DAFNE

A **D**ecision-**A**nalytic **F**ramework to explore the
water-energy-food **NE**xus in complex and transboundary
water resources systems of fast growing developing countries

MODELS OF THE ECONOMIC DEVELOPMENT IN THE OMO-TURKANA BASIN

Deliverable D4.6

December 2018

EU H2020 Project Grant No. 690268

Programme Call: Water-5-2014/2015
Project Number:......................690268
Project Title:.............................DAFNE

Work-Package:.........................WP4
Deliverable #: D4.6
Deliverable Type: ....Document
Contractual Date of Delivery: 31 December 2018 (postponed with PO agreement from 31 August 2018)
Actual Date of Delivery: ....26 January 2019
Title of Document: ....Models of the economic development in the Omo River Basin
Author(s): ....Phoebe Koundouri, Nikolaos Englezos, Ebun Akinsete, Xanthi Kartala, Mike Tsionas, Lydia Papadaki, Eleftherios Levantis, Eirini Rigopoulou, Eric Odada

Availability: ....This report is public.

Document revisions		
Author(s)	*Revision content*	*Date*
Kartala Xanthi and Nikos Englezos	First Draft	20/07/2018
Eric Odada	Kenya Socio-economic Country Profile	31/07/2018
Caroline Van Bers	Second Draft	23/08/2018
Phoebe Koundouri, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Eleftherios Levantis and Eirini Rigopoulou	Second Draft	24/08/2018
Paolo Burlando	Comments and suggestions for revision	28/08/2018
Phoebe Koundouri, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Eleftherios Levantis and Eirini Rigopoulou	First Revision	15/09/2018
Phoebe Koundouri, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Eleftherios Levantis and Eirini Rigopoulou	Empirical Illustration of the model	5/10/2018
Phoebe Koundouri, Mike Tsionas, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Eleftherios Levantis and Eirini Rigopoulou	Revision of the Econometric Analysis	10/11/2018
Phoebe Koundouri, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Lydia Papadaki Eleftherios Levantis and Eirini Rigopoulou	Revision of the Empirical Illustration of the model according to the revised econometric analysis	01/12/2018
Phoebe Koundouri, Ebun Akinsete, Nikos Englezos, Xanthi Kartala, Lydia Papadaki Eleftherios Levantis and Eirini Rigopoulou	Integration of the updated contributions and review of the full document	20/12/2018
Phoebe Koundouri, Ebun	Revision	26/12/2018

Akinsete, Nikos Englezos, Xanthi Kartala, Eleftherios Levanti, Eirini Rigopoulou, Mike Tsionas	(The authors are thankful to Prof. Michael Rauscher and Lydia Papadaki for their comment and suggestions, that were instrumental for the finalization of this deliverable. All errors remain ours)	
Paolo Burlando	Editing, check and comments	28/12/2018
Xanthi Kartala	Additional revision	13/01/2019
Paolo Burlando	Final check and formatting	26/01/2019

Table of Contents

Models of the Economic Development in the Omo-Turkana Basin i

1. Introduction 1
1.1 Methodological Approach 2
1.2 Description Of The Economic Development In The Omo-Turkana Basin 2
1.2.1 Ethiopia 4
1.2.2 Kenya 14

2. FORMULATION OF THE ECONOMIC DEVELOPMENT MODEL 30
2.1 Modelling Of Economic Development From a WEF Nexus Perspective 31
2.2 Generalization Of The Model In the River Basin Water Sharing Case 32
2.2.1 Non-Cooperative Approach 36
2.2.2 Cooperative Approach 37

3. Estimation Of The Production Functions Of The Economic Model By Sector 39
3.1 Mathematical And Statistical Models 39
3.2 Data Collection 42
3.3 Econometric Analysis – Results 43
3.3.1 Econometric Model 44
3.3.2 Empirical Results 48
3.4 Empirical Illustration 53

4. Concluding Remarks 63
4.1 Summary of Results 63
4.2 Additional Remarks 63

5 References 64

Appendix 1 – Ecosystem Services Indices 1

Appendix 2 – Decoupling Method 9

Appendix 3 – Sequential Monte Carlo 16

List of Tables

Table 1 - GDP in Ethiopia by sector (percentage of GDP)........ 5

Table 2 **–** Macroeconomic Indicators for the Ethiopian Economy (Source: *NBE*, 2016/17)........ 6

Table 3 - Guideline water tariff blocks and ranges for medium and large towns in Ethiopia. (*MoWIE*, 2013) .14

Table 4 - Guideline water tariff blocks and ranges for small towns in Ethiopia. (*MoWIE*, 2013)........14

Table 5 - Marketed Agricultural Production at Current Prices, 2012 – 2016. Prices are in Million KES.........19

Table 6 - Average Gross Commodity Prices to Farmers, 2012 – 2016. Prices(**) are in KES per Unit...........20

Table 7 - Water Purification Points and Boreholes Drilled, 2012/13 - 2016/17 (Source: *Ministry of Water and Irrigation*) 21

Table 8 - Water Tariff Structure for Year 2015/16, 2016/17 and 2017/18 (Source: *Nairobi City Water and Sewerage Company*, Water Act 2002)........23

Table 9 - Miscellaneous Charges (Source*: Nairobi City Water and Sewage Company*, Water Act 2002)......24

Table 10 - Ecosystem Services - Source: adopted from *De Groot et al.*, (2002). 42

Table 11 - Empirical results: β parameter for each Sector........49

Table 12 - Empirical results: α parameter for each Sector........49

Table 13 - Price elasticity for each Sector........49

Table 14 - Parameters of the Economic Model 54

Table 15 – Non-Cooperative Approach........55

Table 16 – Cooperative Approach 57

Table 17 - Climate change impact on non-cooperative and cooperative case 59

Table 18 - Description of Indices of Ecosystem Services 1

List of Figures

Figure 1 - Map of Ethiopia, the Omo Gibe River Basin showing the main and tributaries of river network system of the watershed, and hydropower projects configuration. (Source: *Gebresenbet*, 2015).............. 4

Figure 2 - Water Prices in $ per m^3. (Source: *International Benchmarking Network for Water and Sanitation Utilities*, 2014). 14

Figure 3 - Kenya's GDP and overall inflation..16

Figure 4 - Water Prices in $ per m^3. (Source: *International Benchmarking Network for Water and Sanitation Utilities*, 2015) 22

Figure 5 - Demand drivers acting on Kenya's WEF security nexus. (Source: *World Bank*, 2018)..................25

Figure 6 - Fishing and mixed fishing/pastoral Turkana village areas at Lake Turkana. (Source: *Carr*, 2017).29

Figure 7 - Production Function Description...40

Figure 8 - Technical Efficiency and Inefficiency 41

Figure 9 - Curves of the demand function of All Sectors for the Upstream and Downstream Country 50

Figure 10 - Sampling distributions of water elasticities by sector for Ethiopia (upper panel) and Kenya (lower panel) 51

Figure 11 - Sampling distributions of constant terms by sector for Ethiopia (left) and Kenya (right)...............52

Figure 12- Sampling distributions of technical inefficiency by sector for Ethiopia (left) and Kenya (right).......52

Figure 13 - Sampling distributions of technical change by sector for Ethiopia (left) and Kenya (right) 53

Figure 14 - Sampling distributions of productivity growth (%) by sector for Ethiopia (left) and Kenya (right) ..53

Figure 15 – Noncooperative Case: Water Use average in Ethiopia in myopic and optimal case 56

Figure 16-Noncooperative Case: Water use average in Kenya in myopic and optimal case 57

Figure 17 – Water average use in Ethiopia for $n_1 = 0.7$ 58

Figure 18 - Water average use in Kenya for $n_1 = 0.7$. 58

Figure 19 – Non-Myopic Case: Water Use average in Kenya with $\sigma_O = 0.025$ and $\sigma_O = 0.3$ 60

Figure 20 - Cooperative Case: Water Use average in Kenya with $\sigma_O = 0.025$ and $\sigma_O = 0.3$ 60

Figure 21 - Non-Myopic Case: Water Use average in Ethiopia with $\sigma_W = 0.089$ and $\sigma_W = 0.3$..................61

Figure 22 - Cooperative Case: Water Use average in Ethiopia with $\sigma_W = 0.089$ and $\sigma_W = 0.3$ 61

Figure 23 - Non-Myopic Case: Water Use average in Kenya with $\sigma_R = 0.431$ and $\sigma_R = 0.1$ 62

Abbreviations

ADPF:	Auxiliary Disturbance Particle Filter
AfDB:	African Development Bank
AFREC:	African Energy Commission
ATA:	Agricultural Transformation Agency
CIA:	Central Intelligence Agency
COMESA:	Common Market for Eastern and Southern Africa
CPD:	Country Programme Document
D:	Downstream
DAFNE:	Decision-Analytic-Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast growing developing countries
ERC:	Energy Regulatory Commission
EPI:	Environmental Performance Index
ES:	Ecosystem Services
EU:	European Union
EWURA:	Energy and Water Utilities Regulatory Authority
FAO:	Food and Agriculture Organization of United Nations
FBSDEs	Forward Backward Stochastic Differential Equations
FDI:	Foreign Direct Investment
FTA:	Free Trade Area
GCI:	Global Competitiveness Index
GDP	Gross Domestic Product
GOE	Government of Ethiopia
GTP	Growth and Transformation Plans
GVA:	Gross Value Added
HA:	Hectares
HJB:	Hamilton-Jacobi-Bellman equation
IAIP:	Integrated Agro-Industrial Parks
IAPRI:	Indaba Agricultural Policy Research Institute
IEA	International Energy Agency
ILO:	International LABOR Organization
INE:	Instituto Nacional de Estatística
IPF	Independent Particle Filter
ITCZ:	Inter-Tropical Convergence Zone (ITCZ).
IO:	Inputs-Output
IUCN:	International Union for Conservation of Nature
IV:	Instrumental Variable

JMP:	Joint Monitoring Programme
K2O:	Potash
KES	Kenyan Shilling
MALA	Metropolis Adjusted Langevin Algorithm
MDGs:	Millennium Development Goals
MoANR:	Ministry of Agriculture and Natural Resources
MoWIE	Ministry of Water, Irrigation and Energy
MRIO:	Multi-Region Input-Output Table
MT:	Mozambican Metical (currency)
MW:	Mega Watts
N:	Nitrogen
NE:	Nash equilibrium
NBE:	National Bank of Ethiopia
NB:	Net Benefit
NSO:	National Statistics Office
NVA:	Net Value Added
OECD:	Organization for Economic Co-operation and Development
OLS:	Ordinary Least Square
OTB:	Omo-Turkana Basin
PMCMC	Particle Metropolis-Hastings
PSNP:	Productive Safety Net Programme
P2O5:	Phosphate
PFA:	Production Function Approach
PPPs:	Public-Private Partnerships
REEEP:	Renewable Energy and Energy Efficiency Partnership
RE	Riccati Equation
SADC:	Southern African Development Community
SB:	Social Benefit
SDE	Stochastic Differential Equation
SE4ALL:	Sustainable Energy for All
TEV:	Total Economic Value
TC:	Total Cost
TFEC:	Total Final Energy Consumption
U:	Upstream
UNECA:	United Nations Economic Commission for Africa
UNEP	United Nations Environment Programme
UNICEF:	United Nations International Children's Emergency Fund

WASH:	Water, Sanitation and Hygiene
WASREB:	Water Services Regulatory Board
WB:	World Bank
WER	World Energy Resources:
WDPA:	World Database on Protected Areas
WEF:	Water-Energy-Food
WHO:	World Health Organisation
WP:	Work Package
WTP:	Willingness-To-Pay
WTTC:	World Travel and Tourism Council

1. INTRODUCTION

This report presents the research conducted as part of the European Commission project, 'DAFNE: A Decision-Analytic-Framework to explore the water-energy-food NExus in complex and trans-boundary water resources systems of fast-growing developing countries' (DAFNE Project). The main goal of work package 4 (WP4) is the modelling of economic and social processes and environmental policy with a water-energy-food (WEF) nexus perspective. Specifically, it analyses the sharing of a natural resource in a transboundary setting under different levels of pressure from factors such as demographic and land use trends, industrial development, institutional adequacy and learning culture for each country or region within the Omo-Turkana Basin of Ethiopia and Kenya.

The objective of this deliverable (D4.6) is to focus on the production of an economy-wide model which will describe the economic development of the regions or countries of each case study. The shared resource that is under pressure, namely water, has a central role in this model. In order to provide a more accurate representation than usually provided by abstract models, the sectors associated with each country correspond to a production function, adequately adapted to the corresponding characteristics. More specifically, the analysis includes information on the economic characteristics of each country such as total employment, production output of the energy and food sectors, volume of water use, environmental indicators, etc. In particular, the model developed is able to capture the interdependencies between two neighbouring, possibly different, economies sharing the same resource. It supports also the principle of sustainable development, in the sense that sustainable strategies for economic development will be accommodated given the effects of climate change.

More specifically, the economic characterization of water in the DAFNE regions for the OTB of Ethiopia and Kenya, includes the economic evaluation of water use in the OTB and evaluation of the economic importance of water use in the area. This procedure required the gathering of socio-economic data, such as income, employment, etc., for the two countries and is realized for each sector of economic activity in order to determine the sectors that put more pressure on water use. Furthermore, the different water-use patterns of each sector of economic activity (primary, secondary, tertiary and households) has a different water use pattern. In general, water use is prioritized relatively as follows:

(a) Agriculture and Fishing

(b) Residential Water Supply

(c) Mining and Quarrying

(d) Energy sector which includes hydropower production

(e) Tourism.

Therefore, this report outlines the methodology and approach towards developing the deliverable, before presenting an overview of the economic development of both the OTB countries (Ethiopia and Kenya), providing a snapshot of the inter-sectoral economic profile of each country. The deliverable goes on to detail the formulation of the model of economic development from the WEF Nexus perspective, taking into consideration the Total Economic Value of water. As multiple countries share water resources, the likelihood of conflicts over distributing water resources increases, particularly under the effects of climate change. The model developed in this deliverable captures the influence of stochastic water resources on transboundary water allocation per each of the above sectors, following a multistage dynamic cooperative game theoretic approach. Employing a stochastic Stackelberg differential game, we show how issue linkage can facilitate cooperation between countries, even in the case of climate change. We illustrate the model with the case of inter-sector water sharing between the upstream country, Ethiopia, and the downstream country, Kenya. The "*issue linkage to water sharing*" in this case concerns the trade of agricultural products exported from Kenya to Ethiopia. More precisely, we demonstrate how the two countries can cooperate in order to achieve sustainable transboundary water sharing under such conditions.

In terms of ‘inter’ and ‘intra’ work package interactions; D4.6 is a complementary deliverable to D4.1 (Models of the economic development in the Zambezi river basin). It forms part of a suite of socio-economic models, including D4.2, D4.3 and D4.4, all of which form the basis of D4.5 (Integrated framework of models for social, economic and institutional developments). Work carried out within WP2 in the form of data collection under Task 2.1 (in particular Subtask 2.1.7 and 2.1.8), was used as input for the development of this deliverable. Furthermore, elements of this deliverable will support the development of D2.1 (Baseline Scenario). This deliverable will also be integrated with the models being developed within WP3 and ultimately feed into the work within WP5.

1.1 METHODOLOGICAL APPROACH

The deliverable is a product of work activities carried out within Task 4.1 (Models of Development of the Economy), led by the ICRE8 team with contributions from the ACCESS team. The research carried out towards the development of this deliverable was primarily a desktop study, incorporating data derived from activities within WP2 as well as additional secondary and tertiary data collected under Task 4.1.

Based on extensive literature and archival review, both qualitative and quantitative data was collected from scientific journal publications, official reports, governmental websites, and other forms of grey literature. Quantitative data collected from databases including African development bank, including African development bank, ILO (International LABOR Organization) and the World Bank Group: Climate Change Knowledge Portal For Development Practitioners and Policy Makers, the United Nations Statistics Division, Unesco World Heritage list, OpenDataSoft, Environment & Climate Change Data Portal, Eora multi-region IO table (MRIO) database, and offices of national statistics.

While the deliverable adopts primarily quantitative methods of analysis, it also incorporates some elements of a qualitative thematic analysis within the literature review. The technique of multistage stochastic Stackelberg differential game theory is employed. This amounts to solving sequentially a series of free end point problems, each of which defines endogenously the date when an economic sector exits the market as its quantity demand of water reaches zero.

The main limitations of the study concern data and assumptions of the model. In terms of limitations relating to data, the primary issue has been data availability and quality, particularly at subnational and river basin level. Partners have been presented with challenges in terms of accessing data at a local level in cases where the data is non-existent or process of collecting it has proven too resource intensive. As such, the model has been developed using national level data, sourced from international databases for the estimation of the welfare function for each economic sector due to the lack of regional data.

Regarding limitations associated with the model itself, the stochastic differential equation of Geometric Brownian motion has been extensively used to model the dynamic flow of several natural quantities that entail randomness, such as the water volume of precipitation and runoff of a river (Omo) or of outflow from a lake (Turkana). Additionally, the volume of the annual renewable water resource due to the river basin has been considered as the total precipitation volume over the upstream area.

1.2 DESCRIPTION OF THE ECONOMIC DEVELOPMENT IN THE OMO-TURKANA BASIN

The Omo River forms through the confluence of the Gibe River, by far the largest total tributary of the Omo River, and the Wabe River, the largest left-bank tributary of the Omo River. Given their sizes, lengths and courses one might consider both the Omo and the Gibe Rivers to be one and the same river but with different names. The Omo Gibe River Basin is almost 79,000 km^2 in area and is situated in the south western part of Ethiopia, with an average altitude of 2800 meters above sea level (m a.s.l.).

It is Ethiopia's second largest river system after that of the Blue Nile, accounting for 14% of Ethiopian annual runoff. It flows from the northern highlands through the lowland zone to discharge into Lake Turkana at the Ethiopia/ Kenya border in the south (see Figure 1) and is nourished along its course by some important tributaries. The fundamental characteristic of the Omo Gibe River Basin is its complex topographic feature. Thus, the basin is divided sharply into the highlands in the northern half of the area and lowlands in the southern Half. This division is taken into account in almost all other aspects of the Basin.

The northern highlands are strongly dissected with steep slopes and drained by the Gibe and Gojeb systems which merge to form the Omo in a deeply entrenched gorge which slices into the highlands. The northern part of the catchment contains several tributaries emanating from the north-east, of which the largest is the Walga and Wabe rivers. Another two tributaries are the Tunjo and Gilgel Gibe rivers which drain mainly cultivated lands with less permeable soils in the south-west. The Gojeb River is a significant right bank tributary to the Omo River, draining the uplands that have been less intensively cultivated than the other parts of the basin. To the south of the Gojeb River are the catchments of the Sherma, Guma and Denchiya rivers, which are tapering streams that join the Omo at the northern end of the flood plain.

Except in the driest years, these rivers usually maintain some flow throughout the year. The Sana, Soke, Dame and Zage rivers drain the uplands on the eastern side of the middle and lower Omo Gibe catchment where the rainfall is relatively high and these rivers are deemed to be perennial. Further south, the Meki River, a tapering stream with perennial tributaries drains the highlands along the Omo Gibe Basin boundary and maintains some flow into the Omo River except the driest years (*Gebresenbet*, 2015).

The Omo Gibe River Basin has three distinct climate zones across the watershed in which it follows the country's climate classification, namely, Dega (cool zone), Weyna-Dega (temperate zone) and Kolla (hot zone). The highlands that comprise the areas around Jima and around the headwaters of the Gojeb River are classifiable as tropical humid climate. For the largest proportion of the watershed is classifiable as a tropical sub-humid i.e., intermediate between the tropical humid and the hot. The rest southernmost part of the floodplain toward Lake Turkana has the characteristic of hot arid climate3. The seasonal variation in climate is due to the oscillation of the Inter-Tropical Convergence Zone (ITCZ). ITCZ shifts during the year northwards across southern Ethiopia from September to November and southwards from March to May, giving origin to the alternation of a wet (from June to September) and a dry (from December to April) season. During the wet season the area is under the influence of Atlantic equatorial westerly and southerly winds from the Indian Ocean, producing strong precipitation, mainly due to the Atlantic moisture component, (*Gebresenbet*, 2015).

During the dry season, the moist air comes from the Gulf of Aden and the Indian Ocean, causing little rains. As the main source of moist air is from the Atlantic Ocean, from the South-West, the eastern parts of the highlands are more or less rain shadowed. The area of greatest rainfall is to the North-West of Jima (outside the Omo Gibe River Basin). Rainfall declines sharply in the lower lying southern parts of the basin.

About 90% of the Turkana lake surface water inflow is derived from the Omo River in Ethiopia (*Avery*, 2010). Hence, the lake is almost entirely dependent on this one river basin, and any developments within this basin will thus directly affect the lake. At the core of the region's indigenous economies are complex survival strategy systems that are highly adaptive to changing environmental and social conditions - systems linked together by food-related exchange networks and patterns of cooperation, along with competition for increasingly scarce resources. The water is critical to sustainable economic growth and poverty reduction in the region. In order to meet the basic needs of the people and sustain a rich and diverse natural environment, water plays a central role in the economies of the riparian countries mentioned above. To understand its crucial effect on the economies of the riparian countries, we give an in-depth description of the economic development of each country separately.

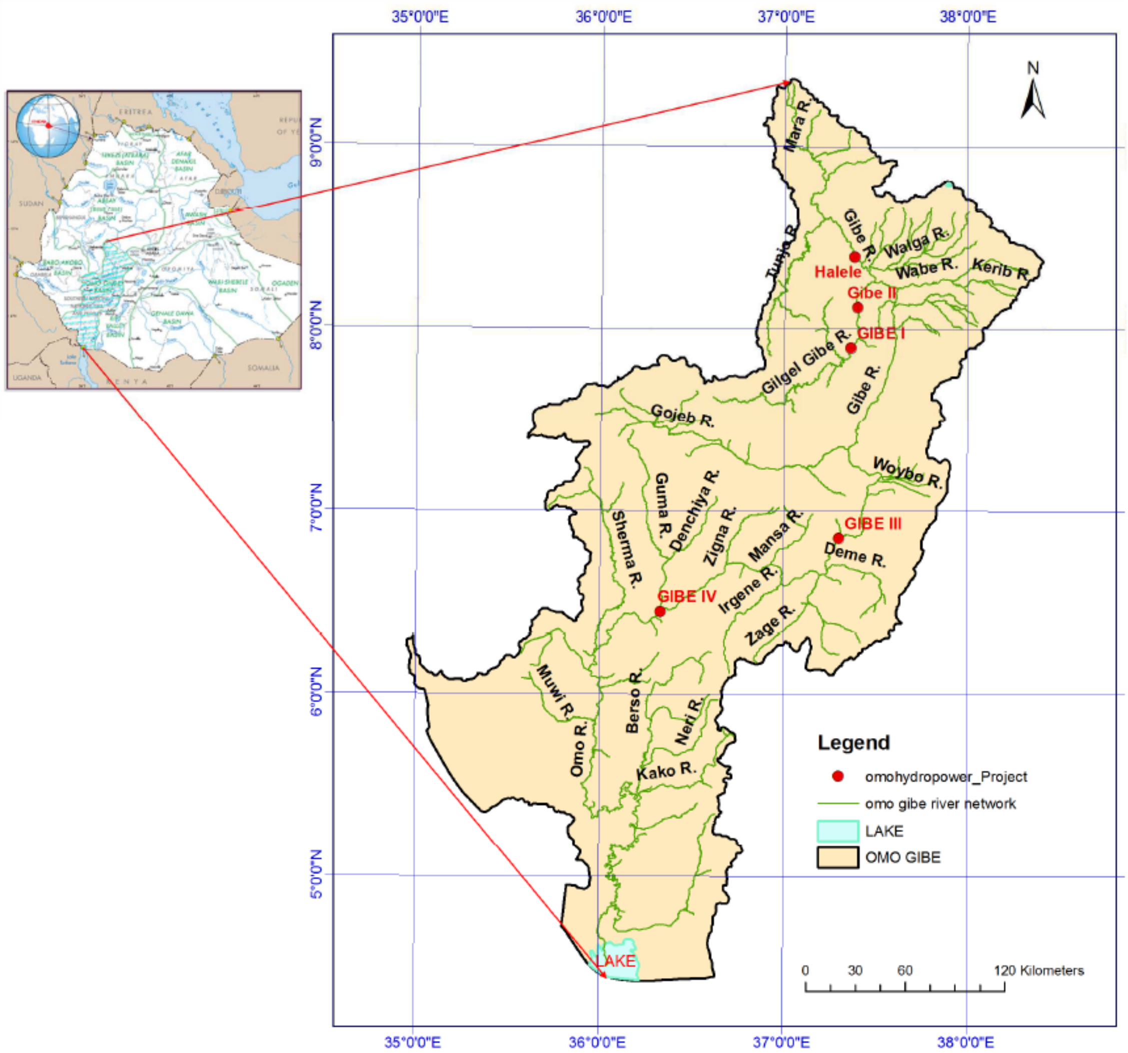

Figure 1 - Map of Ethiopia, the Omo Gibe River Basin showing the main and tributaries of river network system of the watershed, and hydropower projects configuration. (Source: *Gebresenbet*, 2015)

1.2.1 Ethiopia

A widely accepted indicator of the economic performance of a country is GDP. In Ethiopia specifically, it reached $80.56 billion in 2017 being so, the 67th wealthier country in the world. However, with population 104.9 million the GDP per capita in 2017 was $1899.2, which ranks Ethiopia 166th in the world (*World Bank*, 2018). The 2018 Africa Economic Outlook for Ethiopia report (*Sennoga and Zerihun*, 2018), provides an overview of Ethiopian's economic environment and key sectors. The report also highlights significant allocations from the 2017/18 Budget to various sectors of the economy.

Real GDP grew by 10.9% in 2016/17, up from the 8.0% growth registered in 2015/16. The industrial and services sectors contributed significantly to GDP growth by expanding at a rapid rate of 18.7% and 10.3% respectively. Construction, manufacturing, and electricity sub-sectors were the most important contributors to the faster growth of the industrial sector, and grew respectively by 20.7%, 17.4%, and 11.4% in 2016/17 (compared to 25%, 18.4%, and 15% in 2015/16). Construction benefitted from public infrastructure investment, notably in transport, energy, water and sanitation. Investments in industrial parks contributed to steady growth in manufacturing. Strong growth in Foreign Direct Investment (FDI), particularly in infrastructure and manufacturing, also increased industrial sector value added.

Ethiopia's Growth and Transformation Plans I and II (GTP II and I) both identify infrastructure as a key driver of structural transformation, leading to the prioritization of public infrastructure spending.

However, according to Ethiopia's score on the Global Competitiveness Index (GCI), the infrastructure pillar has remained low. At 2.7 (on a scale of 1 to 7 with 7 being the best), Ethiopia's score in 2017/18 was below the Sub-Saharan African average (2.9). Ethiopia has relied on both concessional debt, particularly external loans from multilateral partners and official bilateral creditors, and commercial loans from non-traditional creditors such as China to finance its infrastructure projects. Reliance on external borrowing is not sustainable, especially given Ethiopia's high risk of external debt distress. Consequently, ensuring sustainability of infrastructure financing requires innovative solutions, such as use of Public-Private Partnerships (PPPs), securitization of infrastructure assets, and implementation of cost reflective tariffs.

The services sector, the leading contributor to real GDP, grew at 10.3% in 2016/17 compared to 8.6% the previous year. Trade, transport and communications, public administration, and real estate led growth in the services sector, which accounted for the largest share of GDP (Table 1). Financial intermediation, hotels and restaurants also supported growth in the services sector, although their contribution was largely unchanged in 2015/16 and 2016/17.

The rain dependent agricultural sector continued to recover from the 2015/16 *El Niño* induced drought, growing at 6.7% in 2016/17 compared with 2.3% growth the previous year. Productivity-enhancing investments such as irrigation and improved rainfall in the major Meher season (May–September) increased crop production and agricultural sector growth.

The negative impact of weather fluctuations on the country's rain-fed agriculture sector and uncertainty in commodity prices are the primary downside risks. Structural reforms to improve export competitiveness and diversification are under way. The development of industrial parks across the country and investments in energy, transport, and logistics infrastructure should increase manufacturing exports. Real GDP growth will remain strong at 8.1% and 7.8% in 2017/18 and 2018/19 respectively, consistent with the Government's phased implementation of public infrastructure projects to stabilize the public debt.

