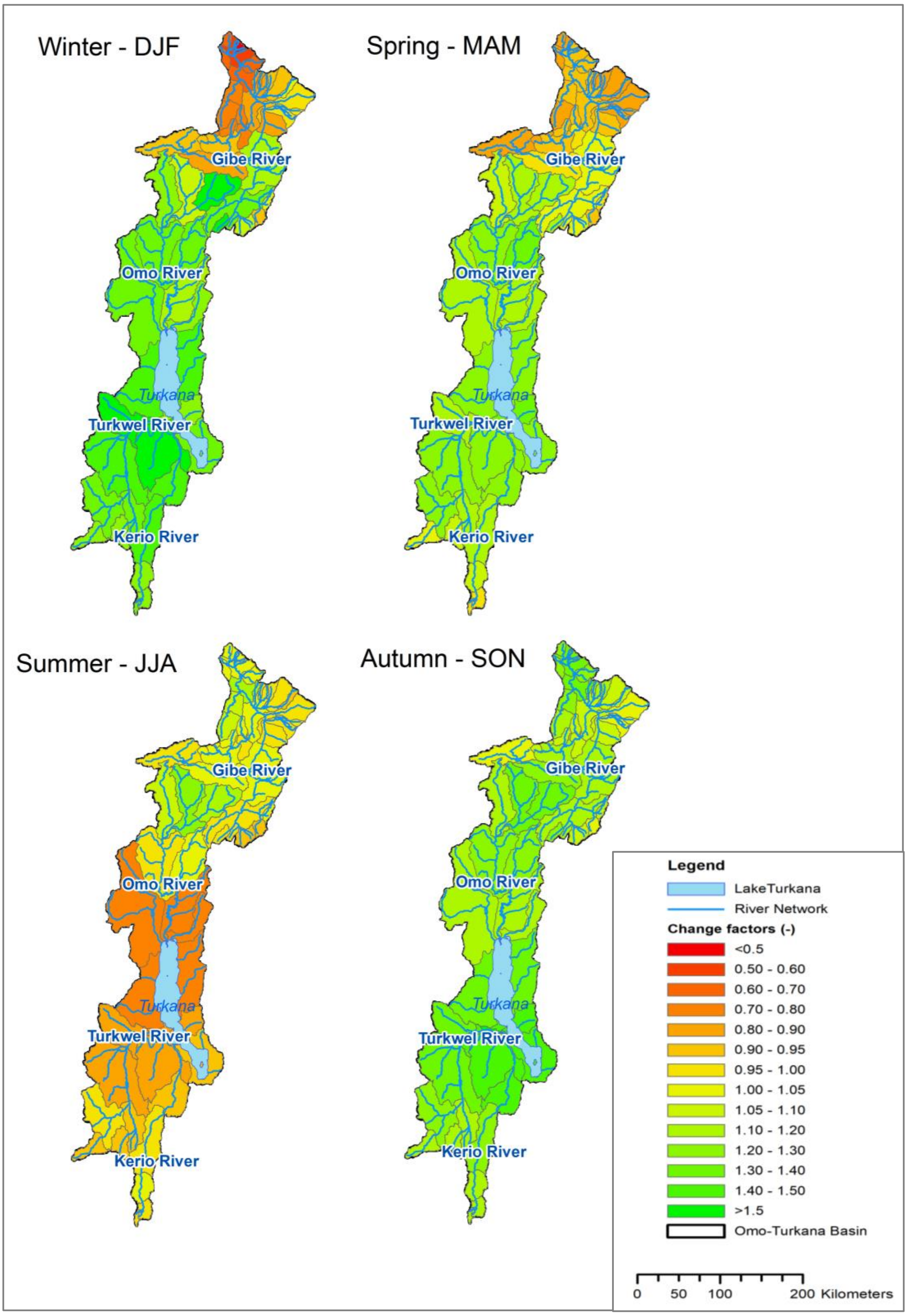


Figure 4.34 Median of seasonal rainfall change factors for 2046-2065 by sub-catchment for emissions scenario RCP4.5. (The seasons are DJF: December-February, MAM: March-May, JJA: July-September and SON: September-November).

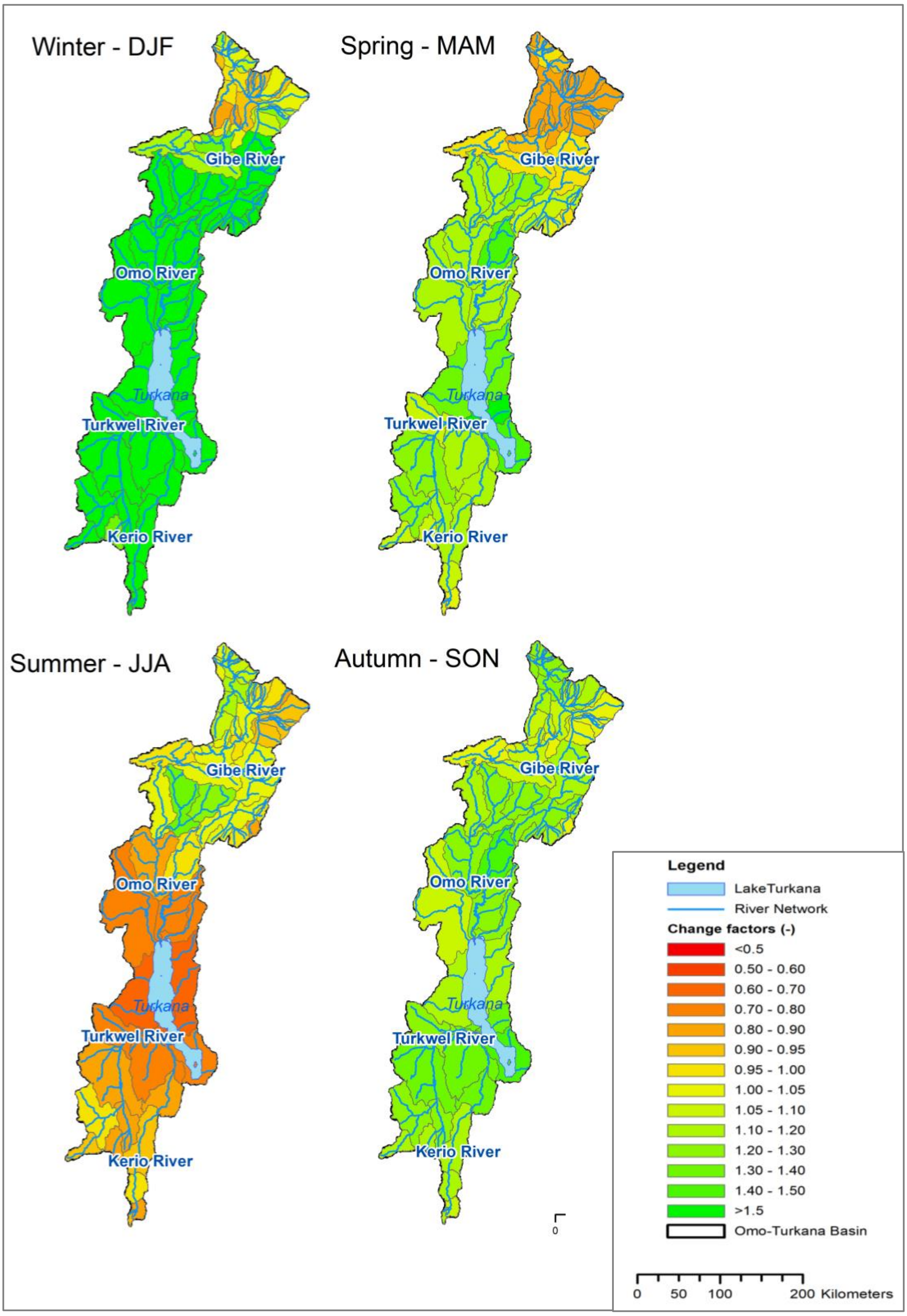


Figure 4.35 Median of seasonal rainfall change factors for 2046-2065 by sub-catchment for emissions scenario RCP8.5. (The seasons are DJF : December-February, MAM: March-May, JJA: July-September and SON: September-November).

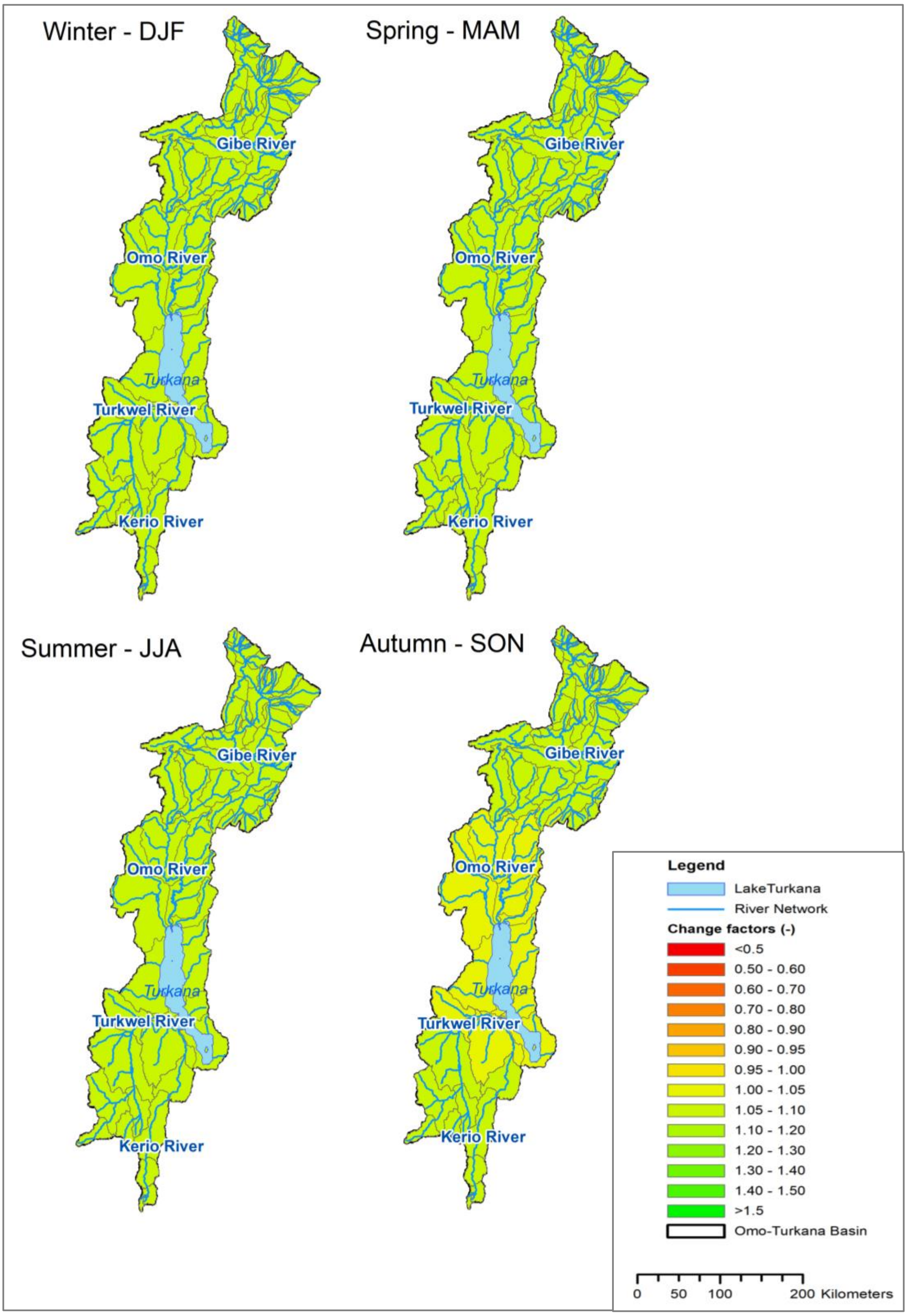


Figure 4.36 Median of seasonal PET change factors for 2046-2065 by sub-catchment for emissions scenario RCP4.5. (The seasons are DJF : December-February, MAM: March-May, JJA: July-September and SON: September-November).