Table 1 - GDP in Ethiopia by sector (percentage of GDP)

Sector	**2011/2012**	**2016/2017**
Agriculture, forestry, fishing and hunting	44.7	36.3
of which fishing	0.0	0.1
Mining and quarrying	1.4	0.3
of which oil	–	–
Manufacturing	4.0	6.4
Electricity, gas and water	1.0	0.8
Construction	4.0	18.2
Wholesale and retail trade; repair of vehicles; household goods; restaurants and hotels	18.5	15.7
of which restaurants and hotels	3.6	2.1
Transport, storage and communication	4.2	4.9
Finance, real estate and business services	11.1	7.9
Public administration and defence, security	5.4	4.9
Other services*	5.7	5.9
Gross domestic product at basic prices / factor cost	100.0	100.0

*Other services include education, health and social work and other services. Source. Data from domestic authorities

As outlined in Table 2, headline inflation in 2016/17 was in line with the single digit inflation objective of the central bank, the National Bank of Ethiopia (*NBE*, 2016/17). The NBE is currently implementing a contractionary monetary policy to address inflationary pressures that emerged during the second half of 2017. The budget deficit in 2017/18 is expected to increase by 0.2 percentage points from 2016/17 and is projected to rise further until 2020. Phased implementation of import-intensive public infrastructure projects, as the Government seeks to stabilize the public debt, will further lessen the current account deficit. Fluctuations in commodity prices remain key downside risks.

Table 2 – Macroeconomic Indicators for the Ethiopian Economy (Source: *NBE*, 2016/17)

Indicator	**2016/17**	**2017/18(e)**	**2018/19(p)**	**2019/20(p)**
Real GDP growth	10.2	8.1	7.8	7.5
Real GDP per capita growth	7.5	5.5	5.3	5.0
CPI inflation	7.8	8.1	7.7	7.5
Budget balance (% of GDP)	-3.3	-3.5	-3.7	-3.8
Current account (% of GDP)	-8.1	-8.5	-8.8	-8.7

Note: Data from domestic authorities; estimates (e) and predictions (p) are based on the authors' calculations

Poverty reduction, social protection and labour

From the 2018 Africa Economic Outlook for Ethiopia report (*Sennoga and Zerihun*, 2018), Ethiopia's high growth trajectory, averaging over 10% between 2003/04 and 2016/17, permitted significant gains in poverty reduction. Poverty dropped from 29.6% in 2011 to 23.4% in 2015/16, surpassing the Millennium Development Goals (MDGs) target of 24%. This reduction is attributed to the implementation of poverty reducing public expenditure policies, with over 65% of the budget allocated to poverty-related sectors. Implementation of welfare programmes also contributed, including the productive safety net programmes (PSNP), food security programmes, and urban productive safety net projects.

Income inequality, as measured by the Gini coefficient, remained low at 0.32 in 2015/16, slightly higher than the 0.3 recorded in 2004/05. However, significant disparity in poverty and income inequality exists within regions and in *woredas* (districts).

The Government established the PSNP in 2005 to provide predictable safety net support to Ethiopians who are chronically food insecure. Subsequently, the Government approved a national social protection policy in 2014 to provide a holistic framework for social protection. The policy and strategic framework focuses on productive safety nets, livelihoods and employment support, social insurance, and access to social services. PSNP provided food and other support to over 7.5 million people affected by persistent droughts during 2015-17.

The labour laws and labour market regulations are generally are enforced. Major labour market challenges are low pay and subsequent high staff turnover. As a result, several labour market programmes are being implemented to expand coverage and the quality of employment. These include interventions to link micro and small-scale enterprises with public works, notably paving urban roads, and housing projects. The recent labour force survey conducted in 2013 estimated urban unemployment at 16.5% (cf. *Sennoga and Zerihun*, 2018).

Ethiopia has ratified several ILO conventions, including ILO Convention 182 on the Worst Forms of Child Labour. However, enforcement of these conventions, especially the child labour convention, needs to be strengthened (*Sennoga and Zerihun*, 2018).

Energy Resources

Total production of electricity in 2015 was 1,708 ktoe with 82.7 % produced from hydropower, 2.8 % from fossil fuels and 2.7 % from geothermal sources (*IEA*, 2016). Final consumption of electricity was 654 ktoe in the same year (*AFREC*, 2015).

Ethiopia has significant biomass energy potential with estimates putting the national woody biomass stock at 1,149 million tonnes with annual yields of 50 million tonnes in the year 2000. Biomass distribution across the country is uneven, with the northern highlands and eastern lowlands having low biomass cover. Population growth is putting pressure on these resources. Agro- processing industries, such as sugar-cane bagasse, cotton stalk, coffee hull and oil- seed shells, present an opportunity for biomass energy. However, currently there are no grid-connected biomass power plants. Municipal waste and biofuels have been underutilized although the current Growth and Transformation Plan seeks to address this by stepping up the dissemination of domestic biogas plants, vegetable oil stoves and improved stoves (*REEEP*, 2014).

There are enormous resources for hydro generation; the gross theoretical potential (650 TWh/yr) is second only to that of the Democratic Republic of the Congo (*WER*, 2013). Despite this, only about 3 % of the country's hydropower potential is being exploited (*REEEP*, 2014). Currently, domestic demand is insufficient to justify its full development. Some of the hydroelectric projects include Tekeze (300 MW in 2009), Gibe II (420 MW in 2010), Tana Beles (460 MW in 2010) and Amerti Nesha (97 MW in 2011). Additionally, three more projects (Gibe III, Ashegoda expansion, Adama II) are completed and the Grand Ethiopian Renaissance Dam is under construction. However, these developments are constrained by the inadequate power transmission system (*REEEP*, 2014).

There exist few proven hydrocarbon reserves although there is potential for oil and gas exploration. By the end of 2011, the proved recoverable reserves of natural gas were 25 bcm (*WEC*, 2013). There is no in-country refinery so all petroleum products are imported.

Ethiopia is known to have some coal deposits in the Dilbi-Moye basin in the southwest of the country. Deposits are estimated at 14,016,730 tonnes (Ministry of Mines and Energy, 2009). Other areas with coal deposits include the Geba basin (250,000,000 tonnes), Chilga basin (19,000,000 tonnes) and Chida Waka (9.38 million tonnes) (*Ethiopian Ministry of Mines and Energy*, 2009).

Ethiopia has one of the largest wind resources in Eastern Africa, with velocities ranging from 7 to 9 m/s. At the end of 2013, 171 MW of wind energy was installed (*Global Wind Energy Council*, Various years). The country installed another 90 MW in 2013, in line with the government's very ambitious plans for build-out of up to 7 GW by 2030 (*Global Wind Energy Council*, Various years). Two wind farms are in operation: the 51 MW Adama I wind farm, which began production in 2011, with a second phase (150 MW) under construction; and the 120 MW Ashegoda wind farm, which came on line at the end of 2013. The Ethiopian government is keen to use renewables to mitigate the seasonal availability of hydropower. To that end, a solar and wind power master plan has also been prepared (Energy Profile: Ethiopia) by the UN Environmental programme (UNEP) (2017).

By the end of 2011, the installed capacity of electricity from geothermal sources was 7.3 MW and the annual output was 10.0 GWh (*WEC*, 2013). The Ethiopian Rift Valley and the Afar depression have considerable geothermal resources and are thought to be able to generate more than 5,000 MWe of electricity. A 7.3 MWe geothermal pilot power plant has been installed at Aluto and is generating 4 MWe; there are plans to expand this project to 70 MWe. Other promising sites include Teo, Danab, Kone and others (*REEEP*, 2014). Ethiopia is also pursuing a $4 billion private sector investment to develop its geothermal power resources and produce 1,000 MW from steam (*REEEP*, 2014).

Ethiopia has great potential for solar energy as it receives a solar irradiation of 5,000-7,000 Wh/m² depending on the locale and the season. The solar radiation averages 5.2 kWh/m^2/day. The values vary with the seasons, ranging from 4.55 to 5.55 kWh/m^2/day, and over space, ranging from 4.25 kWh/m^2/day in the extreme western lowlands to 6.25 kWh/m^2/day in Adigrat area (*REEEP*, 2014). Installed solar capacity in 2011 was 5 MW (*WEC*, 2013).

Ethiopia is one of the top 20 countries with a deficit in access to electricity, with 63.9 million people without access to electricity in 2010 and 81.1 million people lacking access to non-solid fuels (*World Bank*, 2013). The vast majority of the Ethiopian population (83.2 % as of 2010) lives in rural areas, where modern energy services are rarely available. But there has been some progress. The World Bank (2016) indicates that by 2012, 7.6 % of the rural population had access to electricity while the urban population had reached 100 %. Access to modern fuels is low. In 2012, only 2.19 % of Ethiopians were using non-solid fuels; 2 % of these are in rural areas and 18 % in urban Ethiopia (*World Bank*, 2016).

The share of renewable energy in the total final energy consumption (TFEC) was 94.49 % in 2012 (*World Bank*, 2016). Traditional solid biofuels form the biggest share of renewable sources at 92.6 % of TFEC in 2012, while modern solid biofuels contributed only 0.8 % and hydro 1.1 % (*World Bank*, 2015). Renewable sources contributed a 99.4 % share of electricity generation in 2012 (*World Bank*, 2015). Even in urban areas, half of households rely on traditional biomass (wood, dung and agricultural residues) for cooking, and in rural areas, virtually all do (except for 0.2 % who use kerosene and 1.2 % who use charcoal. Ethiopia has made big strides in recent years, however, with 48.3 % of towns and villages connected to the grid as of July 2012, according to the Ethiopia Electric Power Corporation (*UNEP*, 2017).

Agriculture

Ethiopia is endowed with abundant agricultural resources and has diverse ecological zones. Agriculture is the mainstay of the economy. “The Government of Ethiopia (GOE) has identified increasing productivity of smallholder farms and expanding large-scale commercial farms as two of its priority areas. In addition, as part of the second Growth & Transformation Plan (GTP II), the government is looking to the agro-processing sector as one engine to spur future economic growth” (*The International Trade Administration*, 2017).

With respect to increasing productivity, the GOE alongside its international partners have made a number of interventions to support the development of the country’s agriculture sector. These activities have contributed towards higher yields and increased production of both crops and livestock. At the same time, in an effort to accelerate the country’s agricultural development, the government established the Agricultural Transformation Agency (ATA) to address systemic bottlenecks in the agriculture sector by supporting and enhancing the capability of the Ministry of Agriculture and Natural Resources (MoANR) and other public, private, and non-governmental implementing partners (*The International Trade Administration*, 2017).

In order to promote commercial-scale farming, the MoANR created the Ethiopian Agricultural Land and Investment Administration Agency dedicated to overseeing any new large-scale commercial farm deals. The directorate's goal is to increase productivity, employment, technology transfer, and foreign exchange reserves by attracting investors with incentives and favorable land lease terms. Some of the land targeted for commercial development is considered marginal, prone to conflict, and/or has limited access to water. Land ownership is also a complicating factor. Therefore, investment in commercial farming requires considerable due diligence. Separately, the Ministry of Livestock & Fisheries (MoLFis supporting the development of the country’s livestock sector, which is one of the largest in Africa).

According to the GTP II, Ethiopia’s future economic growth in part depends on the development of agro-processing sector (e.g. processed food, beverages, and livestock products – meat, milk, and eggs), as well as the textile/apparel and leather industries. Some of these products, especially the textiles, apparel, leather goods, and finished meat products are targeted for export markets in order to generate foreign exchange. Agro-processed products, which are relatively new to the local market, such as chicken, cheese, butter, eggs, biscuits, bread, juice, etc. will go to help satisfy local demand. In the case of the textile and apparel sector, a shortage of locally-produced cotton suggests a need for cotton imports, including from the United States. In addition, the GOE continues to invest heavily in the expansion of the state-owned sugar industry, with the aim of become one of the top ten sugar producers in the world over the next decade.

In addition, some of Ethiopia's cash crops show potential for growth and offer possible investment opportunities in areas such as coffee, oilseeds, pulses, fruits and vegetables, honey, cut flowers, tea, and spices. Most of these crops are exported to generate foreign exchange. In the future, the government intends to work with the private sector to develop capacity to process some of these commodities, like fruits and vegetables, in order to add value and capture higher export prices.

To attain the agro-processing objective, the GOE is building Integrated Agro-Industrial Parks (IAIP) in four pilot areas: Amhara, Oromia, SNNP, and Tigray regional states. The pilot areas selected for establishment of the Agro-Industrial Parks are mainly based on existing agricultural resources and allied sectors potential, infrastructure, and facilities. Total required investment costs for the IAIPs stand at US $ 870 million and initial investment costs are estimated at US $ 266 million. The project implementation phase is expected to be accomplished in three phases with the first phase kicked-off in February 2016.

As the economy grows and the population expands, consumer demand for certain types of foods is expected to increase. In particular, demand for cooking oil, sugar, meat, eggs, dairy products, wheat-based products, such as pasta and bread, alcoholic and non-alcoholic beverages, among others, are forecast to climb upward. The increased production coming from existing and anticipated investments in the local agro-processing sector, as well as imports, are expected to help satisfy this growing demand.

The expected growth from these above-mentioned agriculture-related industries offers numerous opportunities for agricultural input sales, such as tractors and harvesters, farm trucks, fertilizer, irrigation equipment, grain handling systems, food and livestock processing equipment, as well as cold storage facilities, among others. There are also expanding opportunities for grocery sales to retail and wholesale outlets that are starting to spring up all over Addis Ababa.

With Ethiopia facing its worst drought in several decades, the GOE is renewing its emphasis in developing the country's irrigation systems and water-harvesting methodologies. There is considerable room for investment when considering that about 95 percent of Ethiopia's crop production is rain fed. It is anticipated that there will be growing demand for water supply and drainage systems, pumps, and drilling equipment.

Water Supply

Water supply and sanitation is the top priority of Ethiopian water management policy and strategy. The current GTP-II clearly articulates, based on new water supply standard, to reach 85% from current 59% in rural areas and 75% from current 58% in urban areas by 2020. The GTP-II is also an important vehicle to achieve the universal access of water supply and sanitation in line with the 2030 Agenda for Sustainable Development. GTP-II is a five years programme that is to be implemented from 2016 to 2020 and have similar indicators with the SDG goals of 6.1 and 6.2.

By the end of the GTP-2 period in 2020, the proportion of people using safely managed, adequate and resilient water supply services is planned to be increased to 83% while the proportion of people using safely managed and resilient sanitation services is planned to be increased to 100%. The number of people (particularly mothers) practicing improved hygiene behaviours (Hand Washing, Face Washing, Food Hygiene) and living in healthy environments is planned to be increased to 70%, by 2020, from the current 17%.

UNICEF-Ethiopia is working with the government and other partners to mitigate the problem and reduce vulnerability to water insecurity. Groundwater assessment studies and consideration of multi-village water supply systems are new approaches to provide water to communities where water is scarce by conveying water from other areas where it is available. This approach recently adopted by UNICEF is proved to be promising and have shown successful results in field trials of constructing test productive boreholes. Predicting possible water shortages, carrying out preparedness activities and linking emergency response with development intervention is considered as a strategy to mitigate the problem related to drought while carrying out lifesaving activities at the same time.

It has been estimated that 50% of the consequences of undernutrition are caused by environmental factors that include poor hygiene and lack of access to water supply and sanitation (*Blössner and De Onis*, 2005). There are strong links between sanitation and stunting. Open defecation has a harmful effect of faecal-oral diseases like diarrhoea, which can cause and worsen malnutrition. Diarrhoea is the leading cause of under-five mortality in Ethiopia, causing 23% of all under-five deaths, more than 70.000 children a year.

In 2015 Ethiopia achieved the drinking water MDG target of 57% successfully halving those without access to improved drinking water since 1990. This means that over 52 million people in Ethiopia now have access to an improved drinking water source (within 1.5 km) as compared to only 6 million people in 1990. This achievement is primarily the consequence of significant improvements in access to drinking water supplies in rural areas. Moving forward this improved drinking water access is challenged by the sustainability of water supply schemes associated with the low reliability of water resources particularly in the more arid Regions of Ethiopia.

While Ethiopia did not quite achieve the MDG for sanitation, it did decrease the population practicing open defecation by 63% (the largest decrease in the proportion of the population practicing open defecation of any country globally). This decrease in open defecation means that 67 million people gained access to a latrine over the MDG period at an average of 2.6 million people per year. This does not reflect the acceleration in the reduction of open defecation since the launch of the Community led Total Sanitation and Hygiene (CLTSH) programme by the Federal Ministry of Health (MoH) in 2011. Despite this impressive progress the overall numbers do mask some of the differences in progress between the different Regions as well as the more challenging pockets of deprivation.

Therefore, huge effort is required towards achieving improved sanitation where the coverage in Ethiopia is still very low amounting only 6.3% (*EDHS*, 2016). The report further indicates that 32 % of the population are still defecating in the open (about 32 million people) most of which are located in developing regional states of Afar, Somali, Benishangul-Gumuz and Gambella. In areas where ODF coverage is low, UNICEF is following an approach of implementing CLTSH while in areas where ODF coverage is high, UNICEF is working towards achieving high coverage of improved latrines through the introduction of robust and appropriate sanitation marketing system.

As per the Demographic and Health Survey 2016, the improved water supply coverage of Ethiopia is 64.8% while only 17.7% is contributed from piped systems (14.3 piped into dwelling and 3.4% piped into neighbour). This implies there is still huge challenge to provide basic water supply to about 35 million people who are mostly located in a difficult-to-reach areas and hydrologically challenging environment. With the new plan of the SDG indicators of safely managed water supply system and sanitation facilities, there is a need to accelerate the effort to achieve the planned results. The threatening climate induced water shortage is adding up to the problem indicating the necessity for a climate resilient WASH programming. The 2015/2016 *El Niño* induced drought has demonstrated resilient water supply systems are essential in future water supply programmes that sustain hazards as a result of environmental calamities.

The country programme document (CPD) defining the UNICEF support for the WASH Sector from 2012-16 sought to assist the government of Ethiopia to:

- extend new (or rehabilitated) improved drinking water access to 2.8 million people.
- assist 2.8 million people to obtain access to household latrines and 7,000 villages to achieve open defecation free (ODF) status.
- provide improved WASH facilities to 460 Health Centres & Health Posts.
- introduce a package of improved drinking water & latrines, handwashing & hygiene education programmes in 450 schools (with menstrual hygiene facilities in some schools).

While the CPD targets for household access to water and sanitation facilities were significantly surpassed (enabling 7.85 million people improved access to WASH facilities), the targets for the provision of WASH facilities in schools and health facilities were not achieved. In not quite meeting the WASH in school and health facility targets, it is worth highlighting that the provision of WASH in schools and health facilities has been historically very difficult in Ethiopia. The major challenge of providing improved WASH facilities in schools (the responsibility of the Ministry & the Bureaus of Education) and Health Facilities (the responsibility of the Ministry & the Bureaus of Health) tends to lie in connecting these efforts with the provision of access to a sufficient and reliable source of drinking water (the responsibility of the Ministry & the Bureaus for Water). Through the CPD this challenge appears to have been bridged by linking the provision of WASH facilities in schools & health facilities the provision of resilient community managed piped water supply networks.

WEF nexus in Ethiopia

Ethiopia, located at the Horn of Africa and with over 100 million inhabitants, is the second-most populous nation on the African continent after Nigeria. In the central plateau, where most of the population lives, the altitude varies between 2,000 and 3,000 m. Although Ethiopia has achieved significant economic growth since 2007, making it one of the highest performing economies in sub-Saharan Africa, it still remains one of the world's least developed countries, ranked 174 out of 187 in the 2011 UNDP Human Development Index and 70 out of 76 in the 2012 Global Hunger Index. About 29% of the population lives below the national poverty line (*IFAD*, 2012). Ethiopia's economic structure is unique in Africa. It has no oil or mining sector, and private investment is relatively new. With the country lacking basic growth components, the Ethiopian economy is highly dependent on agriculture. Ethiopia has high spatial disparities in water availability that create conflicts on local as well as transboundary levels. More than 10.1 million people were suffering from drought conditions in 2015. Ethiopia covers its electricity demand almost completely with hydropower. Still, the rural population has no access to energy; thus, the use of fuel wood is widespread.

The major reasons for food, water and energy insecurity in Ethiopia do not relate to a lack of resources but are mainly governance born (infrastructure development, insecurity and conflict, poverty, fall in world prices of cash crops). Despite the liberalization of Ethiopia's market for international investment, the state is still the most dominant actor. However, foreign investments and thus financial resources are increasing with strong enforcement of regulations by the government. If this continues, increased investments could accelerate the progress in Ethiopia's many WEF security issues. In terms of water security, Ethiopia needs to prevent national water conflicts by ensuring water security. Increased water storage for drought-affected areas and extended public services that include safe drinking water supply and sanitation services could impact the disparities in water availability positively. Furthermore, the increase of energy accessibility would have a positive effect on water security, because it would open the option for the rural population to upgrade their techniques to independently access safe water sources. An increased energy demand caused by improved water services coverage could be covered by hydropower and biofuels. Besides, biofuels are an opportunity to decrease food insecurity via technological transfer and the use of revenues for food purchases. (*Al-Saidi et al.*,2016).

Omo River Basin

The course of the Omo River is entirely contained within the boundaries of Ethiopia, and it empties into Lake Turkana on the border with Kenya. The lake is situated primarily in northwestern Kenya, with only its northernmost end, the Omo Delta, inside Ethiopia. The Omo river is the principal stream of an endorheic drainage basin, the Turkana Basin. An endorheic basin is a limited drainage basin that normally retains water and allows no outflow to other external bodies of water, such as rivers or oceans, but converges instead into lakes or swamps, permanent or seasonal that equilibrate via evaporation.

As Ethiopia is situated within the tropical region, ITCZ is the principal factor that influences its weather system. The seasonal rainfall distribution within the Omo Gibe River Basin arises out of the annual migration of the ITCZ. Based on the rainfall distribution patterns, the Basin is characterized by three distinct rainfall regimes. The central eastern part has a bimodal rainfall pattern, the north-eastern region has an asymmetric bimodal pattern, and the western mountain slopes have a strongly flattened unimodal profile. Rainfall pattern strongly decreases from north to south of the watershed particularly less than 300mm/year near Lake Turkana, (*Gebresenbet*, 2015).

The Omo River is a lifeline for southwest Ethiopia's indigenous peoples whose food security and economy depend on the river's seasonal flooding and subsequent flood-retreat cultivation of the river banks. They are primarily agropastoral, combining livestock herding with recessional cultivation (or flood retreat cultivation), most of which occurs along the Omo River or its tributaries. Cultivation is now an essential part of the economy for the vast majority of the population. In this region of highly erratic rainfall in both amount and distribution, recessional cultivation is a key component of subsistence for almost all ethnic groups, especially during periods of prolonged drought or livestock disease epidemics. Shifts to cultivation by a household or village may be temporary or permanent, depending upon circumstances given the apparent increasing environmental deterioration and declining livestock potential of the Lower Basin, however, the transition to cultivation has likely become permanent for most households. According to the Omo-Gibe Master Plan, the Omo Basin's Ethiopian population numbered 8.78m. in 1994 and was forecast to more than double to over 19m. by 2024 (*Woodroofe et al*., 1996). The Lower Omo population was reported to number 173,542 people in 2010, of whom 82,000 (roughly half) are directly dependent on the Omo River (*SOGREAH*, 2010).

In 1996, a development Master Plan was produced for the Omo-Gibe Basin (*Woodroofe et al*., 1996). The terms of Reference were prepared by the Ethiopian Development Studies Authorities (EDSA, 1991) and approved by the AFDB. The aim was to plan the basin's multi-sectoral development strategy, and prepare implementable sustainable projects, mainly agricultural, to exploit the basin's natural resources. This included exploiting the hydropower and irrigation potential of the basin and identifying schemes that would depend on major dams to control the Omo river water.

Ethiopia has abundance of highland rivers providing a large energy potential in the form of hydroelectric power. Power planning studies have estimated that Ethiopia's hydroelectric potential is in the order of 30,000 MW (*Hailu*, 1998) greatly in excess of foreseeable domestic energy demand. Several plants are currently under design and/or construction to make the best use of this valuable energy source. o satisfy energy and water demands and enhance the national economy, the Government of Ethiopia is developing the Gibe Hydroelectric Cascade scheme (4,600 MW)

With abundant rainfall and suitable physical features, Ethiopia has several potential sites for hydropower development. The Ethiopian government has started building a series of dams on the Omo River, primarily to meet the demands of the power industry in the East African region. Gibe I and Gibe II are already commissioned and operational. The Gibe I or Gilgel Gibe– Gibe II hydroelectric system is a starting point in the development of the Gibe-Omo hydropower potential. The system is a cascade scheme of two power plants on the Gilgel Gibe river, with a capacity of 184 MW and 240 MW respectively. The total annual energy production of the two plants is about 2350 GWh. The benefits deriving from the realization of the Gilgel Gibe hydropower system can be

- at national level, helping the country to meet its electrical energy demands enhancing
- socio-economic development;
- at regional level, providing the source for developing the rural electrification program;
- at local level, employing local people for the construction of the plant, and improving the local entrepreneurial development.

On December 17, 2016, Ethiopia inaugurated Gibe III dam, under the aegis of the country's prime minister, the Italian construction company Salini Impregilo's chief executive, the Ethiopian Electric Power chief executive and the Chinese ambassador, among other investors. The dam is purported as set to boost Ethiopian economy and bring prosperity to the country. Located on the Omo River 450 kilometres southwest of the capital Addis Ababa, the dam is the latest in a series being built by the country, to harness its vast water supply. It is an extension of a greater complex that includes two other hydroelectric dams: Gibe I and Gibe II and will generate up to 6,500 GWh of electricity a year, increasing the country's production capacity by at least 80%. These three dams, along with the Grand Ethiopian Renaissance Dam (GERD) being built by Salini Impregilo, are the product of an ambitious programme by the country to arrive at a generation capacity of 40,000 MW by 2035. It is worth to mention that the water reservoir created by the dam holds 15 billion cubic metres, equal to half the volume of Lake Tana, the largest in Ethiopia (*Salini Impregilo,* 2016). The benefits of the project were already evident during its construction, contributing enormously to the local economy. It created jobs for a combined total of 20,000 Ethiopians during the various phases of its construction.

In 2011, large-scale irrigation development by the state-owned Ethiopian Sugar Corporation was in the process of implementing a plan to create 100,000 hectares of irrigated plantations in Lower Omo. This included the flood-retreat cultivation and grazing areas of thousands of resident agro-pastoralists, as well as vast areas taken from two national parks and a wildlife reserve. More precisely, 135,285 hectares to be excised from the Omo National Park, The Mago National Park and the Tama Wildlife Reserve (*EWCA*, 2011) as a first plan. However, currently negotiation is undergoing between the Ethiopian Wildlife Conservation Authority and those concerned on how to minimize the affected area as well as to reduce the impact on the wildlife. This scheme, known as the "Omo-Kuraz Sugar Development Project" will create a huge potential water demand from the Omo river.

In summary, the Omo Basin is undergoing dramatic man-made changes due to hydropower and irrigation development, with oil exploration also in progress. The filling of the dam reservoirs will cause temporary drops in the water level of Lake Turkana and, once in operation, the dams will permanently regulate river flows, changing the hydrological cycle. The abstraction of water from the Omo for irrigation, downstream from the dams, will cause a permanent reduction in lake level. The change in water level combined with alteration of the hydrological cycle by the dams, will lead to destruction of the lake's flood plains fisheries. The impact on the human population will also be significant, with residents of the Lower Omo being evicted from their lands and resettled elsewhere, to make way for commercial agriculture (*Avery*, 2012).

Water Tariffs

In Ethiopia many water supply services are operating with varying and very low tariff structures despite the rising levels of inflation witnessed over the years. As a result, cost coverage has remained very low which has greatly constrained service provision due to inefficient operations and limited investments in system expansion and maintenance. In addition, the low-cost recoveries have a negative impact on the poorest population, many of whom lack adequate access to water supply and are forced to use expensive and unreliable water sources for their domestic needs. The health and socio-economic consequences have been also immense. Thus, developing a better tariff that enables the town water supply services to become financially viable is very critical, now a days, for most of the water supply services to operate smoothly. The tariffs to be set for the water supply services therefore, should be that which enable the utility to achieve full cost recovery and meet most of its short, medium and long-term investments and operating and maintenance costs, while at the same time ensuring increased coverage and quality of service. Town Water Supply Services in Ethiopia, study and submit its tariff proposal to the town water boards if an adjustment of tariff is intended. Based on an analysis of cost level and structure as well as performance and efficiency of the water supply service in service provision, new tariffs will be checked by the town water boards, in consultation with the regional water bureau, and submit to Woreda/ City Council for approval. The council approves the tariff if it believes the tariff is affordable for the town community.