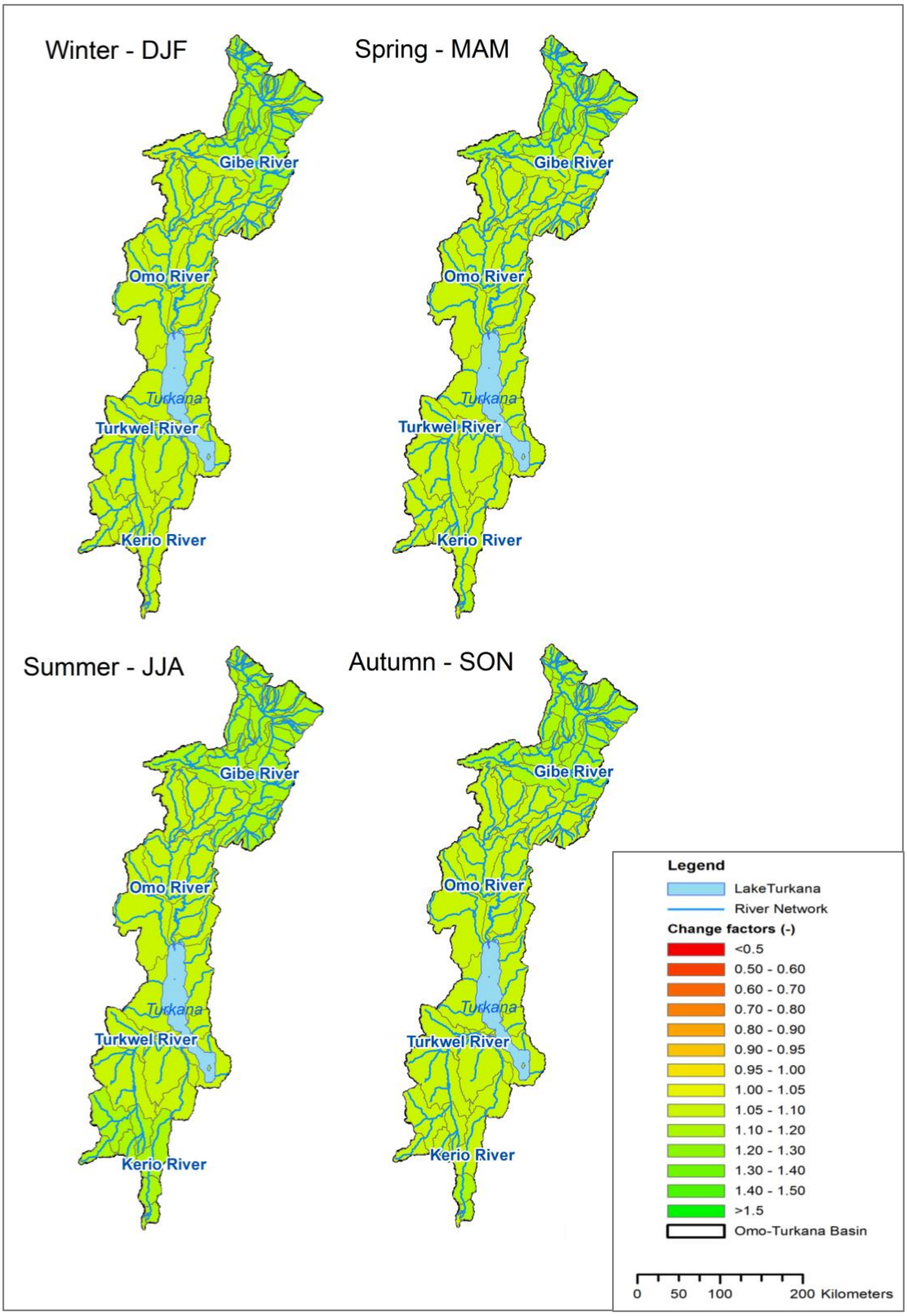


Figure 4.37 Median of seasonal PET change factors for 2046-2065 by sub-catchment for emissions scenario RCP8.5. (The seasons are DJF: December-February, MAM: March-May, JJA: July-September and SON: September-November).

4.7.2 Results

Lake Inflow

As seen in Table 4.2, the inflow from the Omo River to Lake Turkana increases with climate change, by 7% in CC 1 and 11% in CC 2.

Table 4.2 The average inflow to the lake from the Omo River in RAM 1 and the two climate change scenarios.

	Average inflow [m^3/s]	Percentage of RAM1 [%]
RAM1	581.76	
CC1	622.72	107
CC2	643.67	111

The duration curves of the inflow are very similar for the three scenarios (see Figure 4.38), although RAM1 is generally lower.

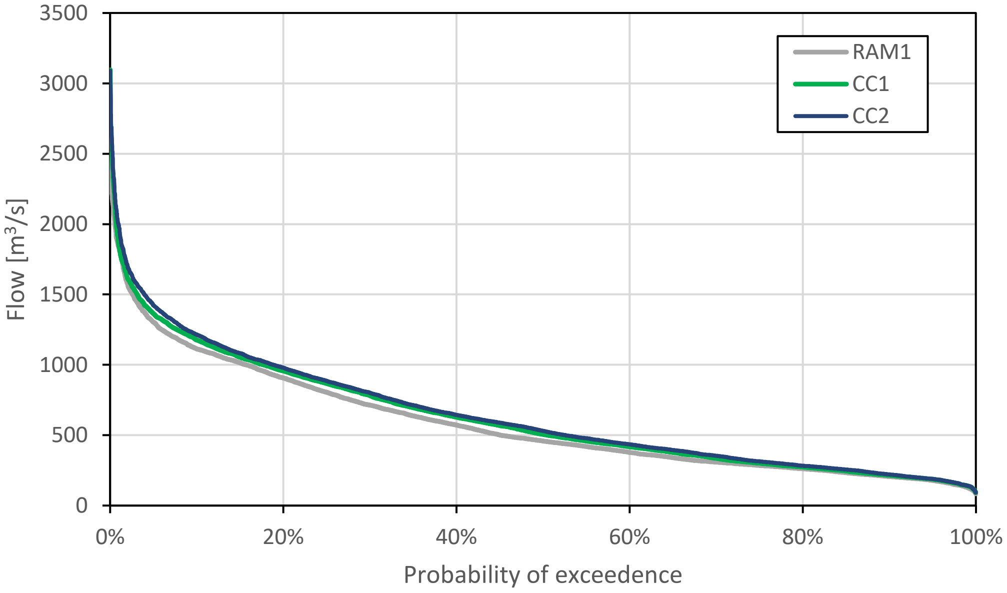


Figure 4.38 Duration curves for the inflow from the Omo River to the lake in RAM1, CC1, and CC2.

The differences are clearer when looking at the monthly means, as shown in Figure 4.39. RAM1 is lower than or similar to the climate change scenarios throughout the year. The differences are largest during March-April and October-December. The climate change scenarios are quite similar although CC2 is slightly higher than CC1 for most of the year.

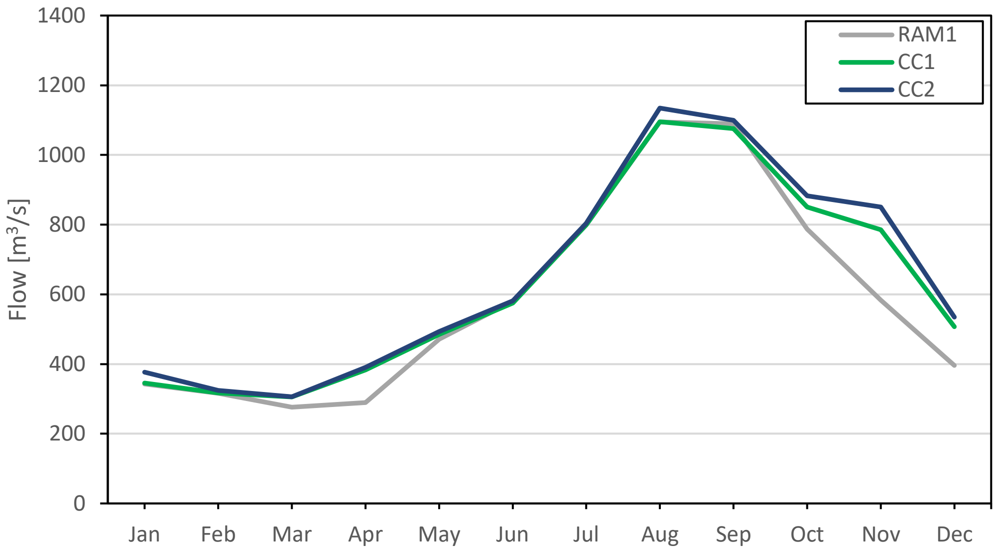


Figure 4.39 Monthly means of the inflow to the lake from the Omo River in RAM1, CC1, and CC2.

When looking at the inflow results, it is important to keep in mind that they are all based on RAM1. RAM1 has measures in place to enforce an inflow to the lake that is a compromise between power production and natural flow in the current climate. Water is only released from Gibe III and Koysha if this inflow requirement demands it or if the reservoirs spill. This means that the full effects of climate change may not be seen in the results. For instance, if the flow regime changes over the year, the inflow requirements will attempt to counteract this by storing and releasing water at appropriate times. This is also the case even if the changes happen downstream of the reservoirs, as releases will be calculated to take this into account.

Over time this must reach an equilibrium as more water cannot be forced through the system than what is available, while additional water will eventually spill as the reservoirs fill up. However, as the climate change scenarios start with the same conditions as all other scenarios, it may take some time to reach equilibrium and this initial period will also reflect in the final results.

Lake Water Level

The lake water level in RAM1 and the climate change scenarios is shown in Figure 4.40. Climate change clearly has a significant impact on the water levels, which rise in both climate change scenarios. At the end of the modelling period, the water level in CC1 is 2.1 m higher than in RAM1, and the difference is 2.7 m for CC2. The average difference throughout the modelling period is 0.8 m for CC1 and 1.1 m for CC2. However, it should be noted that these values also take the first years into account where the water levels are still very similar.

When considering critical water levels, the changes are also quite clear. RAM1 has 12 years where the water level gets below 362 m.a.s.l at least once. This level leads to drying out of one of the major fish breeding grounds, Ferguson’s Gulf, and is thus critical for fish production. In CC1 and CC2 there are only nine and seven years, respectively, where the water level gets below this level at least once. Conversely, when considering the water level 364 m.a.s.l at which severe flooding occurs, there are only two years in which this water level is exceeded at least once in RAM1. For CC1 and CC2, this number is seven and eight years, respectively. In conclusion, climate change leads to more security regarding the fish production, where not only exceeding the level 362 m.a.s.l. is important, but higher water levels generally lead to a higher fish production (Kolding, 1989). However, this comes at the cost of an increased risk of flooding. Fish production and flooding are discussed in more details in the following sections.