Hence, the rising block tariff is used for both domestic and non-domestic users. This means that the consumer pays more as consumption increases. A certain basic allowance of water, the first block, is supplied at a minimal price (or even free) and subsequent blocks of water are charged at increasingly higher rates. The recommended blocks for medium and large towns are shown in Table 3. The Guideline also recommends a set of block ranges for small towns (Table 4).

Based on these block ranges, the price paid by each customer is calculated according to the volume of water they use. The actual costs of water supply differ from town to town, depending on various factors such as the ease of treatment of the raw water and the cost of laying distribution pipes, etc., so the price paid by consumers also varies between towns. As an example, the water prices ($/m^3) in Addis Ababa, are composed by both fixed and variable charges and are demonstrated in Figure 2. The fixed charges, that cover short-term water service administration costs, start from $0.06 per m^3 for no water consumption and decrease to zero as water consumption increases, while the variable charges start from $0.08 per m^3 for consuming just 1 m^3 of water and increase to $0.33 per m^3 as the volume of water usage by the customer increases up to 300 m^3.

Table 3 - Guideline water tariff blocks and ranges for medium and large towns in Ethiopia. (*MoWIE*, 2013)

Block	**Range**	
	Domestic Users	Non domestic users
1st	0-5 m^3	0-5 m^3
2nd	6-10 m^3	6-10 m^3
3rd	11-15 m^3	11-25 m^3
4th	16-20 m^3	26-40 m^3
5th	>20 m^3	>40 m^3

Table 4 - Guideline water tariff blocks and ranges for small towns in Ethiopia. (*MoWIE*, 2013)

Block	**Range**	
	Domestic Users	Non domestic users
1st	0-3 m^3	0-5 m^3
2nd	4-7 m^3	6-10 m^3
3rd	8-10 m^3	11-25 m^3
4th	>10 m^3	>25 m^3

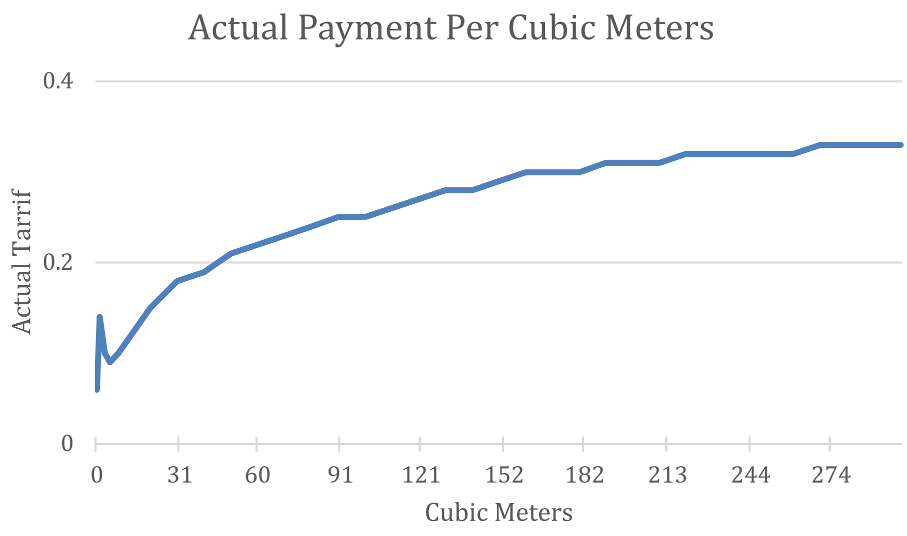

Figure 2 - Water Prices in $ per m^3. (Source: *International Benchmarking Network for Water and Sanitation Utilities*, 2014).

1.2.2 Kenya

The Kenya Economic Outlook 2017 report provides an overview of Kenya's economic environment and key sectors. The report also highlights significant allocations from the 2017/18 Budget to various sectors of the economy.

Economic Environment

A widely accepted indicator of the economic performance of a country is GDP. In Kenya specifically, it reached $74.94 billion in 2017 being so, the 70th wealthiest country in the world. However, with population 49,69 million the GDP per capita in 2017 was $3,285.9, which ranks Kenya 150th in the world (*World Bank*, 2018).

The Economic Intelligence Unit (EIU) predicted real Gross Domestic Product (GDP) to grow at 5.5% in 2017 down from an estimated 5.8% in 2016 due to a combination of domestic and international constraints.

Domestic constraints included the last elections which impacted investments. International constraints include disruptive geopolitical events such as the United Kingdom's impending exit from the EU and Trump's presidency, which were expected to translate to reduced foreign investments to emerging economies.

According to the EIU, growth will remain robust between 2017 and 2021, averaging 5.8% as a result of sustained expansion in consumer services, urbanisation, East African Community (EAC) integration, structural reforms and investment in infrastructure. The country as a whole is urbanising at approximately 4.3 percent per annum (*Cira et al.,* 2016).

The US Department of State notes that Kenya is a favoured business hub for oil and gas exploration, manufacturing and transport. Kenya ranked 92 out of 189 economies in the 2017 Ease of Doing Business report released by the World Bank.

On 20 March 2017, the Central Bank of Kenya (CBK) retained the Central Bank Rate (CBR) rate at 10% so as to anchor prevailing uncertainties such as rising inflation and the impact of the interest rate caps on the effectiveness of monetary policy. The Banking (Amendment) Act, 2016, that came into force in September 2016, capped interest rates charged by lending institutions to 4% above the prevailing CBR set by the CBK. The Act also set the minimum interest rate granted on a deposit held in an interest earning account in Kenya to at least 70% of the base rate. The EIU expects this Act to limit lending to the private sector by banks.

GDP

According to the EIU, investment in infrastructure, strong household consumption, closer integration with EAC and recovery in tourism numbers led to the increase in the country's GDP from 5.6% in 2015 to 5.8% in 2016.

The EIU expects the country's GDP growth to decline to 5.5% in 2017 largely due to a slowdown in investments as the country heads towards the general elections. Reduced lending to the private sector, the result of the enactment of the Banking (Amendment) Act that caps lending rates, will also contribute to a decline in GDP.

According to the Business Monitor Intelligence (BMI), private consumption will drive the country's economic growth going forward. Private consumption will account for an estimated 81.4% of GDP over the coming decade.

Inflation

The Kenya National Bureau of Statistics (KNBS) reported that inflation increased from 7.0% in January 2017 to 9.0% in February 2017 on account of rising food and electricity prices.

Inflation averaged 6.3% in 2016 due to subdued oil prices, lower electricity tariffs (due to increased reliance on drought resistant geothermal power) and low food prices due to improved rainfall.

The EIU forecasts inflation to average 5.1% between 2017 (Figure 3) and 2020 due to prudent monetary policy and efficiency gains arising from regulatory reform and investment in infrastructure. The EIU reported that drought remains a potential risk to inflation and demand pressures will prevent a rapid decline in inflation. Below illustrates trends in GDP and overall inflation. The overall inflation rose to 4.35 in July 2018 reflecting the current trend.

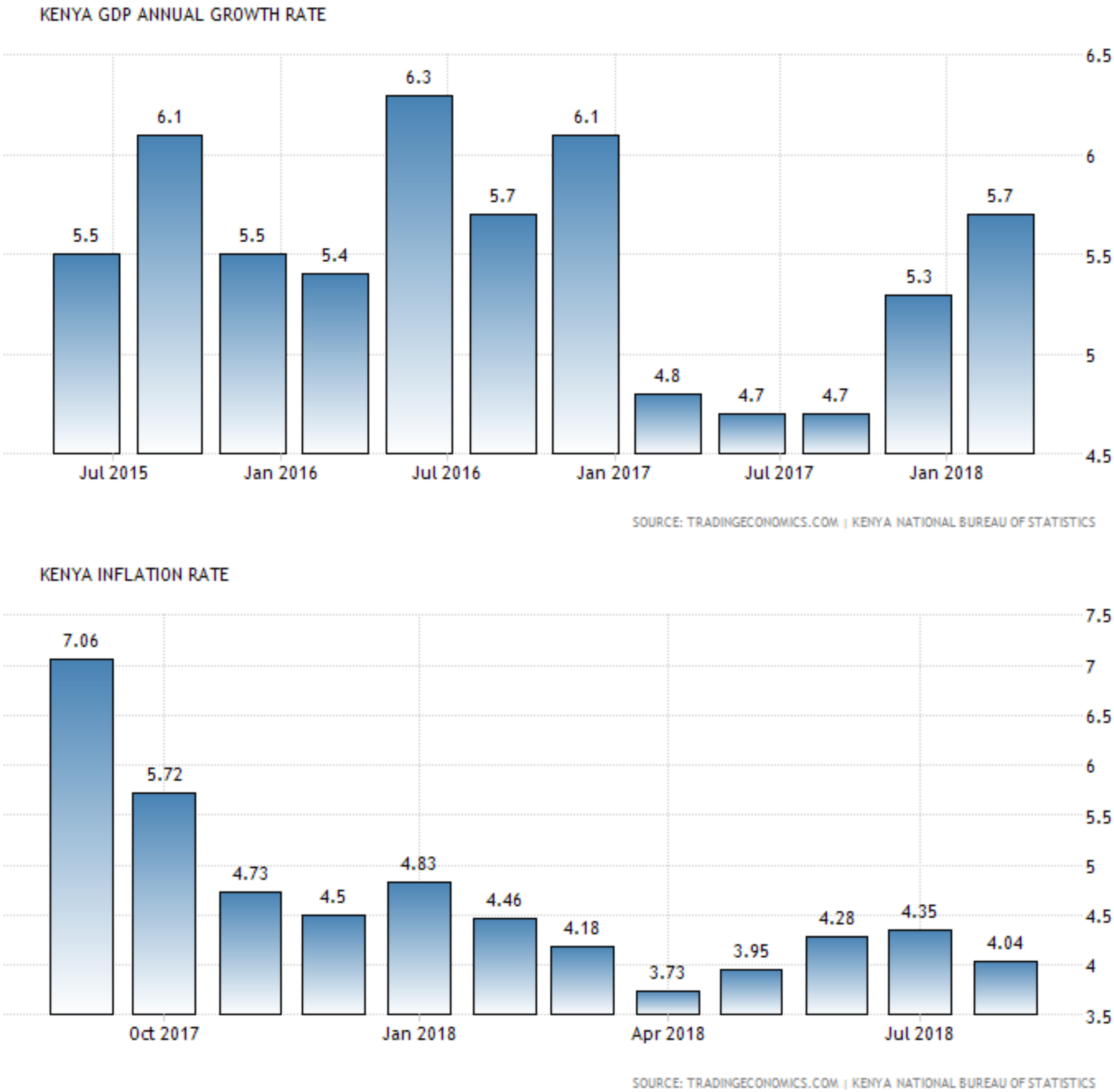

Figure 3 - Kenya's GDP and overall inflation

Women and Youth Empowerment

Youth in Kenya face a myriad of challenges. One of these is the significantly higher unemployment rates compared to the other working age groups. Women and youth also remain underrepresented in most sectors of the economy.

In 2016, Government agencies in the energy sector were heralded for their efforts to improve the environment for more women to participate in the energy sector through various initiatives such as Women in Geothermal (WING) program by Geothermal Development Company, “Bring your daughter to work” program by Kenya Power that exposes the young girls to the energy environment at an early stage and the Pink Energy initiative by KenGen. The Government has also instituted measures that facilitate the participation of women and youth in conducting business with it. This has been achieved by formulating and implementing the 30% Access to Government Procurement Opportunities (AGPO) which offers preferential treatment on all Government tenders. According to the National Treasury, over KES 26 billion worth of tenders have been awarded under the AGPO platform to date.

To continue supporting youth and women, the Government made the following allocations in the 2017/18 budget:

- KES 18.3 billion towards the youth empowerment programme;
- KES 0.6 billion for Youth Enterprise Development Fund;
- KES 0.7 billion for Youth Employment and Enterprise (Uwezo Fund) and;
- KES 0.8 billion for Women Enterprise Fund. Counties, however, received additional allocations in form of conditional grants meant for specific items in their budgets.

These included the allocations under the Equalisation Fund provided under Article 204 of the Constitution, which currently benefits 14 counties categorised by the CRA as marginalised.

Others included funds released for Level Five hospitals and leasing of medical equipment, rehabilitation of village polytechnics, road maintenance, fuel levy fund, loans from World Bank and funds released to fund capacity building initiatives in under the Kenya Devolution Support Programme.

In the 2017/18 budget, the national Government will provide counties with KES 291.1 billion as sharable revenue and an additional KES 38 billion conditional allocations, which include support from the country's development partners. This brings the total allocation to the county Governments to KES 329.3 billion (equivalent to 35.2% of the most recent audited revenues of the national Government).

Energy Resources

According to the Energy Regulatory Commission (ERC), Kenya's energy needs derive primarily from three sources: wood fuel, petroleum and electricity (which account for 69%, 22% and 9%nof total energy respectively).

Given the heavy reliance on biomass and petroleum (non-renewable sources of energy), the Kenyan Government has set its eyes on the development of harnessing viable renewable sources of energy.

Kenya aims to generate more energy at a lower cost and to increase efficiency in energy consumption. The government is committed to institutional reforms, including more private power generators, and the exploitation of new sources of power including geothermal, coal, and renewable energy sources (*Thuo et al.* 2017) and wind. Kenya is actively pursuing development in the geothermal sector, standing currently as Africa's leader and 8th in the world in terms of power generation from the earth. Research has shown that there are still close to 10,000 MW of potential geothermal energy in the highly seismic Rift Valley, which should help drive Kenya toward Vision 2030.Kenya is home to Africa's largest wind power project (the 310MW Lake Turkana Wind Farm) as well as a further 900MW in development or online.

In September 2016, Kenya through the Kenya Nuclear Electricity Board (KNEB) signed a partnership agreement with Korea Electric Power Corporation (KEPCO), Korea Nuclear Association for International Cooperation (KNAIC) and the KEPCO International Graduate School (KINGS). The agreement will facilitate Kenya in obtaining important knowledge and expertise from Korea, the world's fifth-biggest user of nuclear power. The deal is structured at enabling capacity building, specialized training and skills development, as well as technical support for its intended nuclear power program.

As part of the partnership, 16 Kenyan students have been enrolled at the KINGS to undertake Master Degree courses in nuclear power engineering. Kenya plans to set up its first nuclear power plant with a capacity of 1,000 MW by 2027.

This is expected to rise to a total of 4,000MW by 2033, making nuclear energy a key component of the Kenyan energy mix.

The Mining Act 2016 came into force on 27 May 2016. The Act applies to coal and coal seam gas, though it does not apply to matters relating to petroleum and hydrocarbon gases. The new Act sets out the obligations of the state with regards to the environment; in particular, the use of the environment in a sustainable manner. It also legalises Artisanal Miners while creating separate licensing regimes for small-scale and large-scale mining operations.

In February 2017, Acacia Mining announced the discovery of 1.3 million ounces of gold at its mines in the Liranda Corridor in Kakamega County, whose grade is one of the highest in Africa. The Ministry of Mining estimates the discovery to amount to be valued at over KES 150 billion.

In March 2017, the national Government signed a production agreement with the British explorer and producer Tullow Oil, paving way for the exportation of crude oil from Turkana fields. The pact draws the roadmap for Kenya's early oil export plan that is expected to pump out 2,000 barrels per day for transportation by trucks and storage at the defunct Kenya Petroleum Refinery's storage tanks in Mombasa. To harness the potential of the mining sector, the Government allocated KES 200 million for geological mapping and mineral exploitation, KES 150 million for geological databank, KES 103 million for mineral certification laboratory, KES 140 million for mineral audit support and a further KES 140 million for acquisition of survey equipment. The Government also expects a further KES 6 billion support from China for geo mapping once discussions are concluded.

Agriculture

The agriculture industry in Kenya remains the most prominent, important and dominant industry. As of 2016, the industry accounted for over 26% of the total GDP, 20% of employment, 75% of the labour force, and over 50% of revenue from exports. According to the KNBS, the agriculture sector grew by 3.9% in Q3 2016 compared to a growth of 5.5% in the Q3 2015. KNBS attributed this decline in growth to poor performance in the production of tea and coffee that declined by 0.3% and 4%, respectively in the period. The volume of fruit exports also declined by 36.7% during the period contributing to the diminished performance. (*Kenya Economic Outlook*, 2017).

According to World Bank, the late onset of Kenya's second rainy season delayed coffee-bush flowering and the subsequent drought will hurt the size and quality of the nation's Arabica crop. The country, being the world's largest exporter of black tea may also miss a target to raise tea output by 25% to 500 million kilograms given the persistence of dry spell that begun in 2016.

Drought has also affected livestock production causing violent clashes amongst pastoralist communities. The National Drought Management Authority reports that the Government may spend more than the KES 21.5 billion it budgeted to support 1.3 million people who are currently facing drought and hunger.

In 2016, the Government of Kenya launched the Kenya National Agricultural Insurance Program, which is designed to address the challenges that agricultural producers face when there are large production shocks, such as droughts and floods. The program, which is designed as a partnership between the Government and the private sector, was developed with assistance from the World Bank Group and builds on the experience of similar programs in Mexico, India, and China. One program line will focus on livestock insurance, while another will focus on maize and wheat insurance.

Agricultural value addition has also been identified as having the potential to act as a catalyst for the take-off of Kenya's industrial sector. Agri-business initiatives have received support from the Government. The Government is keen on targeting the youth who are increasingly considering it as a viable commercial venture.

In January 2017, following bilateral talks, India extended a KES 10 billion loan to Kenya for agricultural mechanisation.

The following key allocations have been made to the agriculture sector in the 2017/18 budget:

- KES 7.3 billion has been allocated for on-going irrigation projects countrywide and transformation of agriculture from subsistence to productive commercial farming;
- KES 5 billion for inputs subsidy (Fertilizer and Seed);
- KES 1.3 billion for Strategic Grain Reserves
- KES 0.4 billion for Construction of Jetty for RV Mtafiti (Marine Research)

- KES 0.7 billion for Livestock & Crop Insurance Scheme
- KES 1 billion for Food Security & Crop Diversification Programme (Khat (Miraa) Farmers); and
- KES 1.6 billion for Issuance of Title Deeds.

Table 5 presents value of marketed production for both crops and livestock from 2012 to 2016. The value of marketed agricultural production increased from KES 373.5 billion in 2015 to KES 412.0 billion in 2016. Value of marketed crops accounted for 69.7 per cent of overall marketed agricultural production in 2016. Value of fresh horticultural exports increased by 12.3 per cent from KES 90.4 billion in 2015 to KES 101.5 billion in 2016. Cut flowers accounted for 69.8 per cent of the value of horticulture exports. Earnings from marketed tea declined by 1.6 per cent to KES 116.5 billion due to lower prices of the commodity. Value of marketed sugarcane increased by 6.7 per cent from KES 22.4 billion in 2015 to KES 23.9 billion in 2016 while that of marketed coffee increased by 33.9 per cent from KES 12.1 billion in 2015 to KES 16.2 billion in 2016.

Improved prices of sugarcane and coffee coupled with increased marketed volumes for coffee resulted in the increased earnings. Value of marketed maize declined by 7.2 per cent to KES 7.9 billion in 2016 while the value of marketed wheat declined by 2.1 per cent to KES 8.0 billion in 2016.

Table 5 - Marketed Agricultural Production at Current Prices, 2012 – 2016. Prices are in Million KES.

	2012	2013	2014	2015	2016(*)
CEREALS					
Maize	13,153	10,121	9,604	8,506	7,891
Wheat	5,613	6,926	7,618	8,198	8,028
Others	5,721	7,555	7,721	7,489	7,266
TOTAL	**24,487**	**24,603**	**24,943**	**24,193**	**23,185**
HORTICULTURE(**)					
Cut Flowers	64,963	55,976	59,893	62,938	70,830
Vegetables	20,225	22,923	18,781	20,940	23,367
Fruits	4,680	4,483	5,411	6,562	7,317
TOTAL	**89,868**	**83,382**	**84,084**	**90,440**	**101,514**
TEMPORARY INDUSTRIAL CROPS					
Sugar-cane	21,676	24,583	20,295	22,397	23,917
Pyrethrum	17	53	61	51	38
Others	1,706	953	1,439	1,517	1,470
TOTAL	**23,399**	**25,589**	**21,795**	**23,965**	**25,426**
PERMANENT CROPS					
Coffee	15,375	10,910	59,893	62,938	70,830
Tea	100,262	94,722	18,781	20,940	23,367
Sisal	2,915	2,811	5,411	6,562	7,317
TOTAL	**118,553**	**108,443**	**84,084**	**90,439**	**101,514**
TOTAL CROPS	**256,307**	**242,016**	**84,084**	**90,439**	**101,514**
LIVESTOCKS & PRODUCTS					
Cattle &Calves	54,141	58,237	59,273	66,217	84,701
Milk	15,416	16,777	18,785	21,205	23,020
Chicken & Eggs	6,482	7,086	7,441	6,006	8,788
Other	12,267	10,727	12,491	7,417	8,489
TOTAL	**88,305**	**92,827**	**97,989**	**100,845**	**124,999**
GRAND TOTAL	**344,612**	**334,843**	**333,245**	**373,502**	**412,040**

(*) Provisional

(**) The production refers to the fresh horticulture exports.

Table 6 - Average Gross Commodity Prices to Farmers, 2012 – 2016. Prices(**) are in KES per Unit

	Unit	2012	2013	2014	2015	2016(*)
Coffee	100 kg	33,387	28,410	39,186	37,480	40,816
Tea	100 kg	27,130	21,903	19,064	29,656	24,732
Sisal	100 kg	10,462	10,818	11,122	16,925	19,463
Sugar-cane	Tonne	3,792	3,685	3,133	3,125	3,340
Pyrethrum (Pyrethrin equivalent)	kg	12,627	12,626	16,872	12,571	12,907
Seed Cotton	100 kg	4,000	4,200	4,200	4,200	4,200
Maize	100 kg	3,396	3,133	3,318	2,870	2,969
Wheat	100 kg	3,622	3,745	3,495	3,562	3,718
Beef (3rd grade)	100 kg	20,978	26,000	27,500	30,510	35,905
Pig Meat	100 kg	18,176	18,427	20,287	21,267	22,666
Milk	100 L	2,650	3,100	3,470	3,443	3,543

(*) Provisional

(**) Prices refer to the calendar year and may differ from those based on crop years. For tea and coffee, the prices are for black tea and coffee beans, respectively.

Manufacturing

While Kenya is the most industrially developed country in the East Africa region, manufacturing only accounts for 14% of GDP. According to the World Bank this is attributable to the fact that most of Kenya's exports such as tea and coffee require little or no processing.

Kenya has a manufacturing presence in textiles, food and grain milling, cement production, and oil refining. A large portion of Kenya's manufacturing comes from the informal sector, with homemade arts and crafts being a popular product for tourists and residents alike.

According to KNBS, the manufacturing sector registered a declined growth of 1.9% in Q3 2016 compared to a growth of 3.3% in the similar quarter in 2015. The manufacture of food products subsector growth was supported by processing of maize meal, wheat flour and milk.

On the other hand, growth was constrained by contraction in the production of soft drinks and manufacture of beer and stout. In the manufacture of non-food products, growth was hampered by a decline in the assembly of motor vehicles and cement production.

In January 2017, the Kenya Association of Manufacturers (KAM) launched the Manufacturing Priority Agenda (MPA) 2017 under the theme "Driving industrial transformation for job creation and inclusive economic growth". The MPA details the need for investment in technical skills, creating a nurturing environment for the Small and Micro Enterprises (SME's); with a special emphasis on women and youth enterprises. It also aims to transform Kenya to an export hub thereby increasing the competitiveness for local business.

The Ministry of Industry, Investment and Trade has formulated a policy that will promote local industry through procurement of locally made products. The Ministry is working with other Government agencies to implement this program. In line with this drive, the ministry in partnership with a textile and apparel firms organised the first ever export quality sale, dubbed 'Super Sale' in March 2017. The initiative is under the Export Processing Zones (EPZ) Program and aims to provide Kenyans access to quality clothing at affordable prices (KES 50 to KES 600).

To improve efficiency in the manufacturing sector, the Government has allocated resources towards energy generation and distribution, improving on ease of doing business, security, and revival of strategic industries such as textile, pyrethrum, milk processing, and leather development amongst others. Going forward, the Government shall intensify investment in these areas to unlock the Country's economic potential.

Water Supply

The Government enacted the Water Act 2016 with a focus on improving water storage, strengthening regulation, creating viable water utilities and improving sector planning. Under the Act, sector coordination between the National Government and the County Governments under devolved water services provision will be enhanced.

In pursuit of the policy to provide safe drinking water to households within a realistic distance, the Government continued to initiate and maintain modest Water Purification Points (WPPs). The number of WPPs increased from 242 in the 2015/16 financial year to 247 in the 2016/17 financial year as presented in Table 7 .

In 2016/17 financial year, a total of 263 boreholes are expected to be constructed compared to 446 boreholes drilled in 2015/16. The private sector is expected to contribute the highest number of boreholes drilled at 244 despite the decrease from 2015/16, while the public sector is expected to drill 19 boreholes.

Table 7 - Water Purification Points and Boreholes Drilled, 2012/13 - 2016/17 (Source: *Ministry of Water and Irrigation*)

	2012/13	2013/14	2014/15	2015/16	2016/17*
Water Purification Points (WPP)[1]	218	230	234	242	247
Boreholes (BH) Total	99	376	607	446	263
Public	99	74	13	4	19
Private Sector	-	302	594	442	244

* Provisional, - Data not Available, [1] Cumulative

Water development expenditure was expected to grow by 49.1 per cent from KES 23.2 billion to KES 34.6 billion in the 2016/17 financial year, accounting for 63.4 per cent of the total development expenditure. Expenditure on Rural Water Supplies is expected to increase from KES 1.4 billion in 2015/16 financial year to KES 2.5 billion in 2016/17 financial year. Expenditures on Irrigation Development is expected to more than double over the same period.

Expenditure on National Irrigation Board (NIB) is expected to decline by 11.9 per cent to KES 11.1 billion in 2016/17 financial year from KES 12.6 billion in 2015/16 financial year.

The expenditure on Training of Water Development Staff and National Water Conservation and Pipeline Corporation is also expected to decline by 79.3 and 80.6 per cent, respectively.

Under the Water Act, 2002 the Government of Kenya adopted a new approach for the provision of water services and established a new institutional structure for the sector. As part of this structure, the Government created a Water Services Regulatory Board (WASREB) to regulate Water and Sanitation Services. Among the key functions of the WASREB is to develop guidelines for the fixing of tariffs for the provision of water services. The objective is to establish tariffs that balance commercial, social and ecological interests by ensuring access to all while allowing Water Service Boards (WSBs) and Water Service Providers (WSPs) to recover justified costs. In the revised Water Act of 2016, WASREB is required to establish Guidelines for tariff setting by water providers. The objectives of tariff review are to:

- Ensure financial sustainability
- Foster access to Safe Water as a Human Right
- Promote efficiency in the delivery of water services

- Encourage conservation
- Ensure simplicity in the pricing structure of water

The tariff review process is necessitated by the following by the factors:

- Dependence on subsidy which has become unsustainable.
- Tariffs that outlived their usefulness.
- Continued rise in cost of inputs.
- Increments in cost of electricity, fuel and their spiraling effect.
- Unsustainability of most WSPs and WSBs

Under the Licence, tariffs charged are meant to accommodate the need to have cost recovery, cross subsidization, and where feasible the expansion of infrastructure.

The tariff review process focuses on balancing commercial and social interests in water service provision. The fixing of tariffs considers justified costs, in order to eliminate any costs that may result from inefficiency, and which should not be borne by consumers.

WASREB has developed Tariff Guidelines with the objective of fixing tariffs that balance commercial, social and ecological interests thus ensuring access to all while allowing WSPs and WSBs to recover justified costs. Recognizing that WSPs differ in category and size (see Table 8), the Guidelines address different requirements as follows:

- Setting out approaches to tariff adjustment
- Spelling out requirements that WSPs and WSBs should meet for tariff adjustment applications
- Setting out methodologies for tariff review analysis, approval and subsequent adjustments over time

The water price structure in relation to consumption in Nairobi is illustrated in Figure 4. The water price (\$/m^3) in Nairobi is composed by fixed, variable and other charges that contribute to the sustainability of the water supply service. The fixed and other charges start from \$2.03 per m^3 for no water consumption, increase to \$3.02 per m^3 for just 1 m^3 water consumption and then decrease gradually to zero as water consumption increases. On the other hand, the variable charges start from \$0.08 per m^3 for consuming 7 m^3 of water and increase to \$0.61 per m^3 as the volume of total water usage by the customer increases up to 200 m^3.