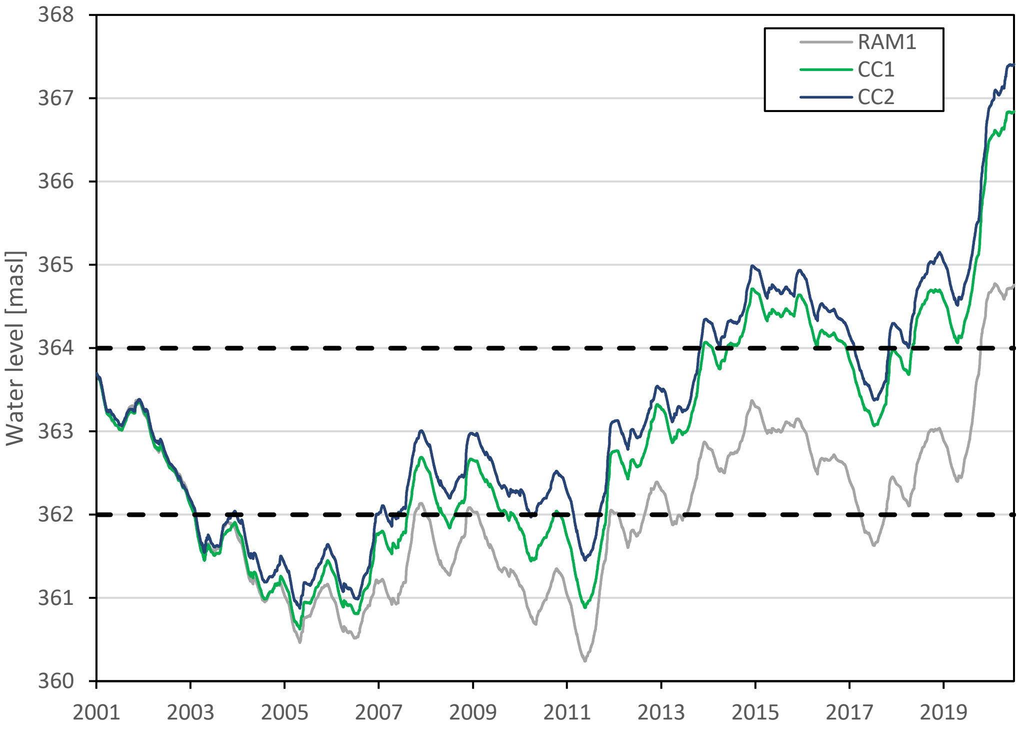


Figure 4.40 Water level in Lake Turkana in RAM1 and the two climate change scenarios. The lower black line indicates the water level 362 m.a.s.l at which Ferguson's Gulf dries out. The upper line is the water level 364 m.a.s.l which is estimated to be where severe flooding occurs.

The water level fluctuations are not as clearly affected as the water levels, although they increase for climate change compared to RAM1 in almost all years, as seen in Figure 4.41.

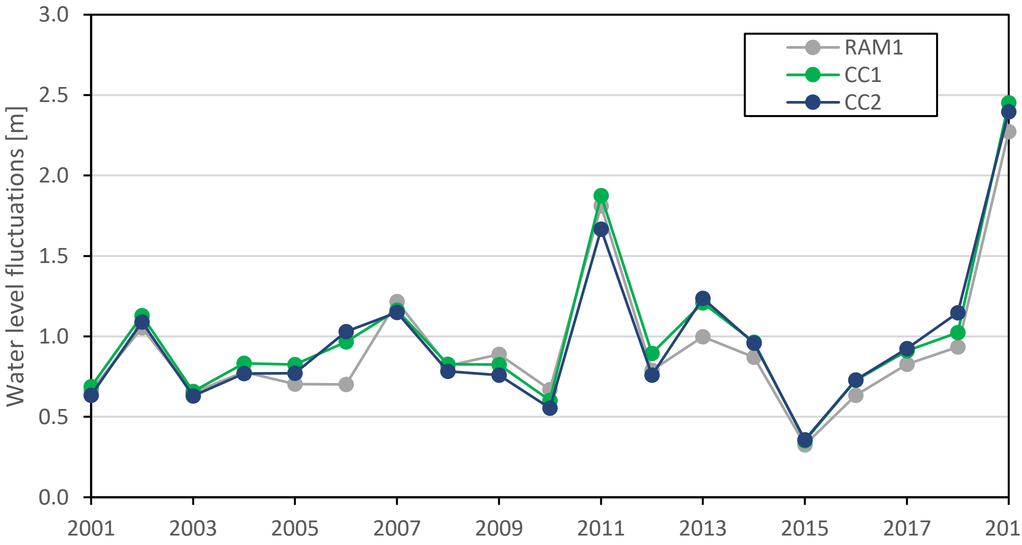


Figure 4.41 The water level fluctuations (the difference between maximum and minimum water level each year) for RAM1, CC1, and CC2. Note that the plot covers only full years in the simulation period, i.e. from 2001-2019.

Fish Production

Table 4.3 presents indicators related to fish production. As discussed previously, both water levels and the size of the water level fluctuations increase, which is beneficial for fish production. As seen in the table, the fish production as a function of water level increases from an average of 11 tonnes/boat/year to 14 tonnes in CC 1 and 15 tonnes in CC 2.

The percentage of the period where the fluctuations are too low with respect to fish production decreases from 80% in RAM1 to 70% in CC1 and further to 65% in CC 2. The percentage of years with optimal fluctuations increases accordingly. The largest fluctuation in the modelling period is just below 2.5 m, which is still much lower than fluctuations of 4 m which are assessed to be detrimental.

Table 4.3 Fish production indicators for RAM 1, CC 1, and CC 2.

		RAM 1	**CC 1**	**CC 2**
Average fish production as function of water level [tonnes/boat]		11	14	15
Water level fluctuations [% of simulation period]	Too low	80	70	65
	Optimal	10	20	25
	Neutral	10	10	10

Flooding

Table 4.4 shows the flooding indicators. The change in inundated settlements is dramatic, rising from eight inundated settlements in RAM 1 to 20 in CC 1 and 28 in CC 2. This clearly shows that significant negative impacts due to flooding can be expected in the future and that the events seen in 2020 may become more common. It should be noted, however, that following the riparian land legislation (see section 4.5 for more details) would result in no settlements being inundated, even for CC 2.

As has also been discussed previously, the percentage of time where the water levels are above the critical level of 364 m.a.s.l also increases significantly.

Table 4.4 Flooding indicators for RAM1, CC1, and CC2.

	RAM1	**CC1**	**CC2**
Inundated settlements	8	20	28
Percentage of years with severe water level (above 364 masl) [%]	10	35	40

Power Production

Table 4.5 shows the power production in the two climate change scenarios compared with RAM1. As seen, the power production falls in all the Ethiopian hydropower plants, while it increases for Turkwel in Kenya. The largest relative reduction happens for Gibe II, where production decreases by 13.1% and 18.1% in CC1 and CC2, respectively. The smallest decrease happens for Koysha, where it is only around 1%. In all cases, the effects of climate change (increase/decrease) are largest in CC2, with the exception of Koysha where the difference between the two is very small. The total power production in the basin drops by 5.1% and 7.2% in CC1 and CC2, respectively.

Table 4.5 Power production in the five reservoirs in scenarios RAM1, CC1, and CC2 as well as the percentage with which power production has changed from RAM1 in the two CC scenarios.

	Gibe I	**Gibe II**	**Gibe III**	**Koysha**	**Turkwel**	**Total**
RAM1 (MW)	88.9	195.1	654.4	771.7	36.8	1746.9
CC1 (MW)	77.3	175.2	599.5	763.7	42.3	1657.9
CC2 (MW)	72.8	165.4	574.8	765.0	42.4	1620.4
CC1 change (%)	-13.1	-10.2	-8.4	-1.0	14.9	-5.1
CC2 change (%)	-18.1	-15.2	-12.2	-0.9	15.3	-7.2

Figure 4.42 and Figure 4.43 show the average monthly production in Ethiopia and Kenya, respectively, for the three scenarios. Note that the production in Kenya is only from one reservoir, namely Turkwel. In Ethiopia the reduction is happening mainly in January-February and August-October. Note that there are a few times where production is higher in the climate change scenarios. In April, CC1 produces more than both RAM1 and CC1, and in November-December, production is slightly lower in RAM1 than in both climate change scenarios. The differences between CC1 and CC2 are smaller. The main difference is in the months February-May where production is higher for CC1.

In Kenya, the climate change production is higher than RAM1 throughout the year. The smallest increase is in January-March. The climate change scenarios have very similar production. CC2 produces slightly more from January-April and CC1 produces slightly more in November.

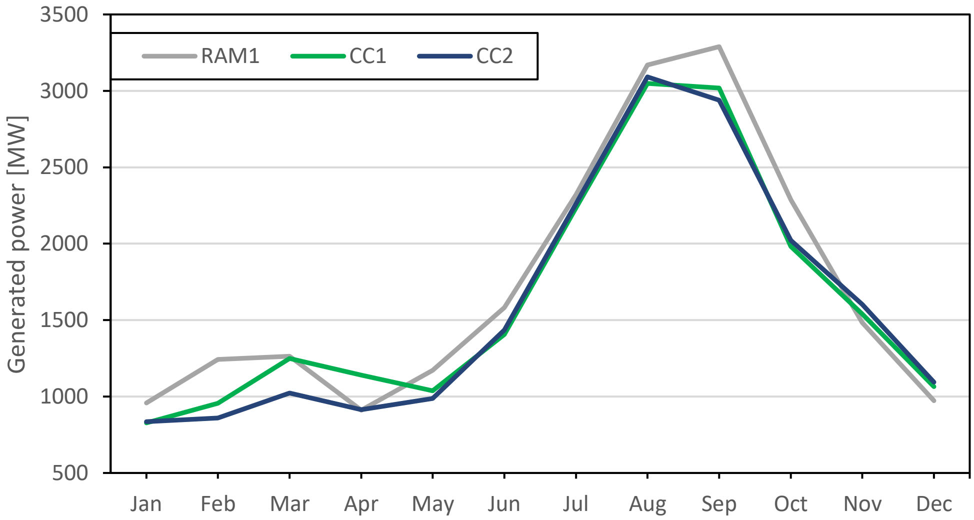


Figure 4.42 Average monthly power production for RAM1, CC1, and CC2 in Ethiopia.

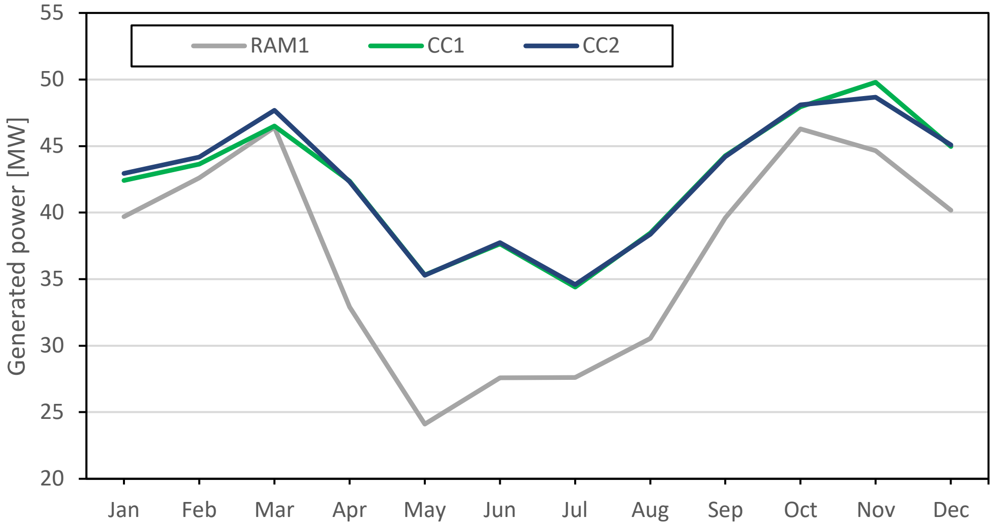


Figure 4.43 Average monthly power production for RAM1, CC1, and CC2 in Kenya (Turkwel).

When looking at the power production in Ethiopia, which is dominated by Gibe III and Koysha, the requirements of RAM1 must be kept in mind, as has also been discussed for lake inflow in the previous section. Production at these two reservoirs solely happens when the lake inflow requirements demand it or when the reservoirs spill. This means that power production will not reflect the changes in flow right away as what is released corresponds to lake inflow requirement in current conditions.

The net present values of the hydropower plants are shown in Table 4.6. There are clearly significant impacts of climate change.

Table 4.6 NPV of hydropower plants in RAM1, CC1, and CC2. The values are in million USD.

	Gibe I	**Gibe II**	**Gibe III**	**Koysha**	**Turkwel**
RAM1	-29	92	683	-184	-127
CC1	-75	11	458	-219	-119
CC2	-94	-30	360	-207	-118

Inflow Changes

It seems counterintuitive that the lake inflow from the Omo River increases while power production in Ethiopia decreases. The explanation can be found in the distribution of the climate change factors for rainfall. The annual averages of these for RCP8.5 are shown in Figure 4.44.

This illustrates that while rainfall is set to increase in most of the basin, there are decreases in the northern parts which is where most of the water in the upstream part of the Omo River is generated. Major increases in rainfall happen downstream of Gibe III and especially Koysha, thus explaining the increased inflow to the lake. While the map shows the annual means for RCP8.5, the trends are consistent with the seasonal climate change factors for both RCP4.5 and RCP8.5 in Figure 4.34 and Figure 4.35, respectively. The climate change factors for evaporation (see Figure 4.36 and Figure 4.37 for RCP4.5 and RCP8.5, respectively) vary less across the basin and consequently, increases in rainfall in the middle part of the basin are not counteracted by evaporation.

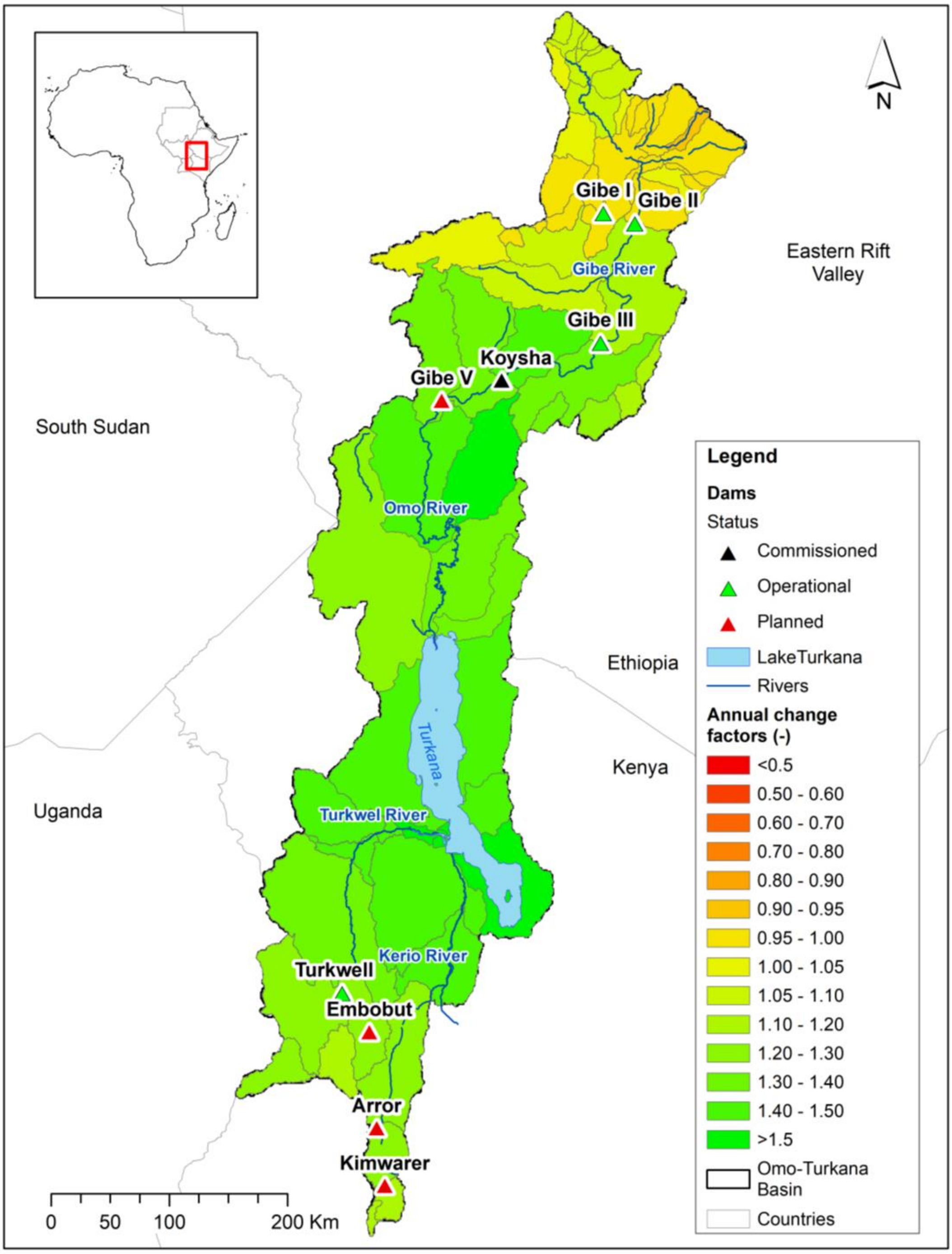


Figure 4.44 Annual average climate change factors for rainfall for RCP85 (2046-2065) for the basin, including the locations of the hydropower plants.

Figure 4.45 and Figure 4.46 illustrate the impacts on rainfall on the inflow to Gibe III and flow downstream of the Kuraz Sugar Plantation, respectively. The differences are very clear in the plots. The inflow to Gibe III is clearly higher for RAM 1 throughout the wet season and similar to CC 1 and CC 1 the rest of the year. Downstream of Kuraz, the flows are more similar and often lower in RAM 1.

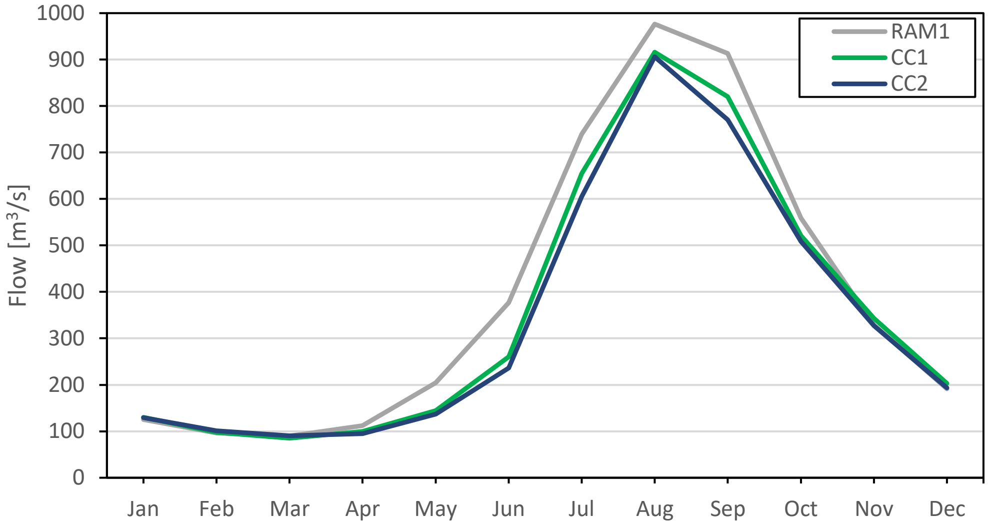


Figure 4.45 Inflow to Gibe III in RAM1, CC1, and CC2. Monthly means.

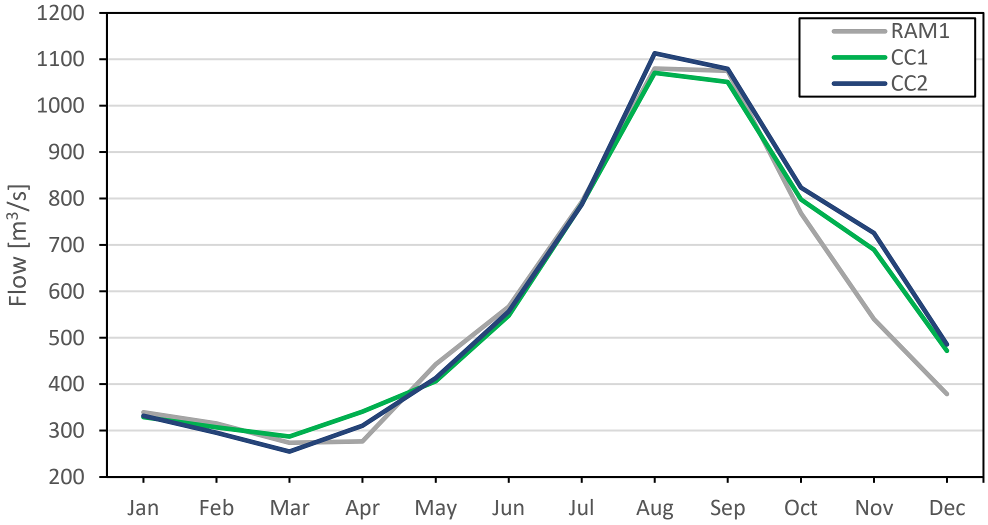


Figure 4.46 Flow downstream of Kuraz. Monthly means.

Mass Balance

In order to investigate the source of the increasing water levels, a mass balance for the lake has been carried out. As the lake has no outflow, and infiltration is not taken into account, the mass balance is described as

$$\Delta S = Q_{ET} + Q_{KE} + P - Eo$$

where ΔS is the change in storage, Q_{ET} and Q_{KE} are the inflows from Ethiopia and Kenya, respectively, P is the precipitation, and Eo is the evaporation. The values can be seen in Table 4.7.