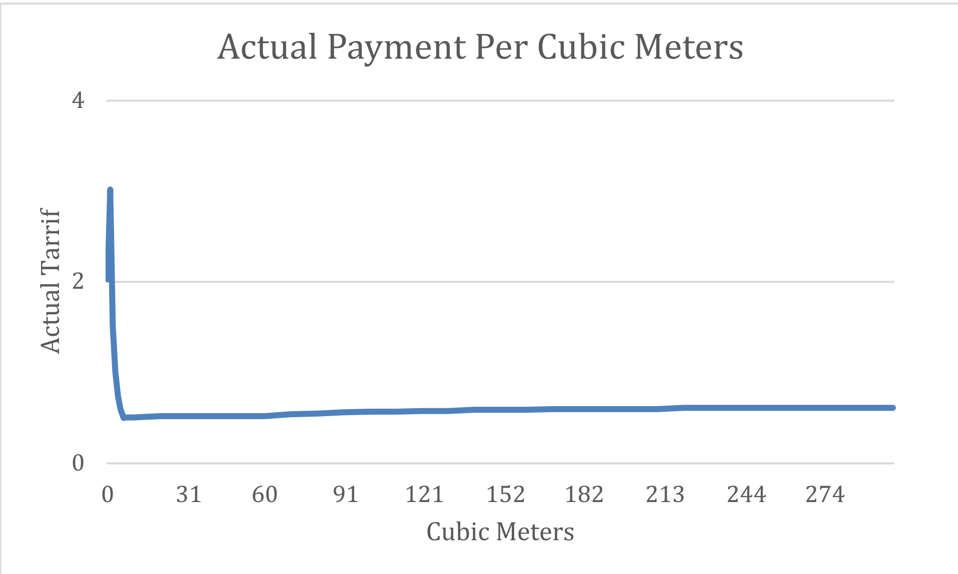

Figure 4 - Water Prices in \$ per m^3. (Source: *International Benchmarking Network for Water and Sanitation Utilities*, 2015)

Sewerage Tariffs

Sewerage is charged at 75% of the water billed for all customers with a sewer connection. Disconnected water accounts shall be charged based on the average of the last three months' sewer charges before the disconnection. Customers with no water connection but connected to the sewerage system are charged as follows:

- Domestic Customers: flat rate of KES. 200 per month
- Government, Schools, Multi-dwelling units, Gated Communities and
- Commercial/Industrial customers: 75% of volume of water used as per the metered source of water

Additional details are provided in Table 9.

Table 8 - Water Tariff Structure for Year 2015/16, 2016/17 and 2017/18 (Source: *Nairobi City Water and Sewerage Company*, Water Act 2002)

Type of customer	Approved tariff per m^3 (KES)
Domestic/Residential	
Consumption Block	
0 - 6	Flat rate 204
7 - 60.	53.00
> 60	64.00
Commercial / Industrial	
Consumption Block	
0 - 6.	Flat rate 204
7 - 60.	53.00
> 60	64.00
Government Institutions	
Consumption Block	
0 - 6.	Flat rate 204
7 - 60.	53.00
> 60	64.00
Government funded Public (pre-primary, primary and Secondary) Schools	
Consumption Block	
0 - 600	48.00
601 - 1200	55.00
> 1200	60.00
Water Kiosks	20.00
Water at ATM Water Dispenser	25.00
Bulk Water to residential flats/ gated communities (from 25 households and above)	53.00
Pre-paid Meter customers	52.00
Bulk Water to WSPs for resale (to be supported by a bulk sale agreement)	30.00

Table 9 - Miscellaneous Charges (Source*: Nairobi City Water and Sewage Company*, Water Act 2002)

Item	**Approved Charge (KES.)**
Meter Rent Per Month	
Meter Size	
½ inches	50
¾ inches	100
1 inch	250
1 ½ inches	250
2 inches	250
3 inches	450
4 inches	800
6 inches	1250
8 and above	2000
Water Deposit	
Category of consumer	
Domestic	2,500
Water Kiosks	5,000
Commercial	25,000
Industries	50,000
Domestic Construction	25,000
Commercial construction	50,000
Other Charges	
New Water Connection fee, $^{1/2}$ inch to 1 inch	2,500
New Water Connection fee, $1^{1/2}$ to 3 inch	7,500
New Water Connection fee, above 3 inch	15,000
Reconnection fee – at meter point	1,000
Reconnection fee – at mains	5,000 and double deposit
Illegal connection-Commercial, Industry, Construction (Fraud)	100,000 plus estimated consumption during the period of the illegality
Illegal connection (Fraud) – Domestic	30,000 plus estimated consumption during the period of the illegality
Tanker – 8000, 16,000 litres	2,500, 5,000 respectively per tanker within WSP area for all consumers
Replacement of stolen or damaged meters	100% of the market cost of the meter
Meter testing on request	100
Leak detection services	1,000
Sewer Connection- Residential	5,000
Sewer Connection- Commercial	7,500
Sewer Connection- Industrial	15,000
Private sewer unblocking (per manhole)	2,500
Sewer Reconnection	15,000
Exhauster Services (Company Exhauster)	5,000. for other customers and 4,000. for informal settlements
Private Exhausters (Dumping into the company's sewer system)	15,000. per Truck per month

WEF nexus in Kenya

WEF in Kenya is of particular interest because of four reasons (*Wakeford,* 2017). First, it is experiencing a high rate of population expansion (Figure 5), rapid urbanisation and robust economic growth, which are all placing increasing demands on limited resources. Second, the country is acutely vulnerable to climate change and variability, given its geographical location in equatorial East Africa and its current dependence on largely rain-fed agriculture for nearly one-third of its gross domestic product (GDP). Third, following discoveries of oil resources in recent years, Kenya begun oil production in 2018, which could have a substantial impact on the country's ensuing developmental trajectory. Fourth, Kenya has been a leader within Africa in developing certain types of renewable energy, such as geothermal power and roof-top solar photovoltaic electricity.

According to Wakeford (2017), Kenya's rapid economic growth is also generating growing pressure on the WEF nexus. Real GDP grew by an average rate of 5.3% between 2006 and 2015 and the International Monetary Fund (*IMF*, 2016) forecasts that the economy will continue expanding at close to six per cent per annum in the next four to five years. Economic growth brings with it rising incomes and an expansion of the middle class, which implies increasing demand for water and energy services and food. GDP per capita grew by an average rate of 2.5% over the past decade (*World Bank*, 2018). In addition, if Kenya is to meet the sustainable development goals, then it will have to expand provision of basic necessities to the roughly quarter of the population living in poverty (i.e. on less than US$1.90 per day). For more details see Figure 5.

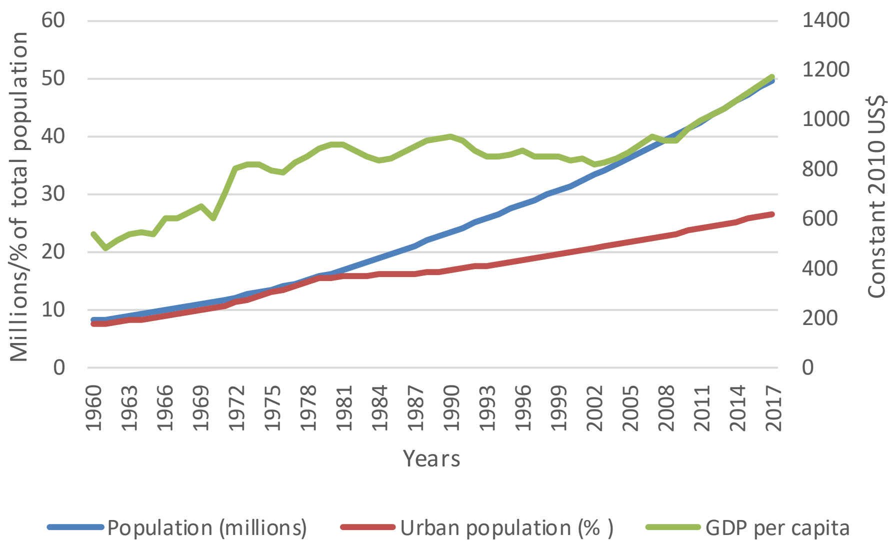

Figure 5 - Demand drivers acting on Kenya's WEF security nexus. (Source: *World Bank*, 2018)

Institutions and public agencies responsible for WEF related activities in Kenya is extremely complex. It shares several cross-border river basins with Ethiopia, Uganda and Tanzania. The Nile River basin, which Kenya shares with eight other countries, has been a source of contention for decades, although thus far outright conflict has been avoided (*Salman*, 2012). According to *Wakeford* (2017), a further geopolitical element of the nexus concerns regional energy trading arrangements. Kenya is currently a transit route for petroleum imports by Uganda, Rwanda and Burundi, and plans to import large amounts of electricity from Ethiopia in the future (*Cuesta-Fernández*, 2015). Such arrangements rely on the continuation of good relations among these countries.

Turkana Basin

The area has several rivers with the major ones being Turkwel and Kerio both originating in the highlands to the south. Most rivers are seasonal. Kerio is a river in Rift Valley province; it flows northward into Lake Turkana. It is one of the longest rivers in Kenya, originating near the equator. In south it flows through the Kerio Valley between Tugen Hills and Elgeyo escarpment. The river also partly bounds the South Turkana National Reserve. The river starts from Eldamaravin and ends at Lake Turkana. Turkwel River is a river flowing from Mount Elgon in the border of Kenya and Uganda to Lake Turkana. The river is called Suam River from its source to the border with the West Pokot District of Kenya. Turkana North, Central and South districts of larger Turkana County have both arid and semi-arid lands (ASAL). Mean temperature ranges from a low of 24º C to a high of 38º C with a mean of 30º C. The lowest rainfall recorded in the central plains around Lodwar. This area receives an annual average rainfall of 120 mm. The heaviest rainfall is experienced in the northwest area around Lokichogio, which has an average rainfall of about 430 mm. Lokitaung to the northeast and Kaputir in the Turkwel valley to the south, have an average of 300 mm and 280 mm respectively. The rainfall pattern and its distribution has been unreliable and erratic over the years. Rain is usually accompanied by sharp thunderstorms in the late afternoons and at night. The long rains usually fall between April to June, and short rains in October to December. The beneficial effect of rainfall depends on its amount and distribution due to conditions of poor soil cover, high evaporation and rapid run-off (Source 25: *Arid Lands Resource Management Program, Lodwar*).

The climatic conditions of Marsabit North District of the eastern side of Lake Turkana are characterised largely by desert like temperatures where days are very hot with soaring temperatures of 38° C on average, and cool breezy nights falling below 18° C on average. The temperature changes towards Hurri Hills and Northern Arid and ASAL of Forole and Dukana falling between average 27-33° C. Rainfall comes in both short and long seasons but is often erratic and poorly distributed. Annual precipitation averages are 250-400 mm.

About 90% of the lake surface water inflow is derived from the Omo River in Ethiopia (*Avery*, 2010). Hence the lake is almost entirely dependent on this one river basin, and any developments in this basin will directly affect the lake.

Traditionally, people around the lake derive their livelihood through nomadic pastoralism activities and some fishing. According to *Avery* (2010), it is estimated that about 60% of the population derive their livelihood from livestock-based activities. This is prevalent in the northern part of the district where rainfall is slightly higher to sustain pastures. Agro-pastoralism occupies about 16% and is prevalent in the south, along Turkwel and Kerio rivers, which are the main river systems in the county. Most of the residents are livestock keepers who own large herds of animals such as cattle, sheep, goats and camels. They are nomadic pastoralists who move around with their animals in search of water and pastures for their animals. The high numbers of animals kept has led to certain land degradation effects such as desertification and increased soil erosion due to removal of all the ground cover by the animals.

Settlement patterns

The settlement pattern in the district and divisions is determined by the availability of pastures and social facilities mainly found in urban and peri-urban centers. Turkana people under normal situation settle in the plains. But due to variations in weather, very few of them settle permanently in one place. During and shortly after the rains the Turkana people are concentrated on the plains. As drought starts, they move mostly to high mountain areas and even to neighboring countries of Sudan and Ethiopia in search of pasture and water for their animals, which comprises mainly goats, sheep, cattle, donkeys and camels. The population density in the district varies from as low as 8 persons per Km^2 in Kerio Division to as high as 63 persons per Km^2 in Central Division. This is based on the 2008 population projections. The low density in Kerio Division is attributed to the aridity of the area occasioned by frequent drought occurrence.

In event that the lake is affected adversely, communities living adjacent to the western shores of Lake Turkana who are likely to be affected are Turkana. Other minor tribes include Luo, Kisii, and Luhya who have migrated from western regions of Kenya. Turkana are predominantly the main ethnic group on the western part of Lake Turkana.

The Turkana are notable for raising camels and weaving baskets. The Turkana rely on several rivers, such as the Turkwel River and Kerio River. When these rivers flood, new sediment and water extend onto river plain that is cultivated after heavy rainstorms, which occur infrequently. When the rivers dry up, open-pit wells are dug in the riverbeds which are used for watering livestock and human consumption. Livestock is an important aspect of Turkana culture. Goats, camels, donkeys, and sheep are the primary herd stock utilized by the Turkana people. In this society, livestock functions not only as a milk and meat producer, but as a form of currency used for bride-price negotiations and dowries. Among the Turkana tribe, most of the women in a normal set up are taken as house wives while men provide for the family. The duties which come with being a house wife includes: cooking, fetching water and firewood. This heavy burden leaves little time for them to be engaged in other income generating activities. Traditionally, men and women both wear wraps made of rectangular woven material, but each sex adorns themselves with different objects. Women will customarily wear necklaces and will wear their hair in a faux-mohawk style which is often braided and beaded.

The Turkana area on the western side of the Lake is remote. Living standards are low with majority of people living below the poverty line. This can be clearly depicted from the indicators of wealth, limited access to social services and poor infrastructure. With exception of the peri-urban area and urban centres like Lodwar, the majority of the rural people are poor. The vulnerable members of society include orphans, windows and poor families. The vulnerability has been caused by drought, low levels of education and lack of knowledge on how to improve food production. Cattle rustling from neighbouring districts and at the Uganda boarder to the west worsen the poverty situation. The poor are also found in the major towns and market centres of the district. They include migrants from other parts of the County in search of relief food and assistance from relatives engaged in productive economic activities in towns and market centres.

Energy System

The main sources of energy for rural areas is fuel wood. There is lack of electricity supply in the whole Turkana central district with the exception of Lodwar where diesel driven generators supply a few commercial buildings and business. Most of the businesses operate private generators. There is also low utilization of other sources of energy like solar and wind due to low incomes of the people. At Kalokol, a few people have solar energy. At Lorengelup, the main source of energy is fuel wood. Sources of energy for lighting for interviewed households are kerosene, Solar, batteries, candle, firewood, candles, and grass. 72.7% of households in Kalokol use firewood to light up their houses at night while 19.6% use torch batteries as a source of light for houses. Few people use kerosene, solar, or dry grass to light their houses. At Kang'arise 89.3 % use firewood to light their houses at night while others use candle, batteries, kerosene. At Lorengelup 51.2% use firewood while 25.1 % use batteries and 15.8 5 use grass to light their houses. At North Horr, 84.8 % use batteries to light house at night. Others use kerosene and firewood. At Illeret 63.6% use firewood to light their houses while 26.6% use batteries. At Loiyangalani 39.1 % use Kerosene to light their houses while 38.6% use batteries and 15.9% use firewood. At Lorengelup, 64% do not incur cost of lighting their houses. Another 21.2% spend less that KES 100 per month while 10.8% spend 100-200. As one moves further down the lake to Kang'arise, 90% do not incur cost of lighting their houses while 4.4% spend less than a KES 100 and another 3.9% spend KES 100-200 per month. Similarly, at Kalokol 80.9 % do not incur cost of lighting their houses, 7.2% less than KES 100 while 10.5% spends KES.100 to 200. 13% of communities at Illeret do not incur cost of lighting their houses while 36.4 % use less than a KES 100 and 29.4% use KES 100 to 200 to light their house. The rest use more than KES 300 per month to light their houses. 39.7% household walk daily to collect firewood while 25.4 % once week. 24.4% of households claimed that they fetch firewood every two days or twice a week. At Loiyangalani 18.6% claimed that they do not incur cost of lighting their houses, implying that they use firewood to light their houses at night. 17.7% spend less than KES 100 while 55.5% spend KES 100 to 200 per month to light their houses. At North Horr 35.5% spends less than KES 100 per month on firewood. While 59.9% spend 100 KES to 300 KES per month to light their houses.

Public Health

The nomadic pastoralist way of life has led to little demand for sanitation facilities like latrines hence latrine coverage is estimated to be low. There is low hygiene and sanitation awareness, low priority and poor perception on hygiene issues. Households interviewed dispose their liquid waste by tossing it out of the house.

Water System

Kenya is characterised by absolute water scarcity (less than 500 m^3 per capita per year), which is the most severe category of water stress (*WWAP*, 2015). However, a few years ago a giant aquifer with an estimated volume of 207 billion m^3 was discovered in the arid north-west Turkana region (*The East African*, 2013) in the Lotikipi Basin Aquifer. The total area equipped for full control irrigation in Kenya in 2010 was 144,100 ha, of which 94 per cent (135,900 ha) was actually irrigated (*FAO*, 2016a).

Larger Turkana County receives an average rainfall of 120-500mm per annum which is erratic and poorly distributed. The district water needs are mostly met from ground sources such as boreholes, shallow wells and water pans. Laisamis and Marsabit North Districts face similar problems. The district being Arid Semi Land areas has been faced with challenges of water scarcity and continued environmental degradation due to over reliance of the community on wood fuel as a source of energy. The major sources of water found in the district are sub surface water resources such as springs, dams and shallow wells for domestic and livestock development.

Information from location chiefs indicates that, the main source of water at Lorengelup is traditional wells. Also, there are some seasonal rivers. The water is saline. According to the village government the average distance to water sources is 8 kilometres at Kalokol, the main sources of water are traditional wells and tap water. According to Kalokol location Chief, the average distance to water source is 5 km. From households' survey data, 56% of households at Kalokol obtain water from traditional wells, and 32.5% obtain water from communal pump onsite while 1% obtains water from communal pump offsite. 10.5% fetch water from the Lake. At Lorengelup 77.8 % obtains water from traditional wells while 4.5% from community pump off site. The main source of water for 83.5% inhabitant of Kang'arise is traditional wells 16.5% fetch water from community pumps on/offsite from their households (cf. *Oduor et al.*, 2012)

The main source of water for communities living at El molo Bay is Lake Turkana. The water is salty. Since El Molo Bay community is located at the shores of the lake, the average distance for majority to water source is 60m. Major sources of water for communities at Illeret are traditional well and Lake Turkana. The water has a salty taste. The main source of water for domestic consumption and livestock at Loiyangalani is tap water system from Loiyangalani springs. Other sources include traditional wells, boreholes, waterholes dug in riverbeds and lake water. A permanent source of surface water is at the top of Mount Kulal. The water at Loiyangalani is reported to be salty but is within reach for majority of people.

The construction of Gibe III was expected to cause altered water flows, the most obvious of which will be substantial changes in the low flow regime. This could bring a corresponding loss of habitats for fish and other aquatic organisms.

Currently, UNESCO is set to add Lake Turkana to a list of endangered World Heritage sites due to what monitors say are threats posed by an Ethiopian dam, sugar factories, and the Lamu Port-South Sudan-Ethiopia Transportation project (LAPSSET) - a multi-billion Shilling infrastructure project involving Kenya. Estimated to cost more than Sh2.5 trillion, it consists of a new port at Lamu, three resort cities, including one at Lake Turkana, highways, crude and product oil pipelines, railway lines, international airports, and a dam. The LAPSSET Program is part of the Kenya Vision 2030 Strategy which is the national long-term development policy that aims to transform Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens by 2030 in a clean and secure environment.

The food system

Unlike the Dasanech and Nyangatom at the Omo River (and Turkana along the Turkwel River to the south), the northernmost Turkana have no practicable flood recession agriculture opportunities, since watercourses in their lands are relatively small and ephemeral *Carr* (2017). Along the Turkwel River to the south, some Turkana undertake flood recession agriculture. Stresses have forced the northern Turkana to rely far more on secondary production activities, especially wild food gathering, chicken raising and charcoal production (primarily for marketing**).** Fishing in wide areas of the lake is commonplace for both northern and central Turkana (Figure 6). Fishers with sailboats, for example, form seasonal, or temporary camps along the eastern shoreline.

The food system can have various negative impacts on water quality and availability. Conversion of forested lands to agriculture can lead to soil erosion and subsequent siltation of water courses.

Figure 6 - Fishing and mixed fishing/pastoral Turkana village areas at Lake Turkana. (Source: *Carr*, 2017)

The food produced locally is insufficient to cover local requirements (*Wakeford*, 2017). Based on these locally derived estimates (*Carr*, 2017), the indigenous population in the shoreline area between Kalokol and Todenyang (Figure 6) is at least 71,460. Combining the above rough estimates, the indigenous population in the shoreline area of Ferguson's Gulf, extending northward Lake Turkana to the Kenya/Ethiopia border (near Todenyang) is at least: 141,000. The true population of those Turkana who are vulnerable to destruction of their survival means from the effects of the Gibe III dam and irrigated agriculture on Lake Turkana is far greater, however. This population includes those fishing and mixed pastoral/fishing villagers who reside slightly more removed from Lake Turkana, but who nevertheless depend on it for their survival, through fishing, working for boat owners, or in post-catch fisheries related work, trading for fish, offering livestock products (meat, milk, skins, live animals) and livestock watering and lakeside grazing.

2. FORMULATION OF THE ECONOMIC DEVELOPMENT MODEL

The analysis developed above demonstrates that all parts of an economy are based on water use in a direct or indirect way. From energy production to sanitation and hygiene rules, water plays a decisive role in their advancement. Moreover, water resources provide important benefits to human kind, which are difficult to be measured as they do not create monetary value, such as recreational and spiritual services or supporting the life cycle of the natural habitat of all animals. Hence, the motor of all societies and the main conductor of their development is access to water.

However, freshwater ecosystems are under threat from the effects of multiple stressors, including organic and inorganic pollution, land use changes, water abstraction, invasive species and pathogens (*Brauman et al*., 2014). Little is known beyond the described effects of single stressors on the chemical and ecological status of water bodies and on their ecosystem functionality. This lack of knowledge limits our capacity to understand ecosystem responses to multiple stressors and to define a programme of measures that can improve the ecological status of a water. People rely on ecosystems to provide many water-related services (*Brouwer et al*., 2013). Stakeholders, the beneficiaries of ecosystem services (ES) and those who own and manage landscapes that produce them play a key role in ecosystem service analysis. They identify the services they receive from a water body and its catchment (*Brouwer,et al*., 2013).

For physical, social and economic reasons, water is a classic non-market resource. Even for commodity uses, market prices for water are seldom available or when observable, often are subject to biases. However, due to the increasing scarcity of water and/or the resources required to develop water, affecting both its commodity and environmental benefits, economic evaluation plays an increasingly important role in public decision on water projects, reallocation proposals and other water policies (*Young*, 1996). People's preferences can also play an important role in pricing the water use. When it comes to sustainable wetland management choices *Birol et al.* (2009) showed that people value higher a possible flood risk reduction than biodiversity conservation or improvement of recreational access through a choice experiment for Bobrek wetland in Poland.

Several studies have been conducted aiming to identify an integrated assessment framework for the management of the aquatic ecosystems. *Pistocchi et al*. (2017) present a five-step framework for the analysis of different pressures to a river basin, while *Koundouri and Davila* (2015) demonstrate a methodology for the assessment of the total economic value of water services in order to enhance current levels of cost recovery. In addition, another paper shows that in order to improve policy design, socioeconomic and environmental dimensions of water policies should be considered in developing supportive methodologies (*Koundouri, et.al.*, 2019).

The ecosystem services framework aims to support informed decision making by explicitly linking the goods and services produced by functioning ecosystems to human well-being, illustrating the broad impacts of various land-use scenarios. The "Economics of Ecosystems and Biodiversity" approach, as explained by *Kumar* (2012), provides a framework for assessing multiple stressors and multiple outputs of a river Basin, facilitating management of complex systems. Therefore, we will focus on using economic – mathematical tools which can describe and value an ecosystem services approach in our study.

Based on the above we developed the following model, which aims to identify the optimal economic development pathways and their dependence on water resources availability, focusing on five sectors, which are the pillars of the countries of our study, agricultural, energy production, mining, residential and tourism sector. There are only two countries in our model, the upstream (Ethiopia) and the downstream (Kenya), which are characterised so, due to their physical location and so their hierarchical access to the water deriving from Omo river. Through a cost-benefit analysis, two different scenarios will be explored: the non-cooperative, where the two countries maximise their net benefit curves without considering the externalities caused to their neighbours or the benefits arising from a possible trade, and the cooperative scenario, where the two countries are trading goods between them. At the end, this model determines which pathway is the optimal one for both countries and also the impact on the water levels of lake Turkana.

2.1 MODELLING OF ECONOMIC DEVELOPMENT FROM A WEF NEXUS PERSPECTIVE

One of the most direct methods for estimating the total economic value (TEV) of water is to look at the market price for water. Here the market price of water means the market price of:

- goods and services that are used to maintain good quality and sufficient quantity of water;
- goods and services that are affected by the quality and quantity of water.

Although a market price may be observed for water, the simple single observation of what people pay for water, or the price it is sold at, does not allow an estimate for the overall value of water to be developed. In order to use the market price for estimating the value of water to consumers, market transactions for water must be observed across a number of different price levels and demand situations. By tracing the relative amount of water demanded at different prices, it is possible to map out the demand curve for water. This demand curve is the consumers' willingness-to-pay (WTP), i.e. value, which can then be used to calculate the change in consumer surplus, resulting from a policy that changes the demand curve.

There is a standard method used to measure the value of input in the five-core water-dependent economic sectors of a country:

(a) Agriculture (including aquaculture),
(b) Residential Water Supply,
(c) Mining (Industry),
(d) Energy Production,
(e) Tourism,

by evaluating the benefit of the input into the overall production. This approach defines water as one of the necessary inputs to production. More specifically, the **production (output)** Y_i, per specific sector $i = 1, 2, \ldots, 5$, is related with the water quantity w_i, which is one of the necessary inputs to production procedure, and with other factors of production (variables) such as labour, capital, natural capital, etc. (cf. Section 3). Collapsing all the variables, except for the water quantity w_i, to their means, we obtain the equation:

$$Y_i = \hat{f}_i(w_i)\,, \tag{1}$$

where

$\hat{f}_i'(w_i)$ = **marginal contribution** of the water to the production of sector i

= **maximum WTP** by sector i for each unit of water

= **price** of the water for sector $i = p$, $i = 1, 2, \ldots, 5$.

Although a good's own price is important in determining consumers' willingness to purchase it, other variables also have influence on that decision; such as consumers' incomes, their tastes and preferences, the prices of other goods that serve as substitutes or complements, and so on. Economists attempt to capture all of these influences in a relationship called the demand function for each sector $i = 1, 2, \ldots, 5$. The demand curve is a graphical representation of the relationship between the price of a good or service, here the water, and the quantity demanded for a given period of time. In other words, the demand curve shows exactly how many units of the water will be purchased at various prices. Thus, estimating the function of (1) (cf. Section 3), we finally obtain the **inverse demand** function (curve) for each sector $i = 1, 2, \ldots, 5$, using $p = \hat{f}_i'(w_i)$.

In general, economists believe that as the price of a good rises, buyers will choose to buy less of it, and as its price falls, they buy more. Therefore, as p increases over time due to decreasing water availability, water demand for each of these economic sectors reaches zero sequentially, given by the ordering of the intercepts $\hat{f}_1'(0) < \hat{f}_2'(0) < \hat{f}_3'(0) < \hat{f}_4'(0) < \hat{f}_5'(0)$. We denote by T_j the **exit time** of the j-th, $j=1, 2, \ldots, 5$, sector, where we also define $T_0 \triangleq 0$, thus time is divided into 5 exit stages and we end up with an ordering of 5 sectors via their inverse demand function.