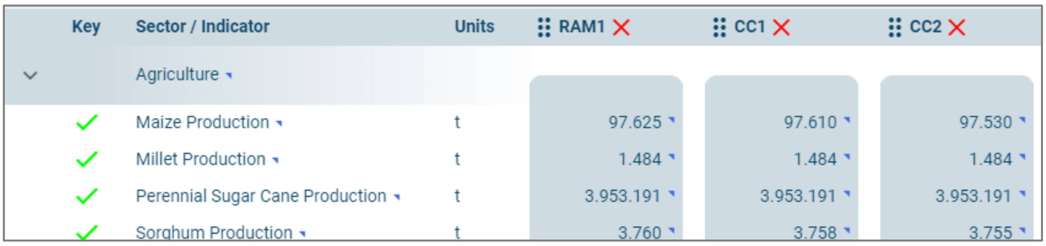
All components of the mass balance, including evaporation, increase in the climate change scenarios. When looking at the absolute values, the largest increases are in inflow from Ethiopia and evaporation. The increases for these two components are very similar in magnitude and roughly cancel each other out. Since evaporation is the only loss component, the increased inflow from Kenya and increased precipitation then go directly into increased storage of the lake. Percentagewise, the largest relative increase happens for the precipitation, followed by inflow from Kenya.

Table 4.7 Mass balance for the lake in RAM1, CC1, and CC2. The values are the means over the simulation period.

		Inflow from Ethiopia	**Inflow from Kenya**	**Precipitation**	**Evaporation**	**Storage change**
Volume [m^3/s]	RAM 1	581.76	45.80	88.87	703.42	13.01
	CC 1	622.72	53.45	107.15	744.07	39.26
	CC 2	643.67	51.89	113.17	762.16	46.56
Volume change from RAM 1 [m^3/s]	CC1	40.97	7.65	18.28	40.65	
	CC 2	61.91	6.09	24.30	58.74	
Percentage change from RAM1 [%]	CC 1	7.04	16.71	20.57	5.78	
	CC 2	10.64	13.30	27.34	8.35	

Crop Production

Crop production in the basin is not significantly impacted by climate change, as seen in Figure 4.47.



Key	Sector / Indicator	Units	RAM1	CC1	CC2
	Agriculture				
✓	Maize Production	t	97.625	97.610	97.530
✓	Millet Production	t	1.484	1.484	1.484
✓	Perennial Sugar Cane Production	t	3.953.191	3.953.191	3.953.191
✓	Sorghum Production	t	3.760	3.758	3.755

Figure 4.47 Crop production in the basin. Screenshot from the Planning Tool.

5 Scenarios for Lake Turkana and its River Basins

The results and the impacts of the different scenarios were discussed in the previous chapter. This chapter will summarize the impacts on the key issues in the basin across the scenarios,, where the impact of the different scenarios on selected key issues will be compared and discussed making use of the Key Result and Trade-off plots from the Planning application.

5.1 Comparison of Scenarios on Key Issues

5.1.1 Impact on Lake Turkana Water Level

Most lakes have an outflow, and change in inflow to such lakes, either permanent changes or seasonal variations, due changes in the upstream catchments, will have a corresponding change in the outflow and a new equilibrium will be established.

However, as Lake Turkana, like many other lakes in the Rift Valley, does not have an outlet, the water level in the lake is much more sensitive and vulnerable to permanent changes in the inflow to the lake.

This vulnerability becomes even more critical because the optimal range of water level for the lake is relatively narrow. Water levels should preferably not go below 362 m.a.s.l. as the Ferguson Gulf, which is a crucial fish breeding site, will then be disconnected from the lake and dry up. On the other hand, the water level should preferably not exceed 364 m.a.s.l. with the presence of settlements around the lake. A substantial number of these settlements will become submerged when the water level exceeds 364 m.a.s.l.. This means that the water level should preferably be within a narrow range of only 2 m from 362-364 m.a.s.l., to avoid both a negative impact on fish breeding and fish catch as well as flooding.

To investigate the source of the difference in water level variations between scenarios, a water balance for the lake has to be considered. As the lake has no outflow, and infiltration is not taken into account, the water balance can be described as:

$$\Delta S = Q_{ET} + Q_{KE} + P - Eo$$

where ΔS is the change in storage, Q_{ET} is the inflow from Ethiopia through the Omo River, Q_{KE} is the inflow from the Kenyan part of the basin (Kerio, Turkwel and the minor contributions from the catchments around the lake), P is the rainfall on the lake and Eo is the evaporation from the lake.

For all the scenarios, except the climate change scenarios, the rainfall on the lake and evaporation from the lake is the same. For the other scenarios, differences in lake water level are due to differences in inflow to the lake. Section 5.1.4 will look more into how changes in rainfall on the lake and evaporation from the lake in the climate change scenarios affected the results.

Thus, when looking at the impact on the lake water level, the causes of this impact and the consequences, the key indicators to focus on are the following:

Water level, Lake Turkana

Mean River Flow, Delta (Inflow from Omo River to the lake)

Percentage of Years with Severe Levels

Inundated Settlements

The mean annual water level variations in Lake Turkana during the whole simulation period is shown in Figure 5.1. WRD 2 scenario, representing all known major water resources developments by 2040, results in a substantial decrease in the water level in the lake as the accumulated difference over the simulation period is about 1.16 m compared to WRD1. As a result, the mean annual water level is below the critical 362 m.a.s.l. for all simulation years except three. On the other hand, the water level does not exceed 364 m during the simulation period.

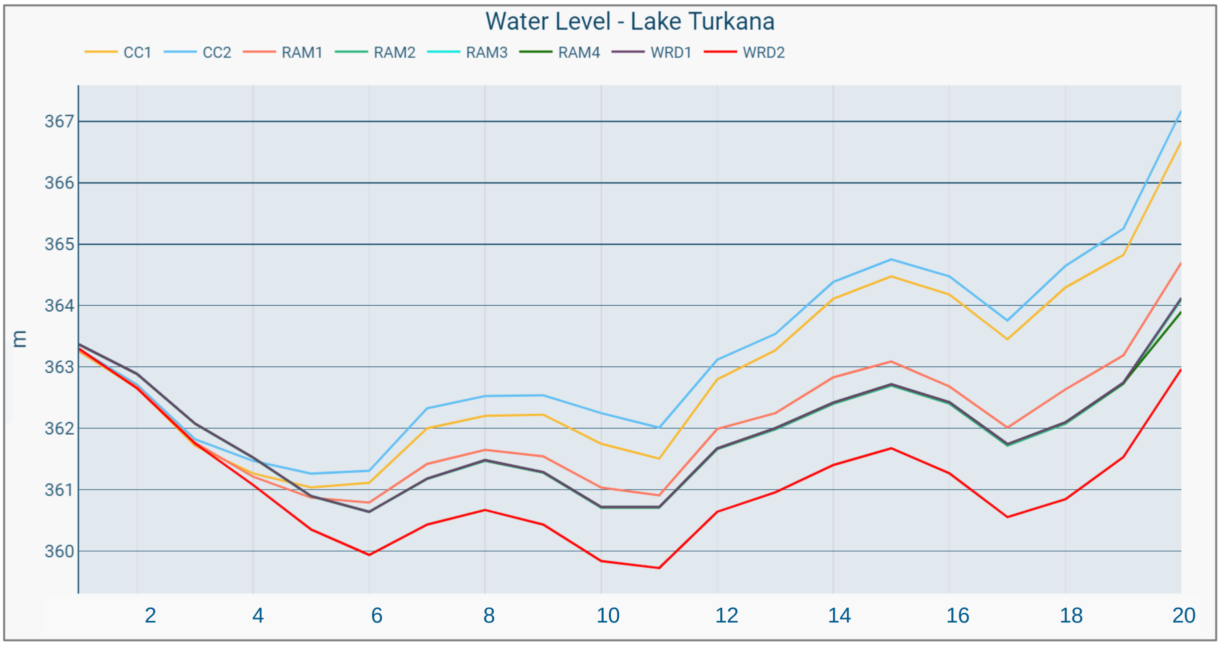


Figure 5.1 Variation in mean annual water level (m.a.s.l.) in Lake Turkana for all scenarios during the whole modelling period. Note that results for WRD1, RAM2, RAM3 and RAM4 overlap.

Contrary to WRD 2, both climate change scenarios result in a marked increase in the water levels in Lake Turkana. The accumulated water level difference over the simulation period is 1.98 and 2.48 m higher for CC 1 and CC 2, respectively, than for RAM 1, which was used as the baseline model for the climate change scenarios. Thus, the mean annual water level is above 362 m.a.s.l. for most of the years. On the other hand, there is a substantial number of years where the water level is above 364 m, where severe flooding of settlements will start to occur.

For RAM 2, RAM 3 and RAM 4 the mean annual water level is almost identical to WRD1. RAM 4 deviates slightly from WRD1 in the last 1 or 2 simulation years, which is the only instance where WRD 1 is above 364 m.a.s.l.. At this water level, transfer of water to Lake Logipi takes place in RAM 4 to ensure that the water level in the lake does not exceed 364 m.a.s.l..

Although the main focus of RAM1 was to increase the annual fluctuations in the lake, it also results in a slight accumulated increase in the water level of 0.58 m as compared to WRD1. This is, among other things, due to slightly lower abstractions at Kuraz, some minor increases in the evaporation from upstream reservoirs, and some minor differences in the storage at upstream reservoirs towards the end of the simulation period as compared to WRD1.

For WRD 2 the decrease in water level is due to a corresponding decrease in inflow to the lake. From Table 5.1 it is seen that the decrease in water level in WRD 2 is almost solely due to a decrease in average inflow to the Delta from the Omo River of about 27 m^3/s, as the inflow from Kerio and Turkwel are very similar for WRD 1 and WRD 2. The decrease in flow from the Omo Rivers is almost solely caused by the increase in the irrigation at Kuraz, as the data shows that there is hardly any difference in the flow upstream of Kuraz between WRD1 and WRD2.

Table 5.1 also shows that there is a huge increase in inflow to the lake from the Omo River in the climate change scenarios, as it is estimated that the inflow will increase by 40.96 and 61.91 m^3/s for CC 1 and CC 2, respectively, as compared to RAM 1. For the climate change scenarios these significant increases in inflow to the lake are somehow counterbalanced by increase in evaporation from the lake. The impact of climate change on the rainfall on the lake and evaporation from the lake will be discussed in more details in Section 5.1.4.

Table 5.1 Difference in inflow to the lake from the main rivers between WRD1 and the other scenarios, showing a marked decrease in lake water level for WRD2 and the corresponding marked increase for CC 1 and CC 2.

Mean flow (m3/s)	**WRD1**	**WRD2**	**RAM1**	**RAM2**	**RAM3**	**RAM4**	**CC1**	**CC2**
Inflow to the Delta from Omo	0.00	-27.21	7.87	0.00	0.00	0.00	48.83	69.78
Inflow from Kerio	0.00	0.14	0.00	0.00	0.00	0.00	3.42	1.26
Inflow from Turkwel	0.00	-0.11	0.00	-0.44	0.00	0.00	2.22	1.80

To conclude on the impact of the different scenarios on the water level in Lake Turkana, the planned water resources developments by 2040 (WRD2) are expected to result in a substantial decrease in the water level in Lake Turkana, and the climate change scenarios (CC1 & CC 2) project substantial rises in the water levels in the lake, with the risk of more regular flooding events around the lake.

Thus, the expected decrease in water level due to upstream developments may counterbalance the projected future increase in water level due to climate change. This situation could have mutual gains for the basin countries, which is discussed in more detail in chapter 5.1.6.

5.1.2 Impact of Annual Fluctuations on Lake Turkana

Intra-annual water level fluctuations of a sufficient magnitude is one of the most important factors for successful fish breeding and fish catch in Lake Turkana, and according to local knowledge intra-annual fluctuations between 1.0-1.5 m are optimal (discussion with local fisheries expert, Mr Evans Lomodei, based on field data collection produced in October and November 2020, as well as January 2021). These intra-annual water level fluctuations are a result of the seasonality in inflow to the lake. However, in chapter 4.3.1 it was shown that with the construction of the hydropower plants and reservoirs, this seasonality in inflow from the Omo River has been dramatically reduced, resulting in a very significantly dampening of the seasonal variations (cf. Figure 4.14). It is estimated that the annual water level fluctuations have been reduced from an average of 1.13 m under natural conditions to 0.75 m in WRD 1.

The purpose of RAM 1 was therefore to regenerate some of the natural seasonality without compromising too much on the total hydropower production (cf. chapter 4.3.1). It was shown that it in fact was possible to increase the annual water level fluctuations from 0.72 to 0.89 m as illustrated in Figure 5.2. However, this is still not within the optimal fluctuation range from 1.0-1.5 m. It is still a considerable improvement taken into consideration that the value for the simulated natural condition is estimated to 1.13, and the fact that it is not realistic to reproduce natural conditions as that would have been too much at the expense of hydropower production.

The figure also shows that at the same time it has been possible to maintain and even slightly increase the total hydropower production, while the firm power production logically has decreased due to the introduced seasonality, so a larger part of the total hydropower production is secondary power. This is discussed in more detail in chapter 5.1.3.

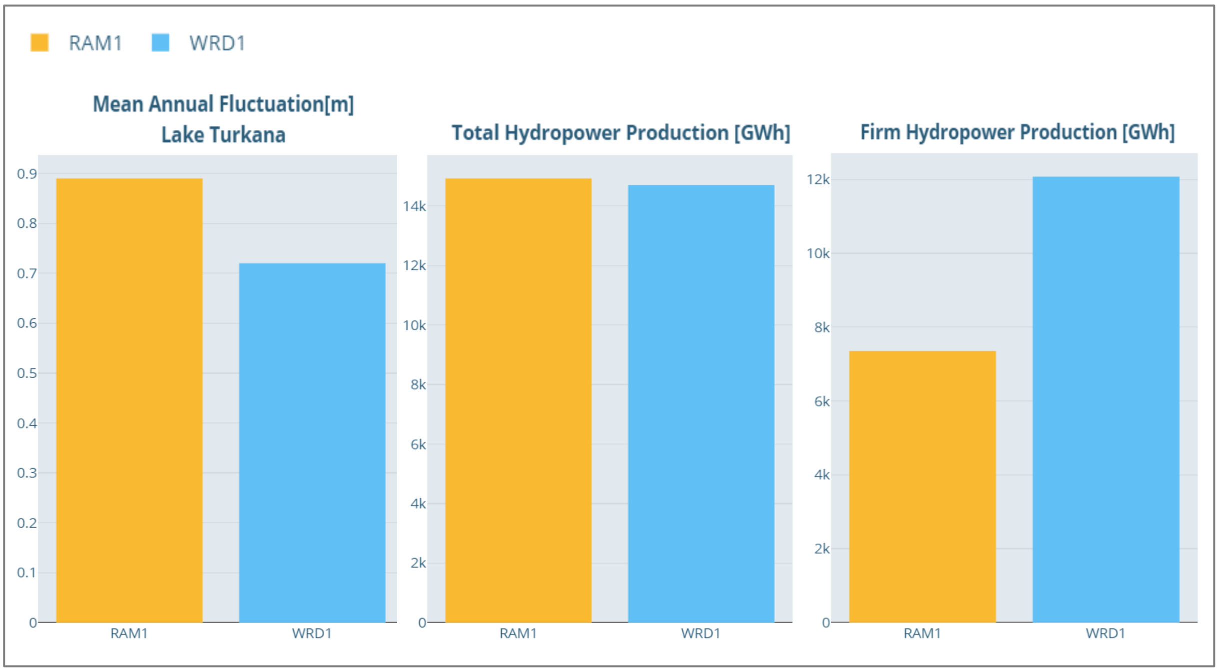


Figure 5.2 Impact of RAM1 on Mean Annual water level Fluctuations in Lake Turkana, Total and Firm Hydropower Production in the basin. It has been possible to increase fluctuations and maintain the total hydropower production.

The impact of all scenarios on the mean annual water level fluctuation in Lake Turkana is shown in Figure 5.3. RAM 2 and RAM 3 are similar to WRD 1, as no model changes are made in RAM 3, and the reforestation and soil and water conservation measures in RAM 2 are only implemented in a smaller headwater catchment in West Pokot. While its effect is significantly locally, it does not have a measurable impact on the water level or water level fluctuations in Lake Turkana as long as it is only implemented in this small catchment. RAM 4 is marginally lower than WRD 1 due to discharge to Lake Logipi in the last years of the simulation. The impact of RAM 1 has already been discussed above.

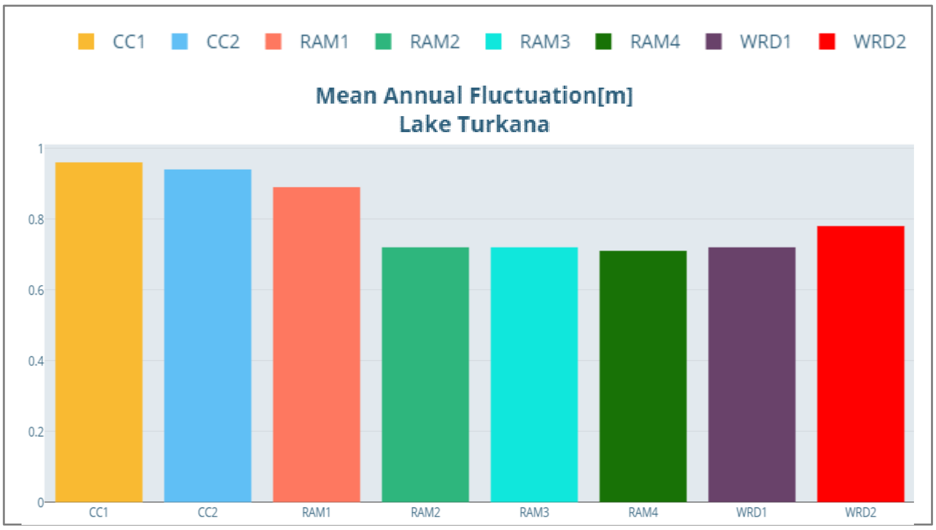


Figure 5.3 Impact of the different scenarios on the water level fluctuations in Lake Turkana.

The two scenarios with the highest mean intra-annual water level fluctuations are the two climate change scenarios with values of 0.96 and 0.94 m for CC 1 and CC2, respectively. However, it should be recalled that RAM 1 serves as the baseline for CC 1 and CC 2. As the climate change scenario fluctuations are only slightly higher than RAM 1, the considerable increase for CC 1 and CC 2 compared to WRD 1 can primarily be ascribed to the fact that these scenarios build on RAM 1.

The increase in inflow to Lake Turkana in the climate change scenarios mainly takes place during the drier part of the year (cf. Figure 4.39) and the climate change scenarios therefore do not increase the seasonality in the inflow to the lake. The smaller difference in fluctuations between RAM 1 and CC1 and CC2 could possibly have been caused by the fact that the flow magnitudes generally are higher for the climate change scenarios.

The annual fluctuations are also slightly higher for WRD 2 compared to WRD 1. This is primarily due to the fact that the increased abstraction at Kuraz Sugar Cane Project mainly takes place during the dry season and thereby increases the seasonality in flow below Kuraz.

To conclude, RAM 1 demonstrated that there is a potential win-win situation, whereby the seasonal fluctuations in Lake Turkana can be increased while maintaining or even increasing the total hydropower production in the Ethiopian part of the basin.

5.1.3 Hydropower Production

Hydropower is one of the key development activities in the basin. Several hydropower plants are already constructed, and more are planned in both Kenya and Ethiopia. Below the impact of the different scenarios on the hydropower production is summarized. The total, firm and secondary hydropower production in the basin are summarized in Table 5.2 for all eight scenarios. RAM2, RAM3, and RAM4 are all unchanged from WRD1 as no changes has been made to affect the reservoirs in these scenarios. A significant increase in hydropower production happens from WRD1 to WRD2 due to the introduction of two new reservoirs / hydropower plants, namely Gibe V in Ethiopia and Arror in Kenya.

Table 5.2 Total, firm, and secondary hydropower production (GWh/year) in the basin for all eight scenarios.

	WRD1	WRD2	RAM1	RAM2	RAM3	RAM4	CC1	CC2
Total Hydropower Production	14,702	17,144	14,925	14,702	14,702	14,702	14,165	13,844
Firm Hydropower Production	12,076	13,848	7,353	12,076	12,076	12,076	7,011	6,914
Secondary Hydropower Production	2,626	3,296	7,573	2,626	2,626	2,626	7,154	6,930

For RAM1, the total hydropower production is nearly unchanged and in fact slightly increased compared to WRD1. This has been possible by producing more energy during the wet season when the reservoirs are full and sometimes even spilling, and then reducing the hydropower production during the dry season, thereby avoiding too much drawdown of the reservoirs. The introduced seasonality in the hydropower production inevitably has resulted in a decrease in firm power, so a larger portion of the total power production is secondary power. However, if connected to an energy grid with other energy sources, the hydropower production may be supplemented by the other sources during the dry season when less hydropower is produced. In this case the decrease in firm power may not be critical and this provides an opportunity for restoring some fluctuations in the lake while still meeting Ethiopia’s energy needs.

Table 5.3 Total hydropower production (GWh/year) by country for WRD1, RAM1, CC1, and CC2

	WRD1	RAM1	CC1	CC2
Ethiopia	14,387	14,611	13,804	13,482
Kenya	314	314	361	362

For the climate change scenarios, the total hydropower production in the basin decreases by 3.7% for CC1 and 5.8% for CC2 when comparing to WRD1. The firm hydropower is also low for these scenarios, but the reason for this is that they are based on RAM1 and as such have a seasonal variation inherited from RAM 1 in the production. The decrease in total hydropower is not evenly distributed between the two countries. There is an increase in production in Kenya, and reduction solely happens in Ethiopia, due to reduced runoff from the northern parts of the basin. Although climate change projections are uncertain, it is an issue of concern for Ethiopia that their hydropower schemes may give less output in the future. This may lead them to investigate alternative power sources.

5.1.4 Fishery

Fishery is another key activity in the basin and not least crucial for many people’s livelihood around Lake Turkana. The fishery in the lake is affected both by the size of the seasonal water level fluctuations as well as the absolute water levels. The values of the fishery indicators are summarized in Table 5.4 for all scenarios. RAM2, RAM3, and RAM4 are all unchanged from WRD1. WRD2 has a small positive impact on the water level fluctuations, with one year (5% of the simulation period) moving from too small to optimal. However, the falling water levels have a negative impact on fishery and the water level-based indicator decreases from WRD1 to WRD2.