In addition, if consumers are the only group deriving benefits from a commodity, i.e. water, then the inverse demand curve is the marginal social benefit curve. Marginal social benefit is the benefit society receives when an additional unit of the commodity is produced. It is obvious that by integration of the inverse demand curve, we obtain the **Social Benefit** (SB_i) of each sector $i=1, 2, \ldots, 5$.

2.2 GENERALIZATION OF THE MODEL IN THE RIVER BASIN WATER SHARING CASE

As multiple countries share a river, the competition over the available water resources is acute under climate change and meeting freshwater demand for agriculture and other vital uses becomes one of the impending challenges for policy makers. In the past, water planners struggled with the problem of estimating water demand with supply uncertainties. Also, the majority of current water-sharing arrangements do not take into account the variability of river flow (*Giodarno and Wolf*, 2003). Climate change challenges the existing water resource management practices by adding further uncertainties (*IPCC*, 2007; *Vorosmarty*, 2002). This becomes a troubling issue, particularly for transboundary water-sharing agreements (*Stephen and Kundell*, 2008). Unless new approaches to water management are developed that take into account these new uncertainties, future conflict over water resource are likely to increase (*Gleick*, 1992).

Several studies have analysed the impact of water scarcity on cooperation in water sharing, of which some take into account deterministic water flows and analyse the factors that influence stability of treaties and motivate negotiations (*Ambec and Sprumont*, 2002; *Beard and McDonald*, 2007; *Ambec and Ehlers*, 2008; *Janmatt and Ruijs*, 2007). Other studies go beyond static measures of water availability. In particular, *Dinar* (2009) shows that, under increased variability of water supply, a cooperative approach in the form of risk sharing may be preferred over an individual solution. In such circumstances, strategic alliance becomes the basis for a cooperative arrangement to address the impact of climate change on the stability of water sharing treaties. Using empirical data, *Dinar et al.* (2010) demonstrate a bell-shaped relationship between water supply variations and treaty cooperation. *Ansink and Ruijs* (2008) also demonstrate that a decrease in mean flow of a river reduces the stability of an agreement, while an increase in variance may have both positive and negative effects on treaty stability.

The approach presented here captures the influence of stochastic water resources on transboundary water allocation, over multiple sectors of the economy, following a multistage dynamic cooperative game approach. We show how issue linkage can facilitate cooperation between countries, even in the case of climate change. We illustrate the model with the case of water sharing between an upstream country, Ethiopia and a downstream country, Kenya. The "*issue linkage to water sharing*" in this case concerns the trade of food produced from the downstream country to the upstream country. Thus, we will investigate if the issue of water sharing can be linked to food export as the basis for attaining sustained cooperation in water distribution.

From the description of the countries socio-economic profiles presented in Subsections 1.2.1 and 1.2.2, we understand that the landscape of the Lower Omo and Lake Turkana basins will soon undergo one of the biggest transformation in its history. Since the Gibe III reservoir began filling in 2015, the shoreline at Ferguson's Gulf, the most productive fishery on the lake, has receded by 1.5 km (*Mutambo,* 2017). Abstraction of increasing quantities of water for irrigation upstream would cause the lake levels to drop further, potentially splitting into two or more smaller lakes (*Avery*, 2013). Indeed, even if irrigation were suspended, fisheries biologists predict that the regulation of the river by Gibe III will lower fish yields from Lake Turkana by more than two-thirds, since the lake's fish depend on the seasonal flood pulse (the nutrients and fresh water that Omo delivers) as a cue for breeding (*Gownaris et al*, 2017). So far, the Kenyan government has not forced its Ethiopian counterpart to acknowledge the threats these developments pose for those whose livelihoods depend on the lake. Despite attempts by the United Nations Environment Program to broker an agreement between these governments, the key problem of water-sharing remains unresolved (*Mutambo*, 2017; *Arnold*, 2013; *Human Rights Watch*, 2017; *Stevenson*, 2018).

Additionally, for centuries the people of the lower Omo valley have relied on a three-pillar strategy to make a living in the semi-arid climate: combining herding, farming on rain-fed land, and farming on land inundated by the annual rise of the river (*Turton,* 1985). The river flood, since it carried water from a large catchment in highland Ethiopia, dependably provided the water and silt needed for farming. With the Gibe III dam, the flood has ended, and the people of the lower Omo are therefore deprived of one crucial component of their livelihood. Some of the most valuable agricultural lands have been annexed by the expanding sugar plantations, and the availability of vital fall-back resources, in the form of game animals and wild foods, is severely constrained, as scrubland has been razed for plantation development (*Buffavand*, 2016). At the same time as thousands of new settlers and migrant laborers converge on the plantations of the lower Omo, a food insecurity crisis looms for the region's indigenous people (*Carr*, 2017). To avert famine, there is a need for a comprehensive and well-funded livelihood reconstruction program (*Turton*, 2015).

Considering the future interests of Lake Turkana, the people within the Ethiopian and Kenyan areas of the Lake Turkana basin and the protection of the Lake Turkana region, a transboundary water agreement to govern the use of Omo River flows is needed. An agreement of this kind should provide a provision to regulate the permanent use of Omo River flows in a way that the hydrologic and ecological impacts of the dams or developmental projects are minimal, while also ensuring protection of the basin and benefitting the Lake Turkana basin communities in both Ethiopia and Kenya. Taking into account that Turkana's indigenous communities are highly dependent on the lake for their food crops, livestock grazing and watering and fishing, any impacts to the lake's ecosystem would disrupt the economy, leading to an increase in conflicts in the area. We will investigate a potential trade of food generated from the downstream country to the upstream country.

On the other hand, as reported in Deliverable 2.1, the 2016 power sharing agreement provides a mandate for the Kenya-Ethiopia Electricity Highway Project (or the Eastern Electricity Highway Project), which will see the construction of a 1,000km power line to run from Ethiopia to Kenya to be completed by 2018.[1] The agreement is built upon an MoU signed in 2006 between the Ethiopian Electric Power Corporation and the Kenya Electricity Transmission Company for the joint development of the project.[2] The environmental and social impact assessment report was approved in 2012, although it has been criticised as it was conducted after any objection could be made.[3] Following a World Bank loan of US$684 million,[4] construction began in June 2016.[5] While the 2016 agreement is not yet publicly available, it is reported that the agreement will allow Ethiopia to supply Kenya with 400 megawatts of hydro-power at less than 1 US cent/kwh.[6] The hydro-power source or sources that will supply this transmission line is not officially stated, although the World

[1] ("Ethiopia, Kenya to enhance cooperation on energy sector.," n.d.)
[2] ("Kenya-Ethiopia Electricity Highway, Kenya," n.d.)
[3] (Abbink, 2012)
[4] ("AFCC2/RI-The Eastern Electricity Highway Project under the First Phase of the Eastern Africa Power Integration Program," n.d.)
[5] ("Kenya-Ethiopia Electricity Highway, Kenya," n.d.)
[6] ("Ethiopia, Kenya to enhance cooperation on energy sector.," n.d.)

Bank modified an official project report specifying that power would be sourced "from Ethiopia's Gilgel Gibe hydropower scheme",[7] changing the reference to the dam in its next report instead to "Ethiopia's power grid".[8] We will also accommodate a potential trade of hydro-power from the upstream country to the downstream country in our model.

We first model the multistage allocation of stochastic water resources between the upstream and the downstream country in a non-cooperative framework, where the upstream (U) country chooses how much water to divert unilaterally per sector in order to maximize its own welfare. The downstream (D) country act as a "follower," whose water availability depends on the flow of water diverted by the upstream country. We next construct a stochastic differential "leader–follower" game setting, where the upstream country offers a discounted price for hydropower to the downstream country and the downstream country offers a discounted price for food exports to the upstream country in exchange for more transboundary water flow. Finally, we compare both the cooperative and non-cooperative outcomes in a possible climate change scenario.

There is a substantial body of literature on stochastic water resource management from which only few studies exist on the influence of stochastic water resource management on transboundary water sharing. *Bhaduri et al.* (2011) investigated the uncertainty in water resource management in a transboundary water sharing problem and evaluated the scope and sustainability for a potential cooperative agreement between countries. On the other hand, *Kim et al.* (1989) studied a deterministic renewable groundwater optimal management problem in the face of two-sector linear demands, while *Koundouri and Christou* (2006) revisited this problem under the presence of a backstop technology.

Our contribution in this framework is the introduction of the five core water economic sectors taking into account their dependence with the social benefit of water use per country. We assume that water resources evolve through time and follow a geometric Brownian motion. However, the characteristics of Brownian motion in terms of variance are different between the upstream and the downstream country, based on the assumption that the effects of climate change are regionally different. Additionally, we are able to determine how the water abstraction of the riparian countries will change in the long run, taking into account the greater variability of water availability caused by climate change. In other words, the suggested model describes water allocation between the upstream and the downstream country in such a case, with and without any cooperation in water sharing, taking into account how uncertainty in water supply affects the water abstraction rates of the countries, and explores the underlying conditions that may influence decisions on water allocations.

The upstream country has the upper riparian right to unilaterally divert water while the freshwater availability of the downstream one partially depends on the water usage in the upstream country. We denote the countries by superscripts, where U denotes the upstream country and D stands for the downstream country.

Following *Bhaduri et al*. (2011), we consider at first a complete filtered probability space $(\Omega, \Im, \Im_t, P)$ and we assume that water flow is stochastic and uncertainty in the flow of water can be attributed to climate change. Then the annual renewable water resource due to the river basin, $W_{\cdot}$, evolves through time according to the Geometric Brownian motion:

$$dW_t = \sigma^W W_t dz_t^W, \quad t \geq 0, \tag{2}$$

where $z_{\cdot}^W$ is a standard Wiener process and σ^W can be considered as the volatility of water flow in the upstream country.

[7] (*Resettlement Action Plan (RAP) Final Report 2012*, n.d.)
[8] (*Resettlement Policy Framework Draft Report 2012*, n.d.)

Let us denote by $w_{i\bullet}^h$ the total freshwater utilization and by T_i^h the **exit time** of the i-th sector, per country $h = U, D,$ and for each sector $i = 1, 2, \ldots, 5$, together with the convention of $T_0 \triangleq 0$ .Then the change in the level of water resources available in the upstream country, $W_\bullet^U$, for the j-th exit stage is represented by

$$dW_{jt}^U = \left[W_t - \sum_{i=j}^{5} w_{it}^U \right] dt, \quad T_{j-1}^U \le t < T_j^U, \quad j = 1, 2, ..., 5, \tag{3}$$

where $W_{oo}^U = wr_0$ is an initial condition. The water availability in the downstream country depends on the total water consumption in the upstream one and runoff, denoted by $R_\cdot$, which is also stochastic in the model. Thus, the latter can be expressed through another Geometric Brownian motion as

$$dR_t = \sigma^R R_t dz_t^R, \quad t \ge 0, \tag{4}$$

where σ^R is considered to be the corresponding volatility and $z_\bullet^R$ is another standard Wiener process independent of $z_\bullet^W$. Thus, the stock of water in the downstream area, where agricultural products and fisheries are produced, is denoted by $S_\cdot$, and is a function of the stochastic water resources and the control variables $\boldsymbol{w}_\bullet^h = (w_{1\bullet}^h, w_{2\bullet}^h, \ldots, w_{5\bullet}^h)$ per country $h = U, D$; in fact, for the (j,k)-th exit stage of the upstream and downstream countries, respectively, it follows the dynamics:

$$dS_{jkt} = \left\{ W_t - \sum_{i=j}^{5} w_{it}^U - \sum_{l=k}^{5} w_{lt}^D + R_t - O_t \right\} dt, \quad T_{j-1}^U \le t < T_j^U \text{ and } T_{k-1}^D \le t < T_k^D, \; j,k = 1, 2, ..., 5, \tag{5}$$

where $S_{000} = s_0$ is an initial condition. Here, O_t denotes the outflow and evaporation of water from this area and can be formulated by a third Geometric Brownian motion as

$$dO_t = \sigma^O O_t dz_t^O, \quad t \ge 0, \tag{6}$$

with volatility σ^O and $z_\bullet^O$ being a third standard Wiener process independent of $z_\bullet^W$ and $z_\bullet^R$.

In view of (1), we assume that the inverse demand function for the water utilization of the j-th exit stage, per sector i and area h, is represented by

$$p_{jt}^h = \frac{a_i^h}{b_i^h} - \frac{1}{b_i^h} \cdot w_{it}^h, \quad T_{j-1}^h \le t < T_j^h, \quad i = j, ..., 5, \quad j = 1, 2, ..., 5, \quad h = U, D, \tag{7}$$

where $p_{j\bullet}^h$ is the price of water at each stage j, which is the same for the different sectors, and $a_i^h \in \sim, b_i^h > 0$ are constant sector-specific demand parameters. The sector-specific inverse demand curves are ordered so that $a_1^h / b_1^h < a_2^h / b_2^h < \cdots < a_5^h / b_5^h$, which implies that water demand for each of the five sectors reaches zero sequentially over time as the price of water increases over time, leading to the endogenously defined exit times $T_j^h, j = 1, 2, ..., 5,$ of the five economic sectors per area $h = U, D.$ Here, aggregate water demand turns out to be a piecewise linear function.

Since consumers are the only group deriving benefits from water, the inverse demand curve is the marginal social benefit curve. Hence, consider further the benefit of water consumption w_i^h per sector i of country h, namely social benefit (SB), as

$$SB_i^h\left(w_i^h\right) = \int_0^{w_i^h} \left(\frac{a_i^h}{b_i^h} - \frac{1}{b_i^h} \cdot w_i^h \right) dw_i^h = \frac{a_i^h}{b_i^h} w_i^h - \frac{1}{2b_i^h} \cdot (w_i^h)^2, \quad h = U, D, \quad i = 1, ..., 5. \tag{8}$$

It is obvious that the benefit function is strictly concave for all possible values of w_i^h.

Water abstraction from rivers may be taken directly from the flowing waters in the channel (surface water abstraction) or can be achieved through inter-basin flow transfer schemes. Thus, we may assume that the marginal extraction cost (MC) for the j-th exit stage of the upstream country is a decreasing function of the available water resources W^U of the form:

$$MC^U(W_j^U) = k_2^U - k_1^U W_j^U, \quad j = 1,2,...,5,$$

where k_1^U, $k_2^U > 0$ are given constants. In fact, we consider that as water becomes increasingly scarce in the economy, the government would exploit water through appropriating and purchasing a greater share of aggregate economic output, in terms of dams, pumping stations, supply infrastructure, etc. (*Barbier*, 2000). Given the high cost of building infrastructure and expanding supplies, this will lead to a higher marginal cost of water. Then the total cost (TC) function of water withdrawing w_i^U from the river per sector $i = j, \ldots, 5$, for the j-th exit stage of the upstream country is given by

$$TC^U\left(W_j^U, w_i^U\right) = (k_2^U - k_1^U W_j^U) w_i^U, \quad i = j,...,5, \quad j = 1,2,...,5, \tag{9}$$

which is an increasing function of the water extraction variable. On the other hand, the downstream area extracts water from its available stock, thus for the (j,k)-th exit stage the MC of the downstream area is a decreasing function of the available water stock S_{jk} and has the form:

$$MC^D(S_{jk}) = k_2^D - k_1^D S_{jk}, \quad j,k = 1,2,...,5,$$

where k_1^D, $k_2^D > 0$ are given constants. Then the TC function of water withdrawing w_l^D from the water stock in the downstream country per sector $l = k, \ldots, 5$ for the (j,k)-th exit stage is given by

$$TC^D\left(S_{jk}, w_l^D\right) = (k_2^D - k_1^D S_{jk}) w_l^D, \quad l = k,...,5, \quad k = 1,2,...,5, \tag{10}$$

which is an increasing function of the water extraction variables.

2.2.1 Non-Cooperative Approach

We present below a non-cooperative framework, where there is no any agreement between the two areas regarding either water or hydropower sharing.

Upstream Case

The upstream area chooses the economically potential rate of water utilization that maximizes its own net benefit (NB) per j-th exit stage, which can be expressed as

$$NB_j^U = \sum_{i=j}^{5} SB_i^U(w_i^U) - \sum_{i=j}^{5} TC^U\left(W_j^U, w_i^U\right), \quad j = 1,2,...,5. \tag{11}$$

Thus, from (8)-(11) the upstream country maximization problem can be formulated as follows:

$$\begin{aligned} J^U &= \max_{\mathbf{w}_\cdot^U} \sum_{j=1}^{5} J_j^U = \max_{\mathbf{w}_\cdot^U} \sum_{j=1}^{5} E\left\{\int_{T_{j-1}^U}^{T_j^U} e^{-rt} NB_j^U dt\right\} \\ &= \max_{\mathbf{w}_\cdot^U} \sum_{j=1}^{5} E\left\{\int_{T_{j-1}^U}^{T_j^U} e^{-rt} \sum_{i=j}^{5}\left[SB_i^U(w_{it}^U) - TC^U\left(W_{jt}^U, w_{it}^U\right)\right]dt\right\} \\ &= \max_{\mathbf{w}_\cdot^U} \sum_{j=1}^{5} E\left\{\int_{T_{j-1}^U}^{T_j^U} e^{-rt} \sum_{i=j}^{5}\left[\frac{a_i^U}{b_i^U} w_{it}^U - \frac{1}{2b_i^U}\cdot(w_{it}^U)^2 - (k_2^U - k_1^U W_{jt}^U) w_{it}^U\right]dt\right\}, \end{aligned} \tag{12}$$

where J_j^U stands for the upstream country's net social benefit of the j-th exit stage, $j = 1,2,\ldots,5$, and $\boldsymbol{w}_{\bullet}^U = (w_{j\bullet}^U, \ldots, w_{5\bullet}^U)$ is the respective sectorial water extraction vector process for the upstream area, subject to the river basin annual renewable water resource equation of (2) and the upstream area water resources (state) equation of (3).

An explicit solution of this stochastic control problem via a decoupling method for forward-backward stochastic differential equations (FBSDEs) is analytically derived in Appendix 2.

Downstream Case

On the other hand, the downstream country water consumption depends on the inflow from the upstream country, and the runoff generated within the country's share of the water stock in the downstream area. Based on the given availability of water, the downstream country maximizes its NB per exit stage (j,k) quantified as follows:

$$NB_{jk}^D = \sum_{l=k}^{5} SB_l^D\left(w_{jl}^D\right) - \sum_{l=k}^{5} TC^D\left(S_{jk}, w_{jl}^D\right), \quad j,k = 1,2,\ldots,5. \tag{13}$$

Hence, putting together (8), (10) and (13) the downstream country maximization problem is given by

$$\begin{aligned} J^D &= \max_{\boldsymbol{w}_{\bullet}^D} \sum_{k=1}^{5} \sum_{j=1}^{5} J_{jk}^D = \max_{\boldsymbol{w}_{\bullet}^D} \sum_{k=1}^{5} \sum_{j=1}^{5} E\left\{ \int_{\left\{T_{j-1}^U \le t < T_j^U\right\} \cap \left\{T_{k-1}^D \le t < T_k^D\right\}} e^{-rt} NB_{jk}^D dt \right\} \\ &= \max_{\boldsymbol{w}_{\bullet}^D} \sum_{k=1}^{5} \sum_{j=1}^{5} E\left\{ \int_{\left\{T_{j-1}^U \le t < T_j^U\right\} \cap \left\{T_{k-1}^D \le t < T_k^D\right\}} e^{-rt} \left[\sum_{l=k}^{5} SB_l^D\left(w_{lt}^D\right) - \sum_{l=k}^{5} TC^D\left(S_{jkt}, w_{lt}^D\right) \right] dt \right\} \\ &= \max_{\boldsymbol{w}_{\bullet}^D} \sum_{k=1}^{5} \sum_{j=1}^{5} E\left\{ \int_{\left\{T_{j-1}^U \le t < T_j^U\right\} \cap \left\{T_{k-1}^D \le t < T_k^D\right\}} e^{-rt} \begin{bmatrix} \sum_{l=k}^{5} \left(\frac{a_l^D}{b_l^D} w_{jlt}^D - \frac{1}{2b_l^D} \cdot (w_{jlt}^D)^2 \right) \\ -(k_2^D - k_1^D S_{jkt}) \sum_{l=k}^{5} w_{jlt}^D \end{bmatrix} dt \right\}, \end{aligned} \tag{14}$$

where J_{jk}^D represents the downstream area's net social benefit of the (j,k)-th exit stage, j, $k = 1, 2, \ldots, 5$, and $\boldsymbol{w}_{\bullet}^D = (w_{jk\bullet}^D, \ldots, w_{j5\bullet}^D)$ is the respective sectorial water extraction vector process for the downstream area, subject to the river basin annual renewable water resource equation of (2), the upstream area water resources equation of (3), the runoff flow equation of (4), the stock of water (state variable) in the downstream area equation of (5) and the outflow equation of (6). For an analytical solution of this stochastic optimization problem we refer the reader to Appendix 2.

2.2.2 Cooperative Approach

In this section, we present the model of the inter-sectoral water sharing strategy between the upstream and downstream country in a cooperative setting. In particular, the downstream country offers a discounted price for food exports to the upstream country, in exchange for greater transboundary water flow that results in a higher water reserve accumulation and sequentially in a higher production of food. The option of the upstream country to offer back a discounted price for hydropower exports to the downstream country is accommodated to the model as well. In what follows, we utilize a differential Stackelberg "*leader–follower*" game to determine the inter-sector optimal water allocation between the upstream and downstream country. The upstream country represents the *leader* and applies his strategy first, *a priori* knowing that the *follower* downstream country observes its actions and *a posteriori* moves accordingly. First, we find the solution to the follower's problem of maximizing his payoff function, and then, using the follower's reaction strategy, we maximize the leader's objective function.

Since all the model coefficients are deterministic functions of time, we assume that the respective countries use *Markovian perfect strategies*. These strategies are decision rules that dictate optimal action of the respective players, conditional on the current values of the state variables (upstream level of water resources, level of water stock reserves downstream, etc), that summarize the latest available information of the dynamic system. The Markovian perfect strategies determine a *subgame perfect equilibrium* and define an *equilibrium set of decisions* dependent on previous actions.

Downstream Case

Receiving hydropower benefits, denoted by the variable $hydro$, from the upstream country (leader) at a discount rate and given its announced intersectoral water abstraction policy $\boldsymbol{w}^U_{\bullet} = (w^U_{jk\bullet},...,w^U_{5k\bullet})$ per (j,k)-th exit stage, the downstream country (follower) is faced with an optimal water management problem as in the non-cooperative case, i.e., maximize (14) augmented by $hydro$, subject to the state equations (2) - (6). For every $j,\ k = 1,\ 2,\ \ldots,\ 5$, the ($j,k$)-th exit stage Hamiltonian of the system is also given by (48), whose necessary optimality conditions (49) and (50) result in the optimal water allocation path of (51) and in the FBSDEs system (52) which will constitute a state system for the upstream country as well.

Upstream Case

The upstream country (leader) receives now food benefits from the downstream country (follower) denoted by the linear function of water stock S_{jk} per (j,k)-th exit stage:

$$F^U(S_{jk}) = \eta^U_1 S_{jk} + \eta^U_2, \quad j,k = 1,2,...,5, \tag{15}$$

where $\eta^U_1 > 0,\ \eta^U_2 \in \sim$, are constants, and its NB function is given by

$$NB^U_{jk} = \sum_{i=j}^{5} SB^U_i(w^U_i) + F^U\left(S_{jk}\right) - \sum_{i=j}^{5} TC^U\left(W^U_j, w^U_i\right), \quad j,k = 1,2,...,5. \tag{16}$$

Therefore, the upstream country, anticipating the downstream country's optimal response as analysed in the previous case, chooses the optimal water abstraction vector process $\boldsymbol{w}^U_{\bullet} = (w^U_{jk\bullet},\ ...,\ w^U_{5k\bullet})$ per (j,k)-th exit stage under cooperation by solving the following maximization problem, imposed by (8), (9), (15) and (16)

$$\begin{aligned}
J^U &= \max_{\boldsymbol{w}^U_{\bullet}} \sum_{j=1}^{5} \sum_{k=1}^{5} J^U_{jk} = \max_{\boldsymbol{w}^U_{\bullet}} \sum_{j=1}^{5} \sum_{k=1}^{5} E\left\{ \int_{\left\{T^U_{j-1} \le t \le T^U_j\right\} \cap \left\{T^D_{k-1} \le t \le T^D_k\right\}} e^{-rt} NB^U_{jk} dt \right\} \\
&= \max_{\boldsymbol{w}^U_{\bullet}} \sum_{j=1}^{5} \sum_{k=1}^{5} E\left\{ \int_{\left\{T^U_{j-1} \le t \le T^U_j\right\} \cap \left\{T^D_{k-1} \le t \le T^D_k\right\}} e^{-rt} \begin{bmatrix} \sum_{i=j}^{5} SB^U_i(w^U_{ikt}) + F^U_{jk}\left(S_{jkt}\right) \\ -\sum_{i=j}^{5} TC^U\left(W^U_{jt}, w^U_{ikt}\right) \end{bmatrix} dt \right\} \\
&= \max_{\boldsymbol{w}^U_{\bullet}} \sum_{j=1}^{5} \sum_{k=1}^{5} E\left\{ \int_{\left\{T^U_{j-1} \le t \le T^U_j\right\} \cap \left\{T^D_{k-1} \le t \le T^D_k\right\}} e^{-rt} \begin{bmatrix} \sum_{i=j}^{5} \left(\frac{a^U_i}{b^U_i} w^U_{ikt} - \frac{1}{2b^U_i} \cdot (w^U_{ikt})^2 \right) \\ +\eta^U_1 S_{jkt} + \eta^U_2 - (k^U_2 - k^U_1 W^U_{jt}) \sum_{i=j}^{5} w^U_{ikt} \end{bmatrix} dt \right\},
\end{aligned} \tag{17}$$

subject to the river basin annual renewable water resource equation of (2) the upstream country water resources (state) equation of (3), the runoff flow equation of (4), the outflow equation of(6), and the Hamiltonian FBSDEs state system of the downstream country (52). In Appendix 2 one can find an explicit solution of this stochastic maximization problem.

3. ESTIMATION OF THE PRODUCTION FUNCTIONS OF THE ECONOMIC MODEL BY SECTOR

In this section, we aim to estimate the main components of our model using a stochastic frontier model and a quadratic production function, the form of which remains unknown. In order to identify the production function, we need to estimate the sample coefficients of its main variables, which in order to be a good reflection of their real values, they need to be unbiased, consistent and efficient. However, the major challenge we faced in this exercise was the existence of endogeneity problems, due to correlation of the explanatory variables, such as capital or labor, with the error term, due to three main reasons explained below. The magnitude of this problem can be seen in the estimations of the coefficients of the model, the expected values of which will not be equal to their real values (biased), as for example in case of omitted variable bias, there will be another variable contained in the error term, i.e. health or age, influencing both labor and production levels. Hence, the upcoming results of the regression cannot be trusted, and they may lead to inaccurate analysis.

However, the most widely used approaches in order to tackle endogeneity problem of using investment by *Olley and Pakes* (1996) or intermediate inputs as a proxy by *Levinsohn and Petrin* (2003) have been both subject to criticism for lack of relevant instruments and collinearity problems. Therefore, in this paper we will present an extension of the model proposed by *Gandhi et al.* (2017), where those limitations are attacked, and we will introduce technical inefficiency in production and also allow for autocorrelation TFP. Using the Copula approach in order to estimate non-parametrically the dependence between the endogenous regressors and the composed error terms directly via a copula function which does not require the use of instruments, we are able to estimate the marginal product function of our mathematical model without being subject to biases. As explained in section 2, the marginal product function is the inverse demand function of water use from which we can calculate the net social benefits of each country and the lake depletion time. Having estimated both of those values, we will be able to determine the optimal path for water use *ceteris paribus* (with all the other parameters being collapsed to their means).

3.1 MATHEMATICAL AND STATISTICAL MODELS

In this context, the key economic drivers influencing pressures and water uses need to be determined including general socio-economic indicators such as income and employment, and environmental indicators related to ecosystem services such as land use, emissions, etc. These economic drivers will need to be accounted for in a dynamic perspective, i.e., to determine how these are likely to evolve over time. The final component of the economic characterization of water in a region is the application of appropriate methodologies to assess sector-specific water demand. This involves deriving the marginal contribution of water in consumption and production of each sector, the maximum willingness to pay for water and the price of the water per sector, concluding with the demand curve from which we obtain the Social Benefit (cf. Section 2).