RAM1 also has one less year with too small fluctuations, but this time it is replaced with a year with the neutral fluctuation size. While this change does not seem much from a scenario aiming to restore fluctuations, Figure 4.22 shows that the fluctuations in RAM1 have indeed increased from WRD1. Even though they do not reach the optimal levels, it must be assumed that this will have some positive effect on fish production.

The climate change scenarios both have an apparent positive impact on the two types of fish production indicators. However, for the water level fluctuations and the water level-based indicator, this is mainly due to the fact that the climate change scenarios use RAM1 as the baseline. For the water level-based indicator, it is positively correlated with water level and as the climate change scenarios results in considerably higher water levels than any of the other scenarios. This explains why the “Fish catch from water level” are highest for the climate change scenarios.

A conflict exists because as the increasing water levels and fluctuations present better conditions for fishery, flood risk also increases. It is likely that the people dependent on a high fish production are the same people who have settled close to the lake and are therefore affected by flooding. This is discussed in more detail in chapter 5.1.6.

Table 5.4 Fishery indicators for all scenarios. Small fluctuations are below 1 m, optimal are 1-1.5 m, neutral are above 1.5 m and below 4 m, and too large are 4 m and above.

	WRD1 (RAM2, RAM3, RAM4)	WRD2	RAM1	CC1	CC2
Years with too small fluctuations [%]	85	80	80	70	65
Years with optimal fluctuations [%]	10	15	10	20	25
Years with neutral fluctuations [%]	5	5	10	10	10
Years with too large fluctuations [%]	0	0	0	0	0
Fish catch from water level [tons/boat]	10	7	11	14	15

5.1.5 Crop Production

Maize is an important crop for small-scale farmers and sugar cane is grown in the Kuraz Sugar Plantation, which is a major investment in Ethiopia. The yearly production of these two crops per country is shown in Table 5.5 for all scenarios. There are few changes within the scenarios. RAM3 and RAM4 are the same as WRD1. WRD2 shows the largest change due to a new irrigation scheme, Arror in Kenya, growing maize and an expansion of the Kuraz Sugar Plantation. RAM1 result in a marginal decrease of maize in Ethiopia but is otherwise unchanged. RAM2 show a small reduction of maize in Kenya. Maize in both countries decreases slightly for the climate change scenarios. None of these changes, with the exception of WRD2, are significant.

There are probably two explanations for the lack of major changes. One is that the water demands of the irrigation schemes, with the exception of Kuraz, are generally small compared to the available water resources. Another is that the crops can handle some water deficit without their yield being significantly affected.

Table 5.5 Production of maize and sugar cane (tonnes) in Kenya and Ethiopia in all scenarios.

	WRD1 (RAM3, RAM4)	WRD2	RAM1	RAM2	CC1	CC2
Maize - Ethiopia	50,872	50,872	50,767	50,872	50,779	50,758
Maize - Kenya	46,858	48,500	46,858	46,828	46,831	46,772
Sugar cane - Kuraz (Ethiopia)	3,953,191	5,847,916	3,953,191	3,953,191	3,953,191	3,953,191

5.1.6 Lake Turkana Flooding

The very dramatic rise in the water levels of Lake Turkana in 2020 reaching a level of 366.8 m.a.s.l. in November 2020 created extensive inundation and flooding and resulted in great damage to settlements and wildlife. This resulted in a wide range of damage, including amongst others, according to Turkana County Government (2020): displacement of thousands of families living along the shores of Lake Turkana, destruction of hotels, campsites and restaurants, access roads to villages and settlements damaged or blocked, fishing landing sites affected by the water level rise, boats and fishing net destroyed, water pollution from destroyed toilets and septic tanks, etc.

During this project's stakeholder consultations, flooding and inundations around the lake and resultant damage was a key concern. Thus, two of the scenarios have focused on flood adaptation measures, namely RAM 3 focusing on enforcement of existing legislation and RAM 4 looking into the possibility of discharging water into Lake Logipi. The two scenarios and their results are presented and discussed in chapters 4.5 and 4.6. Below, their impact on flooding are compared with the results from the other scenarios and possible adaptation measures discussed.

Table 5.6 shows the impact of all eight scenarios, including RAM 3 and RAM 4, on the two key flood indicators 'Inundated Settlements' and 'Percent of years with Severe Water Levels'.

Table 5.6 Indicators 'Percent of Years with Severe Water Levels' and 'Inundated settlements' for all scenarios.

	WRD1	WRD2	RAM1	RAM2	RAM3	RAM4	CC1	CC2
Percent of years with severe water levels	10	0	10	10	10	0	35	40
Inundated settlements	8	4	8	8	0	4	20	28

While there is no direct correlation between "Percentage of Years with Severe Water Level' and 'Inundated Settlements', the higher the former, the higher probability more settlements will be inundated during the simulation period. The relationship between the two indicators is shown in Figure 5.4. It shows there is a clear correlation, except for RAM3. This is due to the fact that this scenario assumes that land legislation is enforced, and no settlements are located below 368.8 m.a.s.l..

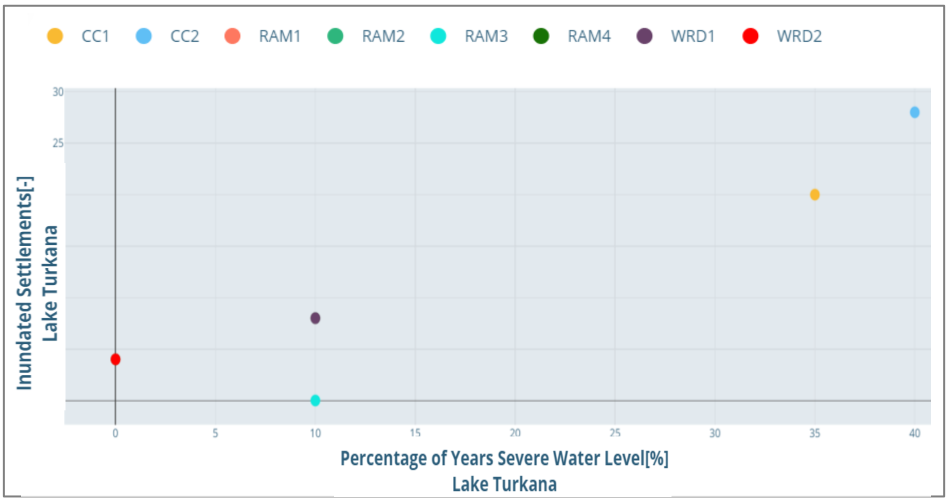


Figure 5.4 Correlation between 'Percent Years with Severe Water Levels' and 'Inundated Settlements'.

WRD 1, RAM 1, RAM 2 and RAM 3 all experience 10% of years with severe water levels (i.e., larger than 364 m.a.s.l.), the number of settlements which may be inundated at least once during the entire simulation period is 8, expect for RAM 3 which is 0.

For both WRD 2 and RAM 4 the percentage of years with severe water levels is zero, yet for different reasons. In WRD 2 the increased abstraction results in a considerable reduction of the water level in the lake, which never exceeds 364 m.a.s.l. during the entire modelling period (see Figure 5.1). In RAM 4 water is discharge to Lake Logipi when reaching 364 m.a.s.l., therefore, the water level does not exceed 364 m.a.s.l.. The reason that 4 settlements are still inundated is because those are located between 363 and 364 m.a.s.l. (cf. Table 3.5). It could have been argued that discharge of water should start at 363 m.a.s.l., yet this would happen with more regularity, and result in higher ecological disturbance to Lake Logipi.

While the climate change scenarios showed a positive impact on fish production due to the positive correlation with water level, then Table 5.6 and Figure 5.4 clearly indicate that there is a negative impact on the same population due to the significant increase in 'Percentage of years with Severe Water Levels' indicator and as a result considerably increased risk of flooding with more settlements around the lake being inundated if no adaptation measures are implemented.

The 2020 flooding around Lake Turkana was from a historical perspective a rare event. Only twice during the last eighty years have similar events with very abrupt water level rise occurred (see Figure 5.5). The first time was during the 1961-62 event, where the water level rose about 4-5 m and remained high for the following 20 years (as in Lake Victoria), having reached a maximum towards the end of the 1970s. The other event was during the El Niño in 1997-98, resulting approximately in a 4 m rise in the water level.

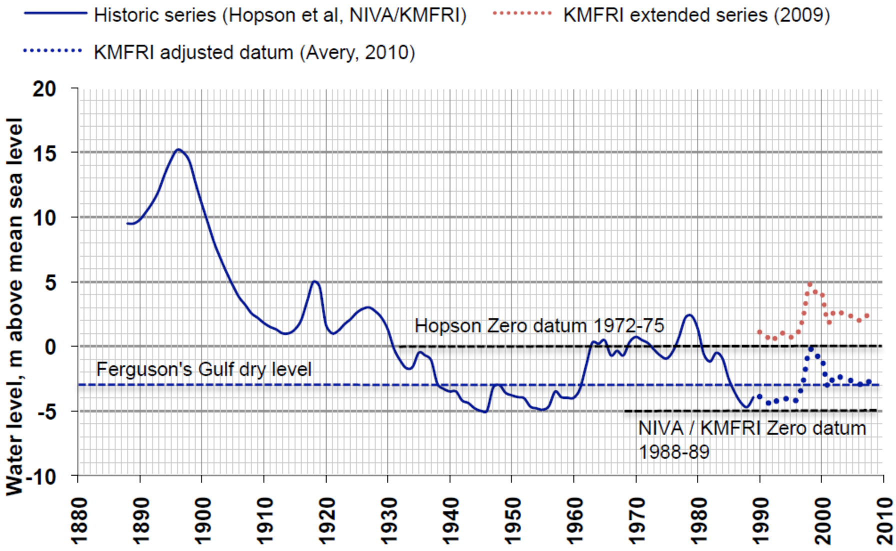


Figure 5.5 Historical water level fluctuations in Lake Turkana from 1880 to 2010 (taken from Avery S., 2010).

Possible Adaptation Measures

As shown above severe abrupt flooding like the in 2020, has been relatively rare within the last 80 years. However, climate change projections foresee that this rare event in the future may become a more regular event, if no adaptation measures are put in place. Although climate change projections are uncertain, it is important to consider possible adaption measures.

Two if the eight scenarios focus specifically on adaption to flooding around the lake, but with two very different methods.

RAM 3 focuses on enforcement of the land legislation, which is already in place, this being the most realistic alternative to implement than for to RAM 4. As the altitude increases rapidly in the vicinity of the lake shore, water level increases up to e.g., 368 m.a.s.l., only those settlements on the lake shore would be flooded (cf. Figure 4.29). Therefore, a starting point could be to ensure that new settlements, schools, hospitals etc. follow the existing land legislation and will thereby be located at sufficiently high altitude to avoid future flooding and aim at relocating the existing settlements over time.

Although included as one of the rehabilitation measures, RAM 4 was not considered a realistic alternative to RAM 3 but rather seen as an “emergency” solution in case that the water level in the future tends to continue to increase without reaching an equilibrium. Additionally, RAM 4 was included to demonstrate that technically and hydrologically it would be a possible solution due to the existence of Lake Logipi at much lower altitude close to Lake Turkana. This alternative would require detailed environmental impact assessments, not least the ecological consequences for Lake Logipi. Furthermore, it would involve complex engineering work, and finally, it would be a very costly solution. Thus, if RAM 4 ever becomes a realistic alternative in the future, it would be useful to investigate if the transfer of water to Lake Logipi could be combined with hydropower production. This would, however, only make sense if inflow increases so much in the future leading to an almost permanent discharge of water – which is probably an unlikely scenario.