The production of marketed goods requires both man-made input as labour and machinery, as well as land and ecosystem-based processes. Not accounting for this can lead to the criticism that the valuation is exaggerating ecosystem service values. A method which is designed to value indirect use values is the production function approach (PFA). Production theory is the study of production or the economic process of producing outputs from the inputs, i.e. a process of combining various material inputs and immaterial inputs (plans, know-how) in order to make something for consumption (the output). More accurately, production function is a mathematical equation representing the "maximum" output that can be obtained from any fixed and specific set of production inputs at a certain level of technology. Thus, the outcome is considered as the dependent variable and production inputs are regarded as independent variables. Accordingly, a *production function* is the relationship that describes how inputs like Capital, Labour and Natural Resource Capital are transformed into output (see Figure 7). Mathematically, we estimate each sector's $i = 1, 2, \ldots, 5$, specific production function via Gross Value Added (GVA) as:

$$GVA\ (\text{sector } i) = F\left(\textbf{Technological Capital Input}; \textbf{Labour Input}; \textbf{Natural Capital Input}\right) \quad (18)$$

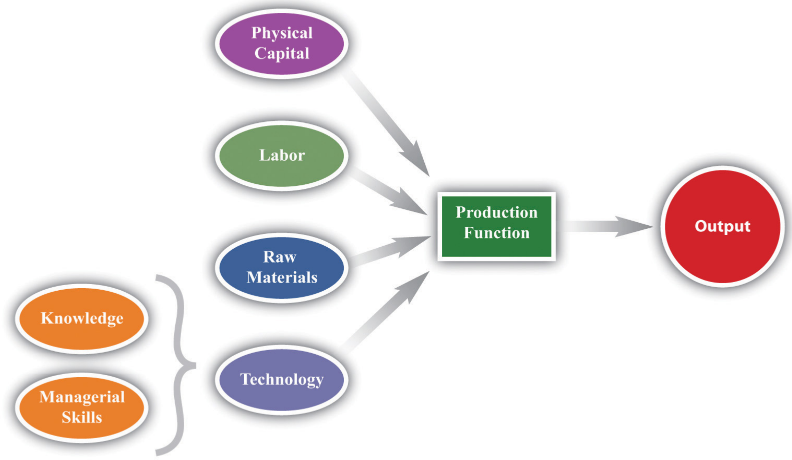

Figure 7 - Production Function Description

One very simple example of a production function is when F is a linear function of the input. More precisely, if F is a *linear function* that relates GVA with only the amount of Capital (C) and the amount of Labour (L) that are used in production, i.e.,

$$GVA = aC + bL + c, \quad (19)$$

where a, b , c are parameters that are determined empirically, then one unit of output (GVA) of a sector can be produced for every unit of Capital or Labour it employs. This form of production function yields that the amount of output will increase proportionally to any increase in the amount of inputs. Another common production function is the *Cobb-Douglas production function*, which has the form

$$GVA = aC^b L^c, \quad (20)$$

where a, b, c are parameters that are determined empirically. For example, if $b = c = 1/2$ then this describes the fact that the production requires the least total number of inputs when the combination of inputs is relatively equal. More specifically, a sector could produce 25 units of output (GVA) using 25 units of capital and 25 of labour, or it could produce the same 25 units of output with 125 units of labour and only one unit of capital. In the contrary, the *Leontief production function* applies to situations in which inputs must be used in fixed proportions; starting from those proportions, if usage of one input is increased without another being increased, output will not change. This production function has the form

$$GVA = \min\left(aK, bL\right), \quad (21)$$

where a, b are parameters that are determined empirically. All the above forms of productions function can be extended in functions with more than two input arguments and their economic description will be relevant with the above.

All the above production functions, as real functions, can be plotted on a graph. A typical quadratic production function is of the form that we will use in our analysis and its graph is demonstrated in the following diagram under the assumption of a single variable input.

Figure 8 depicts the possibility (i) of getting the *maximum* output by a given combination of input and on the contrary (ii) of reducing output from what is technologically possible by the inefficient management. Thus, points on or below the production function make up the production set the set of technically *feasible* combinations of inputs and outputs, and points such as *A* and *B* in the production set are technically inefficient (getting less output from its input than it could). Finally, points on the boundary of the production set (as *C* and *D)* are technically efficient, which means that it is produced as much output as it possibly can be given by the amount of input. For further information about the production function see *Brems* (1968), *Moroney* (1967), *Shephard* (1970) and *Saari* (2006 and 2011).

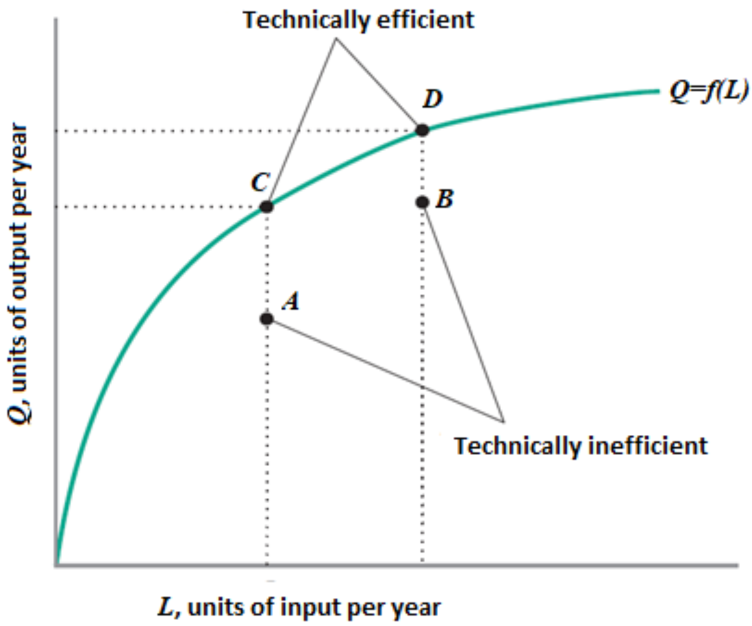

Figure 8 - Technical Efficiency and Inefficiency

Additionally, the existence of natural capital is a necessity in our model due to our final need of the economic characterization of water resource in the region under investigation. Natural capital is the world's stock of natural resources, which includes geology, soils, air, water and all living organisms. It is an extension of the economic notion of capital (resources which enable the production of more resources) to goods and services provided by the natural environment. Some natural capital assets provide people with free goods and services, often called ecosystem services. Two of these (clean water and fertile soil) underpin our economy and society and make human life possible. Ecosystem services can be provided into four main categories: (i) provisioning services, i.e. products obtained from ecosystems, (ii) regulating services, i.e. benefits arising from the regulation of ecosystem processes and functions, (iii) habitat services, i.e. services that are supportive for the production of all other ecosystem services, (iv) cultural services, i.e. benefits for humans such as spiritual enrichment, cognitive development, recreation and education. Table 10 contains examples of ecosystem services across the four main categories.

The challenges involved in the application of production function approach are that data on the relationships between the services (regulation and provision services) and on other non-environmental inputs are often difficult to obtain. In our case we need for each *Core Water-Dependent Economic Sector* $i = 1, 2, \ldots, 5$, to gather data on Natural Capital using Environmental Indices as approximations of both quality and quantity. Thus, at first, we need to define all the relative indices that we will use per sector (see further details in Subsection 3.2), according to the description of the 4 main ecosystem services categories of Table 10.

Table 10 - Ecosystem Services - Source: adopted from *De Groot et al.*, (2002).

Provisioning services	Food (e.g. fish, fruit)
	Water (e.gr for drinking, cooling)
	Raw material (e.g. fiber, timber)
	Genetic resources (e.g. for crop-improvement and medical purposes
	Medical resources (e.g. biochemical products)
	Ornamental resources
Regulating services	Air quality regulation
	Climate regulation
	Moderation of extreme events
	Regulation of water flows
	Waste treatment
	Erosion prevention
	Maintenance of soil fertility
	Pollination
	Biological control
Habitat services	Maintenance of life cycles of migratory species
	Maintenance of genetic diversity
Cultural and amenity services	Aesthetic information
	Opportunities for recreation and tourism
	Inspiration for culture, art and design
	Spiritual experience
	Information for cognitive development

3.2 DATA COLLECTION

The preparation of this report demanded the collection of socioeconomic information from each of the 2 riparian countries of the OTB. As explained in the preceding section, we needed data on Technological Capital, Labour and Natural Capital collected from national accounts. Furthermore, data should be time series (over time), but also cross sections of regional data panel data econometrics that are more robust. Several strands of data collection work including meetings with other partners – ACCESS, WLRC, Ku Leuven, ETH – were ongoing under Subtasks 2.1.7 and 2.1.8, in order to feed into work taking place within Task 4.6.

Apart from this collaboration, ICRE8 team managed to collect all the necessary information needed for the statistical analysis, using many datasets from many sources such as:

- Food and Agriculture Organization of United Nations (FAOSTAT, AQUASTAT),
- ILO (International LABOR Organization),
- The World Bank data,
- The World Bank Group: Climate Change Knowledge Portal For Development Practitioners and Policy Makers,
- The United Nations Statistics Division,
- Unesco World Heritage list,
- OpenDataSoft,
- Environment & Climate Change Data Portal,

which are commonly used databases and well known for their accuracy.

Furthermore, due to our necessity to obtain information for each sector, we used Input -Output (IO) tables that we had in our disposal from the **Eora multi-region IO table** (MRIO) database. The MRIO database provides a time series of high resolution IO tables with matching environmental and social satellite accounts for 187 countries (to 190 in some datasets). The Eora MRIO features:

- 187 individual countries represented by a total of 15,909 sectors,
- continuous coverage for the period 1990-2012,
- 35 types of environmental indicators covering air pollution, energy use, greenhouse gas emissions, water use, land occupation, N and P emissions, 172 crops, Human Appropriation of Net Primary Productivity,
- high-resolution heterogeneous classification, or 26-sector harmonized classification,
- raw data drawn from the UN's System of National Accounts and COMTRADE databases, Eurostat, IDE/JETRO, and numerous national agencies,
- distinction between basic prices and purchasers' prices through 5 mark-ups, and
- reliability statistics (estimates of standard deviation) for all results.

Our main data collection was done according to these IO tables. In our case we have 2 IO tables, each for the time period of 2000-2015 for the 2 countries under investigation. These tables have 2946 rows and columns with massive information each, per sector.

Table 18 in Appendix 1 includes all indices used for the estimation of the production functions from Section 2, their description and the source of the data. The indices representing the ecosystem services were constructed from measures of natural resources and landscapes. As each ecosystem service may relate to several resources and landscapes, and each natural resource may provide various ecosystem services, we can only infer the joint value of ecosystem services from those variables. Thus, for each sector we chose common variables which describe the main types of the ecosystem services, according to their description in Table 18 such as raw materials, forest, natural-cultural-mixed heritage sites, biodiversity and habitats, terrestrial protected areas, water quality, annual freshwater withdrawals, land uses, emissions (CO2 and NO2) and floods/droughts events.

3.3 ECONOMETRIC ANALYSIS – RESULTS

Estimation of production functions has always been a difficult exercise. The reason is that inputs like capital and labour are correlated with the error term for at least three reasons. First, decisions about *inputs* depend on overall productivity. The second source is measurement errors in the right-hand-side variables. The third source is from profit maximization, i.e., the firms choose inputs and output simultaneously to maximize profit.

Olley and Pakes (1996) use investment as a proxy for such unobservable shocks, while *Levinsohn* and *Petrin* (2003) use intermediate inputs as a better proxy that may respond more smoothly to unobserved productivity shocks. Both approaches which are widely used in the literature have been subject to criticism. In this approach, we will present a new estimation method of firm-level productivity dealing with the endogeneity problem which is pervasive in production function estimation.

Neither *Olley and Pakes* (1996) nor while *Levinsohn* and *Petrin* (2003) are devoid of problems (see *Gandhi et al*., 2017; *Ackerberg*, *et al*., 2015; *Doralzeski and Jaumendreu*, 2013). *Gandhi et al*. (2017) show that, besides the collinearity problem pointed out by *Ackerberg et al*. (2015), both the *Olley and Pakes* (1996) and *Levinsohn* and *Petrin* (2003) estimators suffer from the lack of relevant instruments for the endogenous inputs in the model. *Ackerberg et al*. (2006) have shown that the *Olley and Pakes* (1996) and *Levinsohn* and *Petrin* (2003) approaches to estimating TFP have a problem of collinearity if labor and intermediate inputs depend on TFP just like investment. *Gandhi et al*. (2017) also propose a nonparametric treatment of the production function. There could also be non-linearity due to capital-labour substitution in the sense that when labour input is costly, capital could be substituted to replace labour, making the relationship endogenous and non-linear.

In a substantive extension of the model, we introduce technical inefficiency in production and we allow for autocorrelated TFP. Bayesian analysis is performed using a Sequential Monte Carlo / Particle-Filtering approach (*Tsionas et al.,* 2018; *Tsionas and Izzeldin*, 2018a; *Tsionas and Izzeldin*, 2018b; *Tsionas and Mallick*, 2019). For more details see Appendix 3.

Consider the following stochastic frontier model:

$$y_{it} = \varphi(x_{it}, z_{it}; \beta) + v_{it} - u_{it}, \quad i = 1, \ldots, n, \; t = 1, \ldots, T \tag{22}$$

where y_{it} is the output of firm i and date t, $\varphi(\cdot)$ is an unknown functional form, z_{it} is a $p \times 1$ vector of exogenous inputs, x_{it} is a $p \times 1$ vector of endogenous inputs, β is a $d \times 1$ vectors of unknown parameters, v_{it} is a symmetric random error, u_{it} is the one-sided random disturbance representing technical inefficiency. We assume that z_{it} is uncorrelated with v_{it} and u_{it} but x_{it} is allowed to be correlated with v_{it} and possibly with u_{it}. This, of course, generates an endogeneity problem. We also assume that u_{it} and v_{it} are independent and leave the form of u_{it} unrestricted. The model can be easily extended to the case of exogenous (environmental) variables are included in the distribution of technical inefficiency (see for example, *Battese and Coelli,* 1995 and Caudill et al., 1995, and *Tsionas and Mamatzakis*, 2018).

3.3.1 Econometric Model

To address the endogeneity problem, we propose an approach which does not require the use of instrumental variables, which can often be weak or unreliable, is based on copula functions to determine the joint distribution of the endogenous regressors and the composed errors that effectively capture the dependency between them.

We first assume that $v_{it} \sim i.i.d. N(0, \sigma_v^2)$ and $u_{it} \sim i.i.d. \left| N(0, \sigma_u^2) \right|$. Then the density of $\varepsilon_{it} = v_{it} - u_{it} = y_{it} - \varphi(x_{it}, z_{it}; \beta)$ is given by:

$$g(\varepsilon_{it}) = \int_0^\infty f_v(\varepsilon_{it} + u_{it}) f_u(u_{it})\, du_{it} = \frac{2}{\sigma} \varphi\left(\frac{\varepsilon_{it}}{\sigma}\right) \Phi\left(-\frac{\lambda \varepsilon_{it}}{\sigma}\right), \tag{23}$$

where $\sigma^2 = \sigma_v^2 + \sigma_u^2$, $\lambda = \sigma_u / \sigma_v$, $\varphi(\cdot)$ and $\Phi(\cdot)$ are the probability density function and cumulative distribution function of a standard normal random variable, respectively. To avoid the non-negativity restrictions we make use of the following transformation: $\bar{\lambda} = \log(\lambda)$ and $\bar{\sigma}^2 = \log(\sigma^2)$. Let $\theta = (\beta', \bar{\lambda}, \bar{\sigma}^2)'$ then it follows that the conditional pdf of y given x and z is

$$f(y_{it} \mid x_{it}, z_{it}) = \frac{2}{\bar{\sigma}} \varphi\left(\frac{y_{it} - \varphi(x_{it}, z_{it}; \beta)}{\bar{\sigma}}\right) \Phi\left(-\frac{\bar{\lambda}}{\bar{\sigma}_v}(y - \varphi(x_{it}, z_{it}; \beta))\right) \tag{24}$$

and conditional log-likelihood is then given by

$$\log L(\theta) = \sum_{i=1}^{n} \sum_{t=0}^{T} \log f(y_{it}; \theta \mid x, z). \tag{25}$$

Copula Approach

In this subsection, we propose an approach that models the dependence between the endogenous regressors and the composed error terms directly via a copula function which **does not require the use of instruments**. We do not introduce dynamic latent productivity which is left for the local likelihood estimation. For rigorous treatment on copulas, see for example *Nelsen* (2006). We take the function $\varphi(\cdot)$ as given and provide its construction in subsection of the local likelihood estimation.

To this end, let $F(x_1,\ldots,x_p,\varepsilon)$ be the joint distribution of $(x_1,\ldots,x_p)$ and ε_i. Now since the information contained in the correlation between $(x_1,\ldots,x_p)$ and ε_i is also contained in its joint distribution, and if this is known to belong to a class of parametric density, then consistent estimates of the model parameters can be obtained by simply maximizing the log-likelihood function derived from $F(x_1,\ldots,x_p,\varepsilon)$. Thus, there is no need for resorting to instruments nor to consistently estimate the parameters of the model.

In practice, however, $F(x_1,\ldots,x_p,\varepsilon)$ is typically unknown. To address this problem, we follow *Park and Gupta* (2012) and suggest a copula approach to determine this joint density. The copula essentially captures the dependence in the joint distribution of the endogenous regressors and the composed errors. For exposition purpose, suppose we have a joint distribution of $(x_1,\ldots,x_p,\varepsilon)$ with joint density $f(x_1,\ldots,x_p,\varepsilon)$, and let $f_j(x_j)$, $F_j(x_j)$, for $j=1,\ldots,p$, $g(\varepsilon)$ and $G(\varepsilon)$ denote the marginal density and CDF of x_j and ε, respectively. Also let C denotes the "copula function" defined for $(\xi_1,\ldots,\xi_{p+1})\in[0,1]^{p+1}$ by

$$C(\xi_1,\ldots,\xi_{p+1})=P(F_1(x_1)\le\xi_1,\ldots,F_p(x_p)\le\xi_p,G(\varepsilon)\le\xi_{p+1})$$

so that the copula function is itself a CDF. Moreover, since $F_j(x_j)$ and $G(\cdot)$ are marginal distribution function, each component $U_j=F_j(x_j)$ and $U_\varepsilon=G(\varepsilon)$ has a uniform marginal distribution (see for example *Li and Racine*, 2007 in Theorem A.2). Let $c(\xi_1,\ldots,\xi_p)$ denotes the pdf associated with $C(\xi_1,\ldots,\xi_p)$, then by Sklar's theorem (*Sklar*,1959), we have

$$f(x_1,\ldots,x_p,\varepsilon)=c\left(F_1(x_1),\ldots,F_p(x_p),G(\varepsilon)\right)g(\varepsilon)\prod_{j=1}^{p}f_j(x_j). \quad (26)$$

Thus, equation (24) *here* shows that the copula function completely characterizes the dependence structure of $(x_1,\ldots,x_p,\varepsilon)$, and $c(\xi_1,\ldots,\xi_p)=1$ if and only if $(x_1,\ldots,x_p,\varepsilon)$ are independent of each other.

To obtain the joint density in (24), we need to specify the copula function. One commonly used copula function is the Gaussian copula. Other copula functions such as Frank, Placket, Clayton, and Farlie-Gumbel-Morgenstern can also be used. The Gaussian copula is generally robust for most application (*Song*, 2000) and has many desirable properties (*Danaher and Smith*, 2011). Let $\Phi_{\Sigma,p+1}$ denote a $(p+1)$-dimensional CDF with zero mean and correlation matrix Σ. Then the $(p+1)$-dimensional CDF with correlation matrix Σ is given by

$$C(w;\Sigma)=\Phi_{\Sigma,p+1}\left(\Phi^{-1}(U_1),\ldots,\Phi^{-1}(U_p),\Phi^{-1}(U_\varepsilon)\right)$$

where $w=\left(U_1,\ldots,U_p,U_\varepsilon\right)=\left(F_1(x_1),\ldots,F_p(x_p),G(\varepsilon)\right)$. The copula density is

$$c(w;\Sigma)=\left(\det(\Sigma)\right)^{-1/2}\times \exp\left\{-\frac{1}{2}\left(\Phi^{-1}(U_1),\ldots,\Phi^{-1}(U_p),\Phi^{-1}(U_\varepsilon)\right)'\left(\Sigma^{-1}-I_{p+1}\right)\left(\Phi^{-1}(U_1),\ldots,\Phi^{-1}(U_p),\Phi^{-1}(U_\varepsilon)\right)\right\}. \quad (27)$$

The log-likelihood function corresponding to (24) is:

$$\log L(\theta,\Sigma)=\sum_{i=1}^{n}\sum_{t=1}^{T}\left\{\ln c(F_1(x_{1,it}),\ldots,F_p(x_{p,it}),G(\varepsilon_{it};\theta);\Sigma)+\sum_{j=1}^{p}\ln f_j(x_{j,it})+\ln g(\varepsilon_{it};\theta)\right\}, \quad (28)$$

where $\theta = (\beta', \bar{\lambda}, \bar{\sigma}^2)'$ and the form of $c(\cdot)$ is given in(25). Notice that the first term in the summation in (28) is derived from the copula density and this term reflects the dependence between the endogenous variables and the composed errors. In addition, since the marginal density $f_j(x_j)$ does not contain any parameters of interest, the second term in the summation in (28) can be dropped from the log-likelihood function. Finally, it is clear from (26) that if there is no endogeneity problem, (28) collapses to the log-likelihood function of the standard stochastic frontier models.

By maximizing the log-likelihood function in (26), consistent estimates of (θ, Σ) can be obtained, and this can be done as we describe below.

Estimation of $F_j(x_j),\ j = 1,\ldots,p$; and $G(\varepsilon;\theta)$.

Since $F_j(x_{ji})$ are unknown and we have an observed sample of $x_{ji},\ j = 1,\ldots,p;\ i = 1,\ldots,n$; in the first step, we can estimate $F_j(x_{ji})$ by

$$\tilde{F}_{nj} = \frac{1}{nT+1}\sum_{i=1}^{n} 1(x_{j,it} \le x_{0j}),\ \ j = 1,\ldots,p, \tag{29}$$

where $1(\cdot)$ is an indicator function. Note that in(29), we have used the rescaling factor $1/(nT+1)$ rather than $1/nT$ to avoid difficulties arising from the potential unboundedness of the $\ln c\left(F_1(x_{1,it}),\ldots,F_p(x_{p,it}),G(\varepsilon_{it};\theta);\Sigma\right)$ as some of the $F_j(x_j)$ tend to one. To estimate $G(\varepsilon_{it};\theta)$, note that its density $g(\varepsilon_{it};\theta)$ is given in (23) and by definition, $G(\varepsilon_{it};\theta) = \int_{-\infty}^{\varepsilon_{it}} g(s;\theta)ds$, thus $G(\varepsilon_{it};\theta)$ can be estimated using numerical integration, and let $\tilde{G}(\varepsilon_{it};\theta)$ denotes the estimator of $G(\varepsilon_{it};\theta)$.

Maximization of the log-likelihood function

Maximization of the log-likelihood function in (26) with $F_j(x_j)$ and $G(\varepsilon_{it};\theta)$ are replaced by their estimates $\tilde{F}_j(x_j)$ and $\tilde{G}(\varepsilon_{it};\theta)$, respectively, i.e.,

$$(\hat{\theta},\hat{\Sigma}) = \underset{\theta\in\Theta,\Sigma}{\arg\max}\sum_{i=1}^{n}\left\{\ln c(\tilde{F}_1(x_{1i}),\ldots,\tilde{F}_p(x_{pi}),\tilde{G}(\varepsilon_i;\theta);\Sigma) + \ln g(\varepsilon_i;\theta)\right\} \tag{30}$$

Estimating Technical Inefficiency:

Once the parameters have been estimated, the ultimate goal is to predict the values of the technical inefficiency term u_i , and this can be calculated based on *Jondrow et al.* (1982):

$$\hat{u}_{it} = \hat{E}(u_{it} \mid \varepsilon_{it}) = \frac{\hat{\sigma}\hat{\lambda}}{1+\hat{\lambda}^2}\left[\frac{\varphi(\hat{\lambda}\hat{\varepsilon}_{it}/\hat{\sigma})}{1-\Phi(\hat{\lambda}\hat{\varepsilon}_{it}/\hat{\sigma})} - \frac{\hat{\lambda}\hat{\varepsilon}_{it}}{\hat{\sigma}}\right], \tag{31}$$

where $\hat{\varepsilon}_{it} = y_{it} - \varphi(x_{it}, z_{it};\hat{\beta})$ and $\hat{\beta}$, $\hat{\lambda}$ and $\hat{\sigma}^2$ are the parameter estimates obtained from the approach discussed above.

Local Likelihood Estimation

The functional form $\varphi(x_{it}, z_{it};\beta)$ was left unspecified so far. Of course, any parametric form can be used but here we focus on non-parametric estimation by the local likelihood method. We use the simpler notation $\varphi(x_{it};\beta)$ as the extension to the case of exogenous covariates is straightforward.

Since we have a multivariate covariate we use the method of local linear estimation. This means that all parameters of the model become functions of x, and they are denoted by $\theta(x)$. We denote the conditional density of y given x by $p(y \mid x) = g(y;\theta(x)),$ where $\theta(x) \in \sim^k$ is unknown and we define $q(y;\theta(x)) = \log g(y;\theta(x))$. For example, a standard frontier would take the form:

$$y_{it} = m(x_{it}) + v_{it} - u_{it}, \tag{32}$$

where $v_{it} \mid x_{it} \sim N\left(0, \sigma_v^2(x_{it})\right),\ u_{it} \mid x_{it} \sim N\left(0, \sigma_u^2(x_{it})\right)$. Then we have

$$\theta(x) = \left[m(x), \sigma_v^2(x), \sigma_u^2(x)\right]'.$$

Our fundamental departure from the standard model is the **introduction of productivity**:

$$y_{it} = m(x_{it}, z_{it}) + v_{it} + \omega_{it} - u_{it}, \tag{33}$$

where the productivity process is as follows:

$$\omega_{it} \mid x_{it}, \omega_{i,t-1} \sim N\left(r(\omega_{i,t-1}, x_{it}, z_{it})^2_{\omega}, (\omega_{i,t-1}, x_{it}, z_{it})\right).$$

In this specification, $r(\omega_{i,t-1}, x_{it}, z_{it})$ is a non-parametric productivity mean process, and $\sigma^2_{\omega}(\omega_{i,t-1}, x_{it}, z_{it})$ is the variance. For ease in notation we omit explicit dependence on z and we continue to denote $\theta(x) \in \sim^k$ with $\theta(x) = \left[m(x), r(\omega_{-1}, x), \sigma_v^2(x), \sigma_u^2(x), \sigma_{\omega}^2(\omega_{-1}, x)\right]'$,

where ω_{-1} denotes the lagged value of productivity. As productivity is latent special problems are introduced into the analysis. There is a multivariate kernel which satisfies:

$$\int K(u)du = 1, \quad \int uu'K(u)du = \mu_2 I_d.$$

To fix notation, we start with the analysis of the simpler model in (32). The conditional local linear log-likelihood is given by[9]

$$\log L(\theta_o, \Theta_1) = \sum_{i=1}^{n} \sum_{t=1}^{T} q\left(y_{it}, \theta_o + \Theta_1\left(x_{it} - x\right)\right) K_H\left(x_{it} - x\right), \tag{34}$$

where θ_o, Θ_1 is a vector $(k \times 1)$ and matrix $(k \times d)$ respectively, H is a bandwidth matrix which is symmetric, positive definite and $K_H(u) = |H|^{-1} K\left(H^{-1}u\right)$. We choose a multivariate product kernel so that $K(u) = \prod_{j=1}^{d} K_j(u_j)$ in which case

$$\int uu'K(u)du = \left(\int u_1^2 K_1(u_1) du_1\right) I_d.$$

The local linear estimator is $\hat{\theta}(x) = \hat{\theta}_o(x)$ where $\hat{\theta}_o(x)$ and $\hat{\Theta}_1(x)$ maximize the log-likelihood $L(\theta_o, \Theta_1)$ with respect to θ_o, Θ_1. Computational details are in *Kumbhakar et al.* (2007), (Sections 3.1 and 3.2) and we follow this paper closely.

For the model with latent productivity ω_{it} as in (33) the likelihood function is

$$L(\theta_o, \Theta_1) = \int_{\sim^{nT}} \left\{\prod_{i=1}^{n} \prod_{t=1}^{T} g\left(y_{it}, \omega_{it}, \theta_o + \Theta_1\left(\Lambda_{it} - \Lambda\right)\right) \cdot K_H\left(\Lambda_{it} - \Lambda\right)\right\} d\omega, \tag{35}$$

9 In fact, we include z_{it} in the kernel functions because, in this instance, they represent important environmental variables that help in modeling heterogeneity. For ease in notation we redefine x=[x', z']'.

where $\Lambda_{it} = \left[x'_{it}, \omega_{i,t-1}\right]'$, $\Lambda = \left[x', \omega_{-1}\right]'$, and

$$g\left(y,\omega;\theta(\Lambda)\right) = \frac{2}{\sigma(x)}\varphi\left(\frac{y_{it}-\varphi(x_{it};\beta(x))-\omega_{it}}{\sigma(x)}\right)\Phi\left(-\frac{\lambda(x)}{\sigma_v(x)}(y-\varphi(x_{it};\beta(x)))-\omega_{it}\right) \cdot \frac{1}{\sigma_\omega(x,\omega_{-1})}\varphi\left(\frac{\omega_{it}-r(x_{it},\omega_{i,t-1};\gamma(x,\omega_{-1}))}{\sigma_\omega(x,\omega_{-1})}\right). \tag{36}$$

Moreover, $\gamma\left(x,\omega_{-1}\right)$ denotes the localized parameters in the $r(\cdot)$ function in (33). For ease in notation we define $\theta\left(x,\omega_{-1}\right) = \left[\beta\left(x\right)', \gamma\left(x,\omega_{-1}\right)'\right]' \in \sim^{k}$.

In (35) there is an $nT-$dimensional integral which we cannot evaluate analytically, which is obvious from the definition of (36). The computation relies in two steps.

- Step 1: Integrate out $\{\omega_{it}\}$ from (14) using a Sequential Monte Carlo algorithm (*Pitt and Shephard*, 1997).
- Step 2: Maximize the resulting expression using numerical optimization techniques.

For reasons of computational convenience and without sacrificing generality we assume

$$\omega_{it} = \rho\omega_{i,t-1} + \xi_{it},\ \ \{\xi_{it}\} \sim i.i.d.\ N(0,\sigma_\xi^2). \tag{37}$$

We will still need the SMC algorithm in Step 1. For the Sequential Monte Carlo algorithm we use 10^6 particles per likelihood evaluation and a standard conjugate gradients algorithm for maximization. Our results were insensitive to using 10^5 or 10^7 particles per likelihood evaluation.

3.3.2 Empirical Results

In this section we perform a simple nonparametric estimation of the production function per sector in each country, Ethiopia and Kenya, based on the econometric model described in Subsection 3.3.1. Our dataset includes 16 observations for each sector of these countries from 2000 to 2015. This methodology takes into account the regional differences in productivity between the upstream and downstream countries, which is a necessary categorization of these countries due to the formulation of the water resources management problem investigated in Section 1.2.

Data preparation is a critical first step for building high performance predictive models. At first, we convert all the monetary variables to constant 2010 prices, since the prices we had available for each year of our period could not be used for comparisons thanks to inflation effects. Additionally, we perform all the necessary transformations of the variables to end up either with the same units of measurement or with suitably scaled data, so as to standardize predictions subject to the units of the regression coefficients.

The results of the nonparametric estimation are reported in

Table 11 and Table 12. Input and output variables were transformed to their corresponding log values and were normalized by their respective sample means. From the estimated production function for each of the two countries we can easily obtain their corresponding marginal product function, which is connected with the water use input variable via the relationship:

$$\text{Marginal product} = \alpha + \beta \cdot \text{water use} \tag{38}$$

Both coefficients for each country turn out to have the expected signs. As explained at section 2.2, inverse demand function is given by relationship (7) and it is expected to be equal to the marginal contribution of the water to the output of each sector given by equation (38). Consequently, the derived demand curve for water of the producer is represented at equation (61) showing producer's demand for an input, i.e. the water, as a result of the demand for another related good, i.e. energy.

$$\text{Water use} = a + b \cdot \text{price} \quad (39)$$

where a is the intercept of water demand of each sector and b the price elasticity of water demand.

In order to calculate the price elasticities, we used the formula (40). In alignment with Figure 9, it is noticed that all sectors are exceptionally inelastic to a price change for water use, i.e. relatively large changes in price cause very small changes in demanded quantity of water. In particular, Agriculture seems to be perfectly inelastic to any price change, which means that in both countries the demanded quantity will remain stable for any price change and so the price cannot influence the water use. This implies an extremely strong relationship between the input, in this case water, and the corresponding output of each sector such as the seed-producing crops, since the producer lacks alternatives and so values highly the use of water. The elasticities for both countries are presented in Table 13.

$$\text{price elasticity} = \frac{d(\text{water use})}{d(\text{price})} \cdot \frac{\text{price}}{\text{water use}} \quad (40)$$

Table 11 - Empirical results: β parameter for each Sector

	Mining	Energy	Tourism	Residential	Agriculture
Ethiopia	-0.0010	-0.0014	-0.0012	-0.0013	-0.0000321
Kenya	-0.0011	-0.0013	-0.0010	-0.0015	-0.0000319

Table 12 - Empirical results: α parameter for each Sector

	Mining	Energy	Tourism	Residential	Agriculture
Ethiopia	1.80	1.73	1.48	1.65	1.48
Kenya	1.54	1.70	1.56	1.77	1.56

Table 13 - Price elasticity for each Sector

	Mining	Energy	Tourism	Residential	Agriculture
Ethiopia	-0.099	-0.131	-0.096	-0.116	-0.003
Kenya	-0.092	-0.120	-0.085	-0.143	-0.003

Finally, the different demand curves, coming from equation (39) for all 5 sectors of the OTB riparian countries, provide us with an ordering of these sectors via their demand function intercepts. Sequential exits from the market are defined by the relative importance of sector-specific demand parameter ratio a, with $a = \alpha/\beta$. As water demand for each of these economic sectors reaches zero sequentially, its price increases revealing so producers' preferences for water use. At these prices, in Ethiopia Tourism sector should exit the market first followed by the Residential and the Energy sector, while in Kenya Mining sector would exit the market first trailed by the Tourism sector. However, in both cases, in case of river/lake depletion, agriculture sector should be the last one to exit the market, since it is valuing water use more than any other sector.

Figure 9 illustrates the demand derived for water of each sector in each country. In both cases, the agriculture sector is almost inelastic in water use declaring so, an intense connection between water use and crops, which is caused by the existence of large irrigation schemes in the basin. Moreover, producers in mining sector in Kenya values higher the water than in Ethiopia, and that happens because Kenya relies strongly on groundwater for mining production.

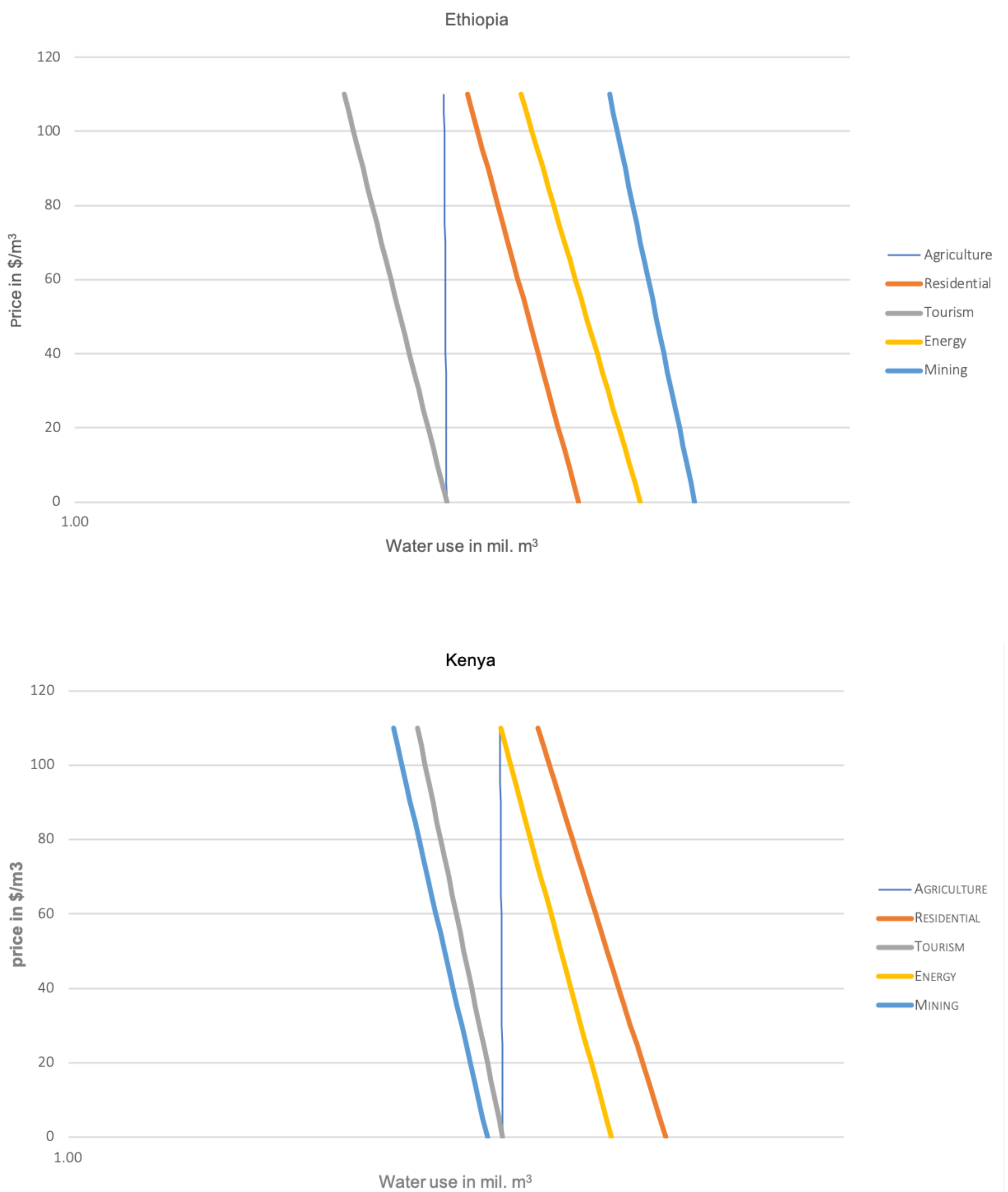

Figure 9 - Curves of the demand function of All Sectors for the Upstream and Downstream Country

As presented at Figure 10, sampling distributions of water elasticities tend to not vary significantly. In particular, only the distribution for the residential sector in Ethiopia (left) is shown to look normally distributed, while the others while the others slightly diverge from the normal distribution at their tails. None of these means is the mode of the distribution as well, although the chasm between those values is not notable. In economic terms, the elasticities for water demand in each sector do not deviate remarkably, letting so similar behavioural patterns to be observed in each sector across the two countries of interest.

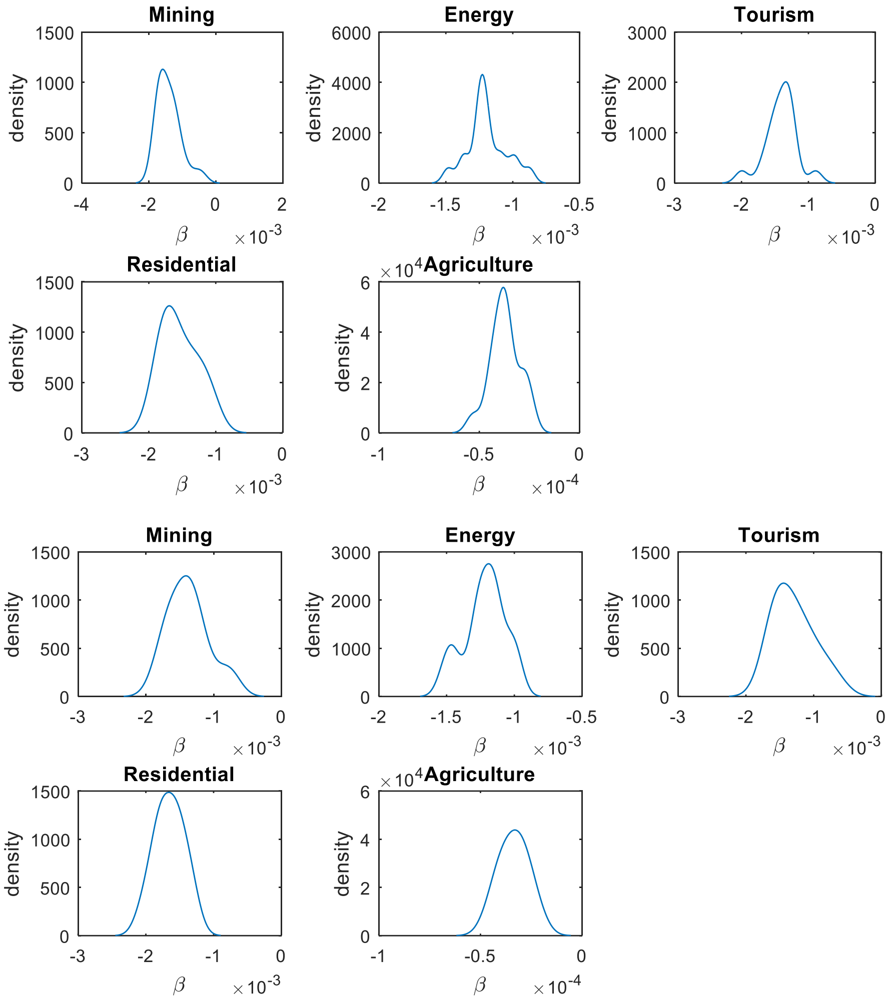

Figure 10 - Sampling distributions of water elasticities by sector for Ethiopia (upper panel) and Kenya (lower panel)

The second parameter of the inverse demand curve is the constant term, which is responsible for the starting point of the demand curve, revealing so the willingness to pay (WTP) of the stakeholders in each sector. Figure 11 shows the distributions of constant terms of the inverse demand functions and interestingly we can see that in most cases the WTP for water use in energy sector is greater than the corresponding one in agriculture and tourism, which implies greater profitability in energy sector. Additionally, in terms of WTP, mining sector in Ethiopia, which follows a leptokurtic distribution seems to be the most stable one.

Figure 12 presents technical inefficiency parameter by sector for the two countries of interest. A zestful outcome is the fact that Mining and Residential sectors in Ethiopia follow exactly the same distribution with a positive skew to the right. In Energy and Tourism sector in both countries, u_{it} has two district peaks (bimodal distribution), which indicates that in these sectors there are two groups of producers, some of them achieve to maximize their outputs given their inputs, while some others do not with technical inefficiency taking greater values than the former group. However, it is noteworthy that Energy sector is more technical efficient in comparison with Tourism, since the lowest peak of Tourism is as great at the biggest one of Energy sector

Another important indicator is the technical change by sector as presented in Figure 13. Residential, Agriculture, Energy and Tourism in Ethiopia. distributions resemble Normal distribution, while Mining sector's distribution has two peaks. However, in Kenya the peak of most distributions is in zero declaring so, that the majority of sectors remains stable without being engaged to innovative changes.

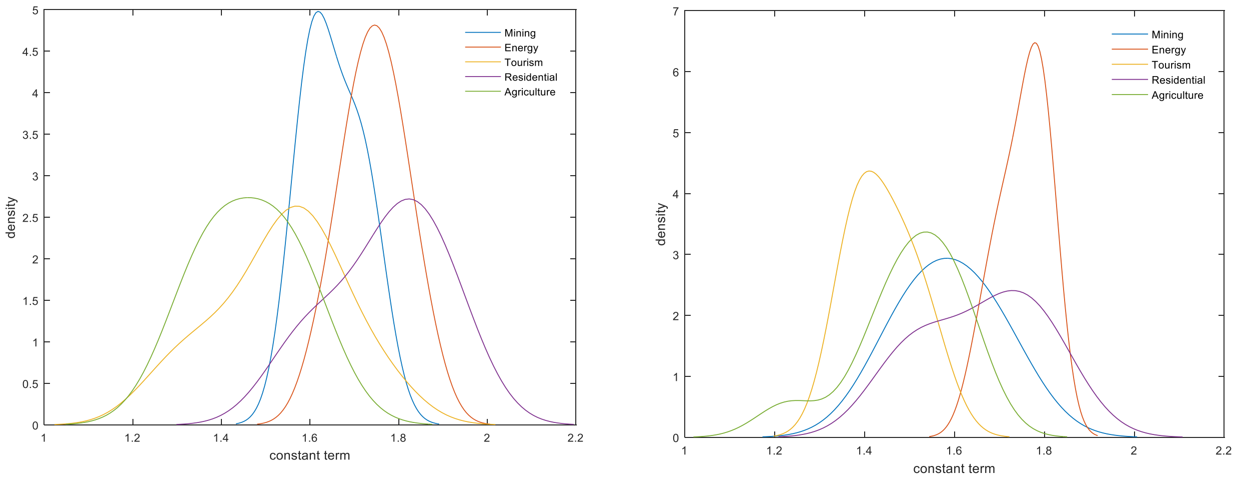

Figure 11 - Sampling distributions of constant terms by sector for Ethiopia (left) and Kenya (right)

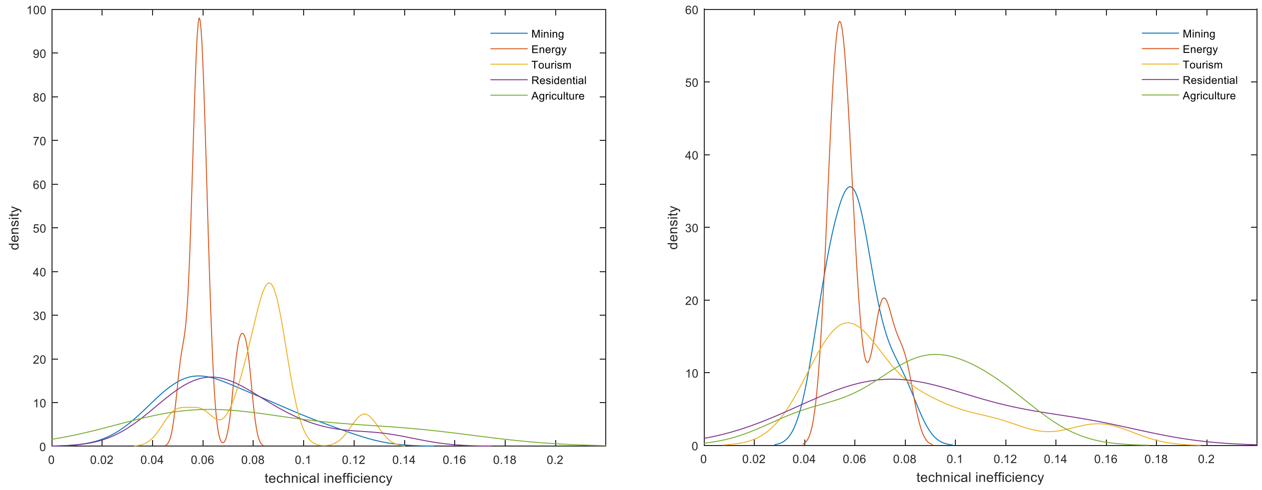

Figure 12- Sampling distributions of technical inefficiency by sector for Ethiopia (left) and Kenya (right)

Figure 14 presents productivity growth by sector with more particular case the multimodal distribution of the Residential sector in Ethiopia. In this case, there are three district peaks, with zero growth rate. Agriculture sector in Ethiopia also formulates two peaks, with the most common having zero mean as well revealing so lack in developing new technologies and making so production more efficient. Additionally, the Tourism sector of Kenya also formulates two peaks, with the most common one lying in the positive side, which underlines the development advantage of the Tourism sector in comparison with the other sectors in both countries.

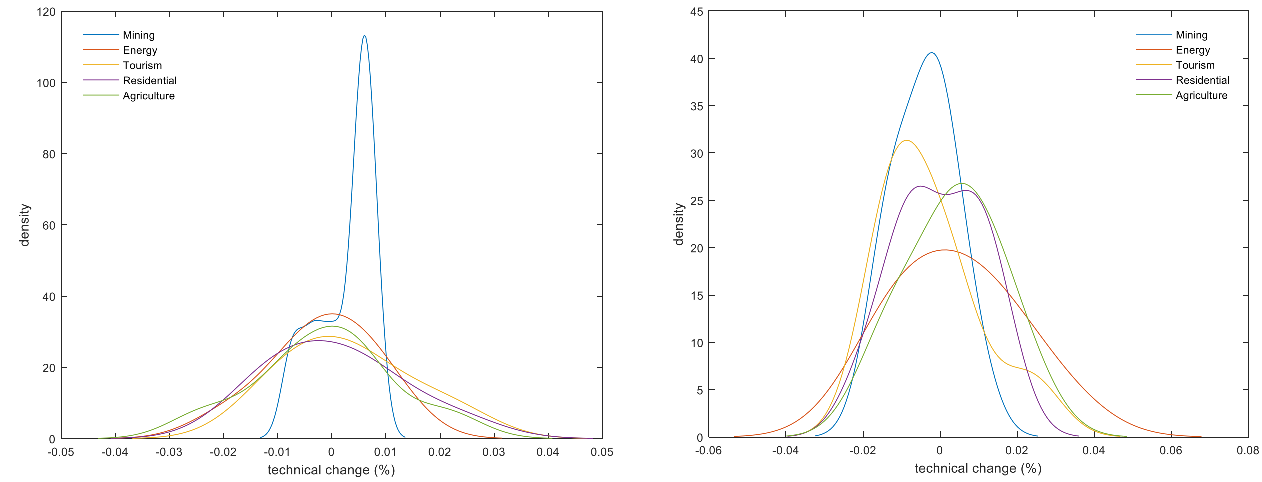

Figure 13 - Sampling distributions of technical change by sector for Ethiopia (left) and Kenya (right)

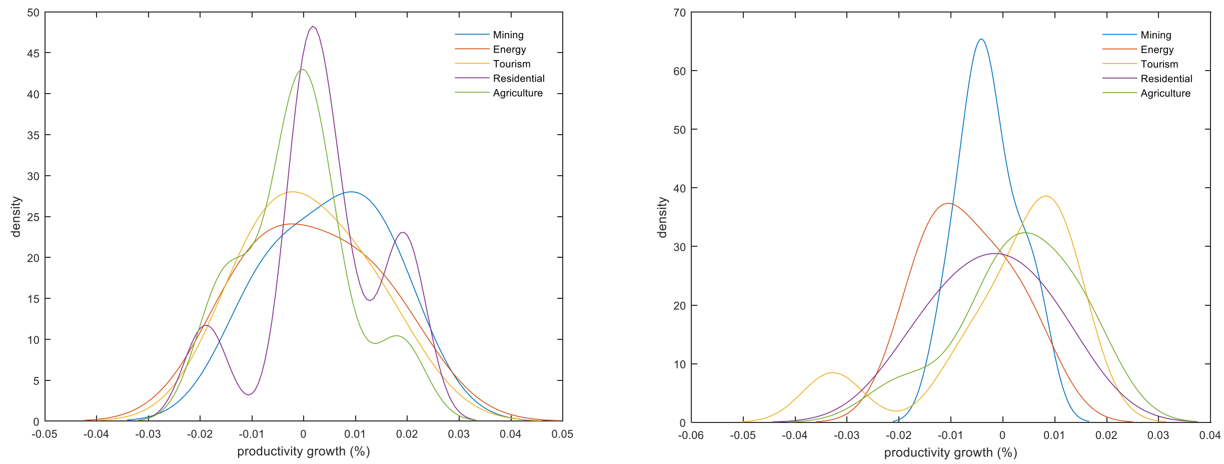

Figure 14 - Sampling distributions of productivity growth (%) by sector for Ethiopia (left) and Kenya (right)

3.4 EMPIRICAL ILLUSTRATION

In collaboration with ETH-Zurich, leading WP3, we were provided with annual data on the total precipitation volume over the upstream Omo area, as the annual renewable water resources of (2), on the runoff of the Omo River to Lake Turkana as in (4), and on the total evaporation from Lake Turkana, as the outflow from the downstream water reserves in (6). From these data we estimated their corresponding historical volatilities, while we were also given with the annual storativity of the lake whose dynamics where described by (5). Additionally, the pumping costs for the upstream and downstream areas are estimated through Figure 2 and Figure 3, which display representative water tariffs in Ethiopia and Kenya, respectively. Simulations were carried out in Matlab R2018b to perform the essential computations required in applying the stochastic optimization method described in Section 2 for both the cooperative and the non-cooperative case. Table 14 contains all the parameters of the model and Appendix 1 provides additional details of the data sources and the individual econometric estimates of water demand for all sectors. Five percent is the real interest rate used initially.

In contrast to the river basin level data we were provided by ETH to simulate numerically the water resource dynamics of the OTB, according to the economic model developed in Section 2, the inverse demand functions per sector for both countries of the OTB were estimated via national level data; limitations concerning data collection are discussed in Subsection 1.1. Due to matters of scale consistency, we downscale our simulation results on both the optimal water abstraction path and the resulting net benefit of each country to the river basin level via the percentage of the water availability inside the river basin over the total water availability of each of the two countries. We approximate the total water availability by the total renewable water resources (*FAO*, 2018a) and the water availability inside the river basin of each of the two countries by their internal runoff within the basin (*FAO*, 2018b). Total renewable water resources may be considered as the sum of internal and external renewable water resources and correspond to the maximum theoretical yearly amount of water available for a country at a given moment. According to this approximation, the percentage of the total water availability to the water availability in the OTB is 0.1475 (=18 km^3 /122 km^3) and 0.325 (=10 km^3/ 30.7 km^3) for Ethiopia and Kenya, respectively.

Table 14 - Parameters of the Economic Model

Symbol	Description	Parameter Value
B^u	Vector of the absolute values of the slope of the water demand for i sector in the upstream area.	[833.33; 31,152.65; 769.23; 714.29; 1,000] Mm^3/$
A^u	Vector of the intercepts of the water demand for i sector in the upstream area.	[1,233.33; 46,105.92; 1,269.23; 1,235.71; 1,800] Mm^3/$
B^d	Vector of the absolute values of the slope of the water demand for i sector in the downstream area.	[909.09; 1,000; 31,347.96; 769.23; 666.67] Mm^3/$
A^d	Vector of the intercepts of the water demand for i sector in the downstream area.	[1,400; 1,560; 48,902.82; 1,307.69; 1,180] Mm^3/$
k_1^U	Cost of pumping in the upstream area 1Mm^3 of water per Mm^3 of volume of the river	0.066 $/$m^3$
k_2^U	The intercept of the pumping cost equation for the upstream area	0.33 $/$m^3$
k_1^D	Cost of pumping in the downstream area 1Mm^3 of water per Mm^3 of volume of the lake	0.61 $/$m^3$
k_2^D	The intercept of the pumping cost equation for the downstream area	2.03 $/$m^3$
s_0	Initial storativity of the lake	292,500 Mm^3
R_O	Initial recharge rate	16,666.155 Mm^3
O_0	Initial outflow rate	22,788.644 Mm^3
w_0	Initial precipitation	$6.8308 \cdot 10^5$ Mm^3
wr_0	Initial renewable water resources	$4.43 \cdot 10^7 Mm^3$
σ_R	Volatility of runoff	0.431
σ_O	Volatility of outflow	0.025
σ_W	Volatility of precipitation	0.089

A numerical simulation of the non-cooperative case for both upstream (Ethiopia) and downstream (Kenya) areas, as illustrated in Subsection 2.2.1, is presented in Table 15. By non-cooperative is described the situation where each country does not have any kind of trade or other relationship with the other one and so, it maximises only its own Net Benefit function, where Total Cost is being deducted from Social benefit function. In alignment with Stackelberg model, the upstream country, which is also the leader of the sequential game ends up with a greater social benefit than the corresponding benefit of the follower country by more than one hundred times. Ethiopia is meant to be the leader of the Stackelberg game due to its advantage of lying norther than Kenya and so having access to the water deriving from the river before Kenya. In other words, if Ethiopia exhausts the river, Kenya's source of water, lake Turkana, will be affected significantly due to the limited available quantity of fresh water.

Both players have two available strategies, myopic and non-myopic, with myopic declaring the case, where the country of interest does not consider the benefits coming from the natural resource, i.e. from the river for the upstream country and from the lake for the downstream country. The optimal scenario is in (Non-myopic, Non-Myopic) combination, where the lake runs out of water after 33 years, while the worst-case scenario in environmental terms is realised when both of the countries follow a myopic strategy, where the lake is being depleted in only 15 years and it can be realised in case of lack of trust, lack of institutions bridging the limited disposable information in the countries or even due to limited technical support.