An alternative solution to these adaptation measures to address the increased inflow could be to abstract more water in the upstream catchments, both the Kenyan as well as the Ethiopian parts of the basin. A transboundary win-win situation whereby Ethiopia could abstract more water to increase their agricultural production and at the same time help avoid flooding around Lake Turkana. To illustrate this, the combined impact of scenarios CC 1 and WRD 2 (red line) are presented in Figure 5.6. It is seen that the impact of CC 1 and WRD 2 will almost counterbalance each other.

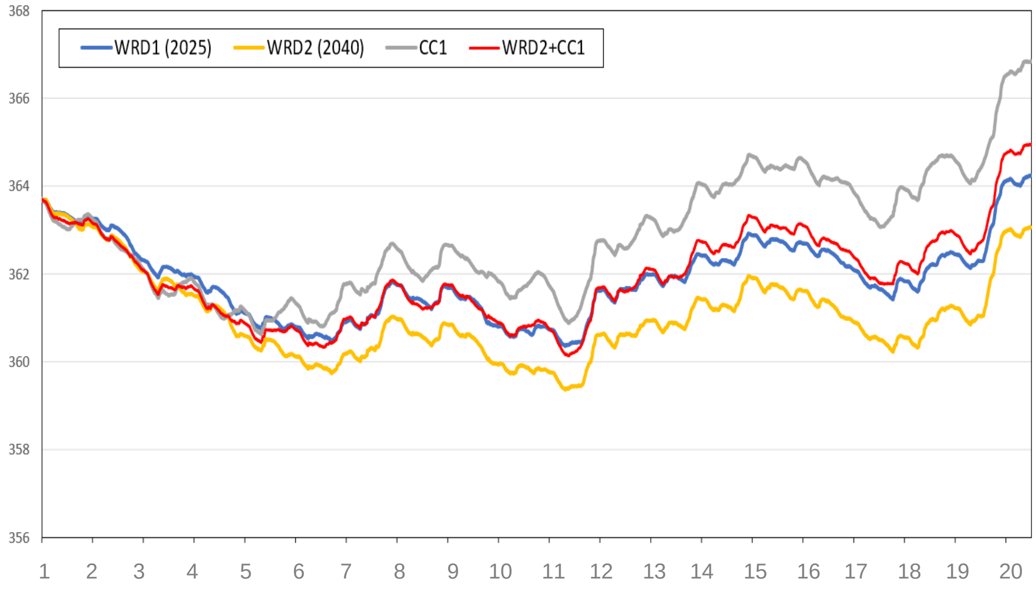


Figure 5.6 The estimated impacts of WRD 1, CC 1, WRD 2 as well as the combined impact of CC 1 + WRD 2 on the water level in Lake Turkana.

6 Conclusions

The conclusions drawn are assigned to two main aspects of the scenario comparison and planning exercise demonstrated in this project: a) with relation to the rehabilitation and adaptation measures analysed and b) to planning with the aim of achieving mutual gains in a transboundary and cross-border context of the SECCCI project.

It is important to note that the models used for this study, while checked and calibrated to the best extent possible, have some limitations and uncertainties. Most importantly, there has been a lack of data for e.g. river discharge, reservoir management, properties of current and planned investments, fish production, etc. The climate change scenarios are also based on assumptions about future global greenhouse gas emissions and their impact on regional climatic patterns, known as the cascade of uncertainty in climate change projections.

For this reason, as comprehensive as the study has been at the basin and transboundary level, the conclusions presented should be taken as an indication of the impact of different measures. In future studies, exact values of hydropower production or lake water level should be used to illustrate the order of magnitude of values and trends. More accurate data on irrigation and livestock water use can also reduce uncertainty. Future work on climate change projections work should focus on clustering a large number of climate change scenarios with statistical analysis of likelihood of and confidence in the different scenarios.

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Rehabilitation and Adaptation Measures

To conclude on the impact of the different scenarios on the water level in Lake Turkana, then the planned water resources developments by 2040 (WRD2) are expected to result in a substantial decrease in the water level in Lake Turkana, and the climate change scenarios (CC1 & CC 2) project substantial rises in the water levels in the lake, with the risk of more regular flooding events around the lake. Thus, the expected decrease in water level due to upstream developments may counterbalance the projected future increase in water level due to climate change.

RAM 1 showed that it is possible to maintain and even improve the hydropower production while restoring a certain level of fluctuations in lake inflow and water level. This would require that Ethiopia has alternative power sources for the dry season as the hydropower production would be distributed over the year. However, if this is possible, it would provide a way to meet some of the ecological requirements of Lake Turkana and its surroundings while still considering Ethiopia’s need for energy.

RAM 2 showed local advantages such as increasing infiltration, reducing surface runoff and therefore, retaining and conserving water, soil and nutrients, and help maintain crop yields. Reforestation will have a similar impact as soil and water conservation measures. Added to that, their root network will help stabilizing the soils. Due to increased evapotranspiration, it will reduce the risk of saturated soils. There are also downstream advantages such as reduction of(flash) flood risk and a clear improvement of the water quality in the rivers downstream, including less turbidity and less E coli. Geographically RAM 2 can be applied throughout the Omo-Turkana Basin, in both Kenya and Ethiopia, where the above-mentioned conditions apply. The type of rehabilitation measures included in RAM 2 is overall considered to be beneficial wherever they are implemented.

RAM 3 focused on enforcement of the land legislation in place. As the altitude increases rapidly in the vicinity of the lake shore, water level increases up to e.g., 368 m.a.s.l., only those settlements on the lake shore would be flooded. Therefore, a starting point could be to ensure that new settlements, schools, hospitals etc. follow the existing land legislation and will thereby be located at sufficiently high altitude to avoid future flooding and aim at relocating the existing settlements over time.

RAM 4, transfer to Lake Logipi, was not considered a realistic alternative to RAM 3 but rather seen as a flood control measure designed for emergency situations, in case that the water level in the future tends to continue to increase without reaching an equilibrium. This alternative would require detailed environmental impact assessments, not least the ecological consequences for Lake Logipi. Furthermore, it would involve complex engineering work, and finally, it would be a very costly solution.

It is important to note, regarding the flood adaptation measures of RAM 3 and RAM 4, that as comprehensive as the study has been at the basin level, there are aspects including economic feasibility studies, which were outside the scope of the study which would have reflected negatively on the positive scores obtained by flood control measures of RAM 3 and 4.

In RAM 3, this scenario does not include any other potential impacts of building permanent structures further away from the lake, for example negative impacts of being a greater distance away from the lake and taking longer to access the lake. In RAM 4 we have not assessed the impact on Lake Logipi which could be significant given the ecological importance of the lake, for example to Flamingos that frequently inhabit the saline waters feeding on cyanobacteria and other plankton (Mathea, 2009). We have also not included assessment of the construction, operation and maintenance costs of building the infrastructure to deliver water from Lake Turkana to Lake Logipi.

Further work could consider investigating expanding the application of legislation to include limits on building permanent structures along riverbanks and flood prone areas. In the case that pastoralist land occurs along flood prone areas, for access to water and fertile grazing and agricultural land (e.g. flood recession agriculture). An indication of how often flood prone riverine areas might flood in different future scenarios would be recommended, so that pastoralists have a better understanding of the risks of using these flood prone areas.

Potential mutual gains

Simulations predict that climate change may result in a marked increase in inflow to Lake Turkana, primarily from the Omo River, but also increased inflow from Kerio and Turkwel rivers. Such a possible increase in inflow will result in an increasing water level in Lake Turkana. Thus, the flooding which occurred in year 2020, which was considered a rare event, is likely to be become more regular in the future without any adaptation measures.

Mutual gains for both basin countries can be achieved if the basin countries develop an arrangement for water cooperation. Possible transboundary mutual gains between Climate Change (CC), Water Resources Developments (WRD) and Rehabilitation and Adaption Measures (RAM) have been identified:

- Increased irrigation abstractions may help to counterbalance increasing water levels in Lake Turkana due to Climate Change. Impacts of water quality of increased abstractions have not been modelled and should be part of transboundary discussions as well.

- Likewise, reforestation and soil and water conservation measures may also help to counterbalance the impact of CC, although to a lesser extent, due to increased evaporation and less runoff from steep headwater catchments.

- It will be possible to partly reproduce the seasonality in inflow to Lake Turkana to maintain fish production and at the same time maintain the same Total Hydropower Production in the Ethiopian part of the basin.

- A cooperation framework should be established to guide planning and development efforts at the basin scale. This is subject of the project deliverable “Draft Framework on Transboundary Water Management”.
- Soil and water conservation and reforestation measures will significantly help reducing the risk of landslides and mudflows as experienced in West Pokot, Kenya. It is considered that both countries will benefit from when implementing these measures. The benefits will mainly be onsite benefits and will particularly ensure a more efficient and not least more sustainable crop production and conversion from other land uses to cultivation.
- From a global perspective reforestation and agroforestry may also help fighting global warming and help restoring habitat loss.
- Agroforestry will have two additional advantages: Intercropping crops with leguminous N_2-fixing agroforestry species, like e.g. Acacia and Caleandra, can help replenish nitrogen harvested with crops and thereby maintain the N-balance and reduce the need for artificial fertilizers. Fodder trees can also be an important feed source for livestock and reduce livestock pressure on grassland.

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APPENDICES

APPENDIX A – Additional Rehabilitation Measures

A Additional Rehabilitation Measures

There are a number of potential rehabilitation measures identified as part of this project during field data collection. These measures cannot be modelled and therefore have not been included in the scenarios. These rehabilitation measures are described in this chapter so that implementation of these measures can be considered in future management and planning discussions.

Mapping and Marking of Sacred Sites and Areas of Historical/Cultural Importance

Mapping and marking community resources and sites that communities would want to ensure conserving can lead to a ripple effect as benefits of conservation begin to be seen. Currently the Turkana County, Kenya, is working closely with the National Museums of Kenya to conserve cultural and natural diversity which could be a good starting point for such interventions.

Improve Direct Access to Markets for Choice Livelihoods

Supporting and improving direct access to markets for existing resource user groups such as fishers and pastoralists increases benefits to communities. Rehabilitation measures that enhance existing and choice livelihoods are more sustainable than introducing new livelihoods (such as beadwork) that are dependent on external patronage. Communities have evolved their way of life over centuries and are more likely to adapt to improved management methods of choice livelihoods than new lifestyles. Interventions aimed at changing choice livelihoods can lead to cultural detachment of the people to the land and resources (e.g. livestock, fish) that are key to their identity, resilience and lifestyle.

Designated, Marked and Protected Livestock Movement Routes

Pastoralism is a key resilient local livelihood and production system and mobility to access resources such as water and pasture is just as important as the management of these resources. Land management to cater for tourism, wildlife conservation, and threat of violence can restrict resource access for pastoralists especially during periods of resource stress such as droughts. Designating, marking and protecting key livestock movement routes would help to secure access to resources for pastoralists and support livelihoods. In addition, research has shown that if livestock movement routes and corridors are designated, marked and protected than they are also utilized by wildlife.