In the case of non-cooperation*, myopic strategy* dominates strictly non-*myopic strategy* in both countries resulting in only one Nash equilibrium (NE), which is also the sub-game prefect Nash equilibrium with an estimated value of the average net benefit of $\$1.5191 \cdot 10^9$ for the upstream country and $\$2.8429 \cdot 10^7$ for the downstream one, where the lake depletion time (LDT) is 15.49 years (see Table 15). At this point it should be reminded that the Net Benefit values represent the average value of the economy as long as there is water to be extracted. Ethiopia's benefit curves are the average of a 200-year period, where there is no sector exit, while Kenya's benefit curves are the average of 15- to 33-year period, until the point, where first all sectors leave, and the lake depletes. Hence, in (myopic, myopic) combination, the 16th year in Kenya is characterized by zero Social Benefit and costs, while all the demand for goods and services is met by imports.

The rationale behind this outcome is that the downstream country (Kenya) although on average it seems to gain more following the myopic path, in total the losses surpass the gains, as for fifteen more years it could have an average net benefit equal to $\$2.2543 \cdot 10^7$, while from the myopic perspective it is zero. In other words, if Kenya controls its water use over time following a non-myopic path, it can increase its total benefits from $743,919,000 to $1,321,810,000 no matter what Ethiopia decides, while in the myopic equilibrium it gains only $342,435,000. At the same time, the upstream country (Ethiopia) overconsumes water, when it cannot see the river basin, while in the opposing case, it makes a moderate use of water, which returns slightly less benefits than the previous case. However, Ethiopia's negative externalities to Kenya in the event of both following the myopic strategy can be seen at the depletion time of the lake, which evacuates in half of the time it would be in the non-myopic situation.

Table 15 – Non-Cooperative Approach

Downstream	**Upstream**	
	Myopic	Non-Myopic
Myopic	$NB_u = \$1.5191 \cdot 10^9$ $NB_d = \$2.8429 \cdot 10^7$ $LDT = 15.49$ years	$NB_u = \$1.4635 \cdot 10^9$ $NB_d = \$5.747 \cdot 10^7$ $LDT = 23.62$ years
Non-Myopic	$NB_u = \$1.5188 \cdot 10^9$ $NB_d = \$1.5141 \cdot 10^7$ $LDT = 22.85$ years	$NB_u = \$1.4637 \cdot 10^9$ $NB_d = \$2.2543 \cdot 10^7$ $LDT = 33.35$ years

Figure 15 illustrates the average water use for all five sectors for the upstream country, Ethiopia, in the two extreme scenarios. In particular, it considers the case (Myopic, Myopic), where both countries exhibit a myopic behaviour and the case (Non-Myopic, Non-Myopic), where both countries exhibit a non-myopic behaviour. One can notice that in the myopic case, the upstream country uses water extensively, which leads to overexploitation of the water resources. This means that the water use in the first case is higher than the non-myopic one, since the actors in the non-myopic path take into account the externalities of their decisions on both water balance and their individual benefit.

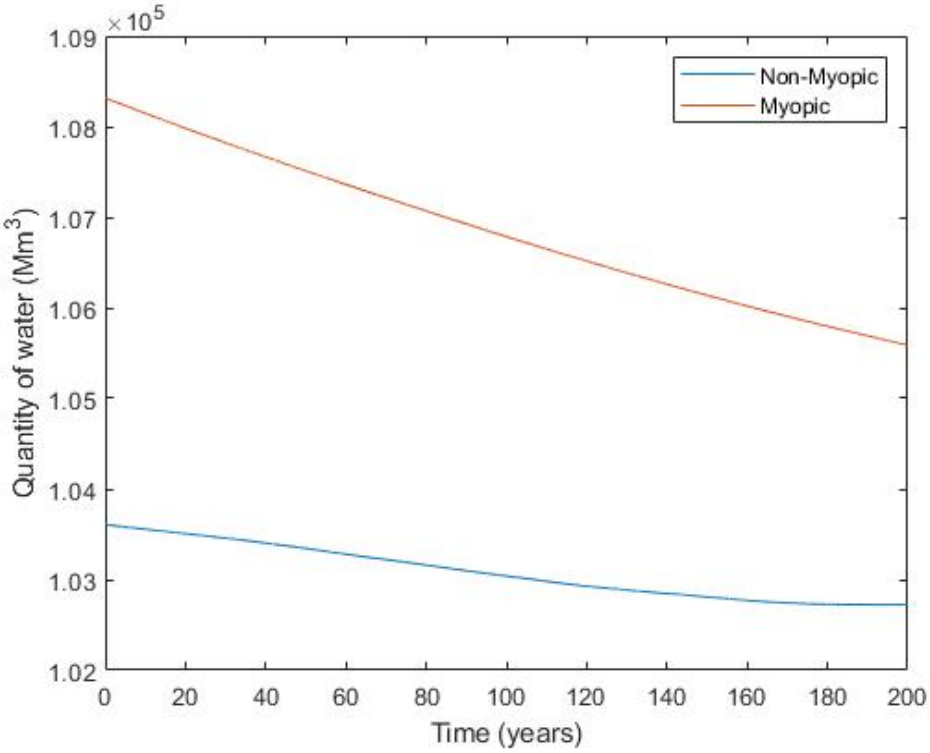

Figure 15 – Noncooperative Case: Water Use average in Ethiopia in myopic and optimal case

Similar results are illustrated in Figure 16 for the downstream country, Kenya, in the myopic and the non-myopic cases, where again in each case both countries exhibit the same behavior. It is worth to mention that as regards the downstream country, the water use becomes zero after a period of time due to the lake exhaustion at 15.5 years in the myopic case and at 33.4 years in the non- myopic case (cf. Table 15). Nevertheless, for the upstream area our time horizon is 200 years since we do not have a limitation for the water reserves of the Omo river. In the first case, Kenya exploits more than the desired water use in the first few years, impacting so its future consumption, which is constantly lower than the one in the non-myopic case and also ends up 15 years earlier than in the myopic case.

On the other hand, a numerical simulation of the cooperative case for both upstream (Ethiopia) and downstream (Kenya) areas for different n_1 values, as illustrated in Subsection 2.2.2, is presented in Table 16. As cooperative is described the situation where each country considers the possible benefits coming from good exchange between the two countries and intends to make an agreement. Consequently, net benefits increase for both countries, due to the comparative advantage of each nation in production. As Ricardo showed 200 years ago, even if country A, i.e. Ethiopia, can produce all goods and services more cheaply than country B, i.e. Kenya, both nations can still trade under conditions where both get benefited. Under this theory, the most crucial concept is relative efficiency.

According to the 2016 power sharing agreement for the Kenya-Ethiopia Electricity Highway Project (c.f. Section 2.2), Ethiopia offers a discounted price for hydropower to Kenya, whose benefit is captured by the variable $hydro = 4000$ in our model. Firstly, in all three occasions of n_1, the lake does not seem to deplete after a certain number of periods, which is a very promising outcome for both countries, since they trade goods and so Ethiopia is interested in the sustainable of development of its neighbour. Granted that $n_2 = 10000$, when n_1 is taking modest values ($n_1 = 0.7$), which implies a temperate valuation of the upstream country for the stock benefits coming from the lake of the downstream country, the average estimated present value of net benefits is $\$24.075 \cdot 10^9$ for the upstream country and $\$3.8182 \cdot 10^7$ for the downstream one. However, in the event of an increase in n_2 by 0.2, the preferences of Ethiopia change to a degree that the average estimated present value of net benefits is $\$39.74 \cdot 10^9$ for Ethiopia and $\$4.0388 \cdot 10^7$ for Kenya.

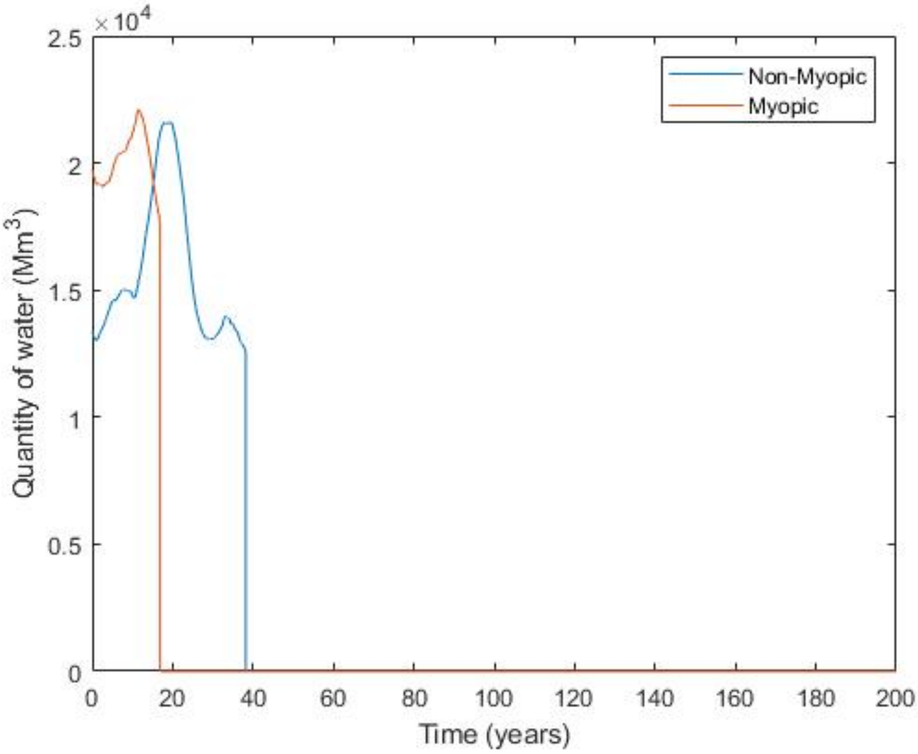

Figure 16-Noncooperative Case: Water use average in Kenya in myopic and optimal case

Table 16 – Cooperative Approach

Cooperative Case: Optimal ($n_1 = 0.7$)	**Cooperative Case: Optimal** ($n_1 = 0.8$)	**Cooperative Case: Optimal** ($n_1 = 0.9$)
$NB_u = \$24.075 \cdot 10^9$ $NB_d = \$3.8182 \cdot 10^7$ $LDT =$ Never	$NB_u = \$30.992 \cdot 10^9$ $NB_d = \$4.0333 \cdot 10^7$ $LDT =$ Never	$NB_u = \$39.74 \cdot 10^9$ $NB_d = \$4.0388 \cdot 10^7$ $LDT =$ Never

Apparently, for all possible outcomes given the preferences of Ethiopia, the net benefits are outstandingly greater in the cooperative case than in the former one. Figure 17 and Figure 18 embody the cooperative and non-cooperative case for the two countries separately, with non-cooperative case considering the non-myopic approach only and cooperative case reflecting the least possible rate of n_1. Here, the upstream country becomes aware of the upcoming benefits coming from giving up a considerable amount of water in exchange of food supply produced by the downstream country (see Figure 17). In response to that action, the downstream country increases significantly its water use over the years, increasing so its producing capacity. However, the total water consumption of both countries in the cooperative case is less than the one of the non-cooperative case, with the Kenya's maximum water consumption in 20th year being seven times less than Ethiopia's maximum water consumption.

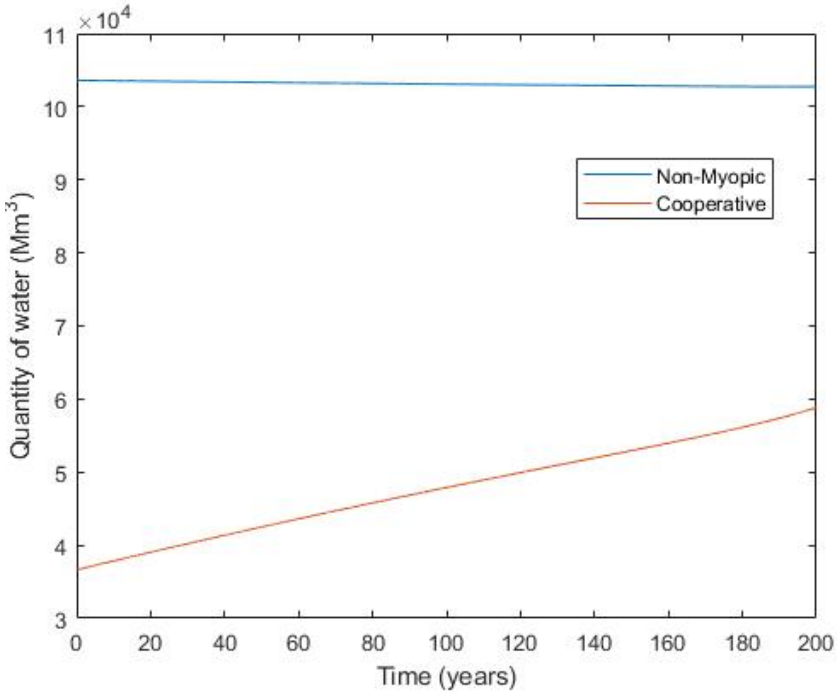

Figure 17 – Water average use in Ethiopia for $n_1 = 0.7$

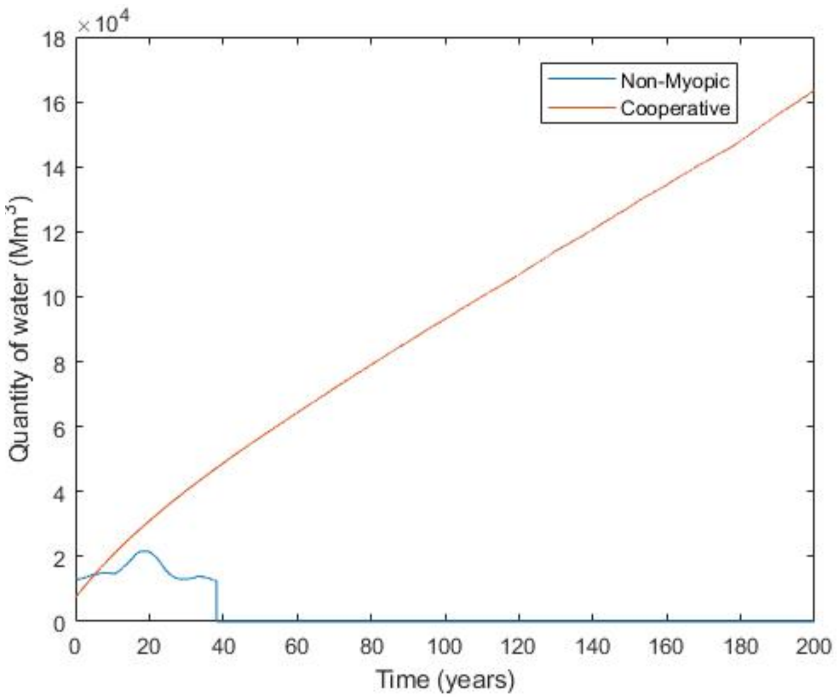

Figure 18 - Water average use in Kenya for $n_1 = 0.7$.

To sum up, clearly the optimal solution of the cooperative case is indisputably more preferable than any of the non-cooperative ones, since it produces a higher net benefit for each country and does not lead the lake to depletion, thus providing sustainable development in the area. In fact, as the upstream country enjoys food benefits from the downstream one, we see from Figure 17 that in comparison with the non-myopic non-cooperative case it diverts more water to the downstream one, which in turn increases its water abstraction as seen in Figure 18. This phenomenon enhances as n_1 increases (Table 16).

Moreover, it would be interesting to examine the consequences of climate change to the two riparian countries. Table 17 shows the impact of altering the volatility of different variables, which affect the stock of water in the downstream country and also the net benefit curve of the upstream country in the cooperative case. In the SET range are identified the exit stages of all the sectors, which occur before the lake depletion (non-cooperative case).

Table 17 - Climate change impact on non-cooperative and cooperative case

Climate Change	**Non-Cooperative Case**	**Cooperative Case** $(n_1 = 0.7)$
Increase of outflow $\sigma_O = 0.3$	$NB_u = \$1.639 \cdot 10^9$ $NB_d = \$2.6384 \cdot 10^7$ $LDT = 33.27$	$NB_u = \$24.269 \cdot 10^9$ $NB_d = \$3.8216 \cdot 10^7$ $LDT =$ Never
Increase of precipitation $\sigma_W = 0.3$	$NB_u = \$1.7031 \cdot 10^9$ $NB_d = \$1.3903 \cdot 10^7$ $LDT = 18.94$	$NB_u = \$4.4280 \cdot 10^9$ $NB_d = \$2.8968 \cdot 10^7$ $LDT = 99.57$
Decrease of runoff $\sigma_R = 0.3$	$NB_u = \$1.6390 \cdot 10^9$ $NB_d = \$2.5545 \cdot 10^7$ $LDT = 31.60$	$NB_u = \$\ 24.091 \cdot 10^9$ $NB_d = \$\ 3.4510 \cdot 10^7$ $LDT =$ Never

Firstly, an increase in the volatility of outflow or evaporation of the water from the lake would be expected to impact significantly the downstream country, since the levels of water in the lake are expected to vary further, increasing so the chances of droughts. However, in this case, the difference between the net benefits of Kenya in non-cooperative and cooperative case is not considerable. Figure 19 shows the impact on the quantity of water consumed by Kenya in the non-myopic case of non-cooperation. Apparently, Kenya tries to moderate its water consumption due to the increased outflow volatility in order to not run out of water considering that Ethiopia does not take into account Kenya's water needs and keeps on consuming as much water as it needs.

As expected, in the cooperative case (Figure 20), Kenya does not change its behaviour, as there is no risk of drought due to the assistance provided by the upstream country to water access.
In addition, an increase in the precipitation levels, i.e. the volatility of rain increasing the waters of the river, would impact the two countries differently. Ethiopia's reaction depends on the cooperation status with its neighbour country. In fact, when it does not trade, it seems to gain higher benefits due to precipitation volatility (see Table 17). When the level of the waters rises, it consumes more, while when it decreases, Ethiopia keeps on consuming as much water as it needs limiting so, the water runoff to Kenya. As presented in Figure 21 over time, the water consumption of Ethiopia tends to zero, which verifies the short-term planning of the country. Kenya is also being affected significantly by that change, reducing so its water consumption significantly because of the inconsiderable consumption of the upper country.

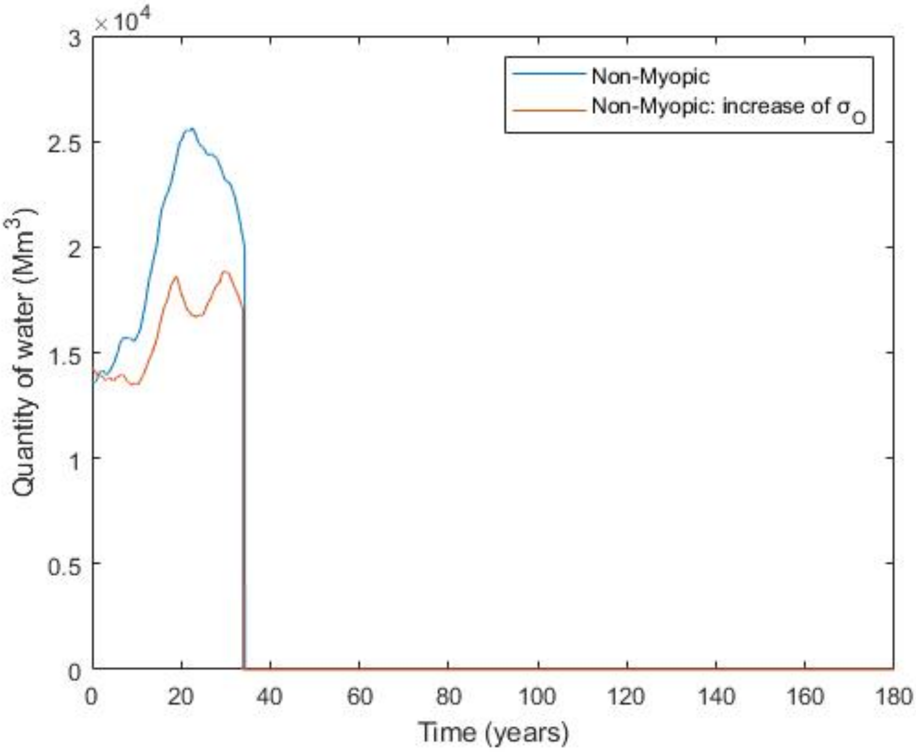

Figure 19 – Non-Myopic Case: Water Use average in Kenya with $\sigma_O = 0.025$ and $\sigma_O = 0.3$

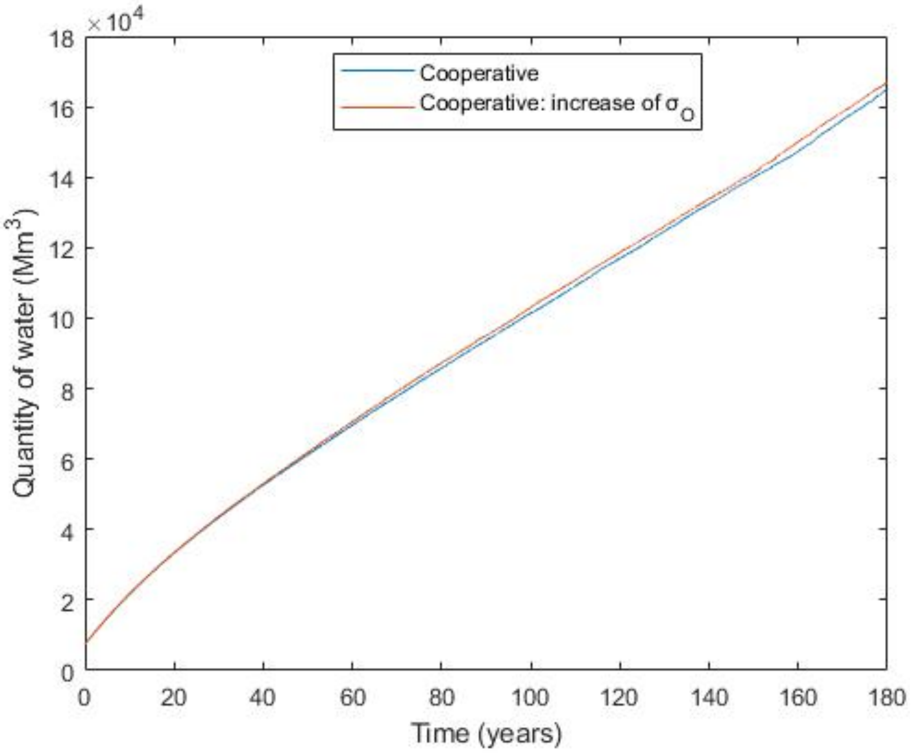

Figure 20 - Cooperative Case: Water Use average in Kenya with $\sigma_O = 0.025$ and $\sigma_O = 0.3$

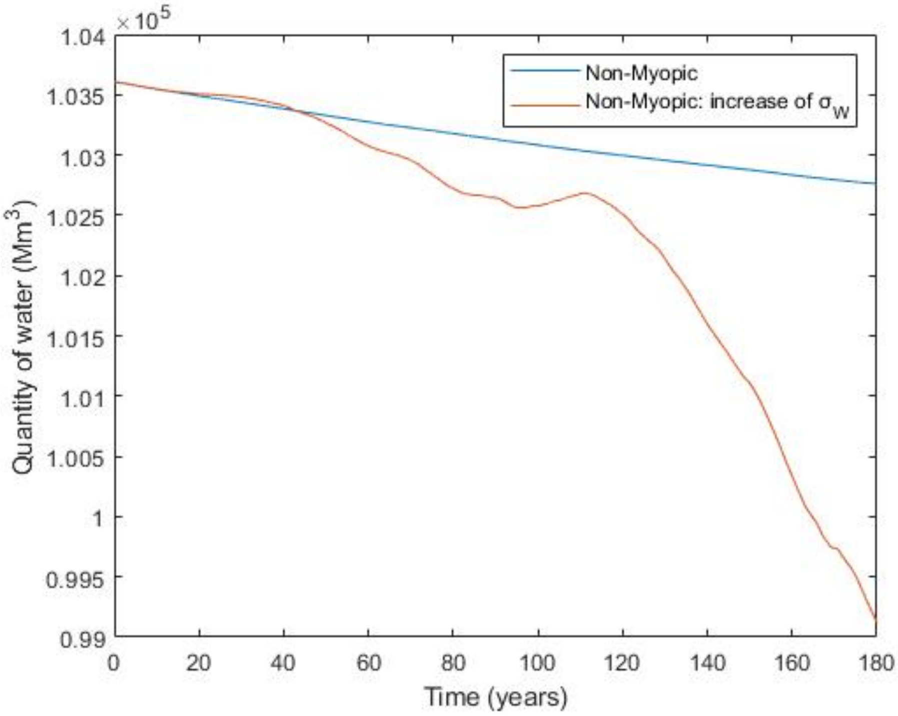

Figure 21 - Non-Myopic Case: Water Use average in Ethiopia with $\sigma_W = 0.089$ and $\sigma_W = 0.3$

However, Ethiopia's behaviour in cooperative case is reversed to the one described above. As illustrated in Figure 22, it follows almost the same path with lower precipitation volatility enabling so, commercial activities with the downstream area. Although the benefits in this case for Ethiopia have fallen significantly, they are still higher their corresponding values in the non-cooperation scenario. The same result occurs for Kenya as well. That difference would be enough to motivate both riparian countries to keep on trading even in extreme climate circumstances.

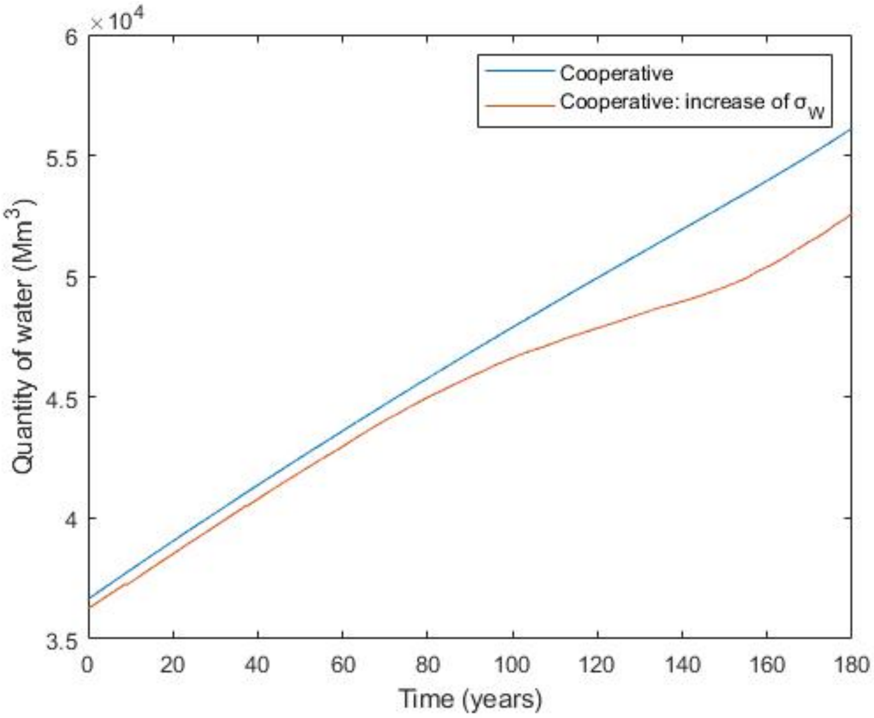

Figure 22 - Cooperative Case: Water Use average in Ethiopia with $\sigma_W = 0.089$ and $\sigma_W = 0.3$

Lastly, we examine the impacts of a decrease in the volatility of runoff, i.e. the water deriving from the river to the lake. Runoff is extremely important, as it does not only keep rivers and lakes full of water, but it also alters the landscape by the action of erosion. However, although runoff decreased by 0.3, which is a noticeable change, not any significant change is being noticed at the net benefit curves and the water consumption over time for both countries in all cases. In other words, in the cooperative case, there is not noticed any change in water consumption for both countries, which implies that when the runoff is low, Ethiopia and Kenya keep on using the same quantity of water due to forward integrated planning. However, in the non-cooperative case, Kenya reduces slightly its water use (see Figure 23) increasing so its average net benefits by $2,002,000, which is not so important if we consider that the lake depletes two years earlier.

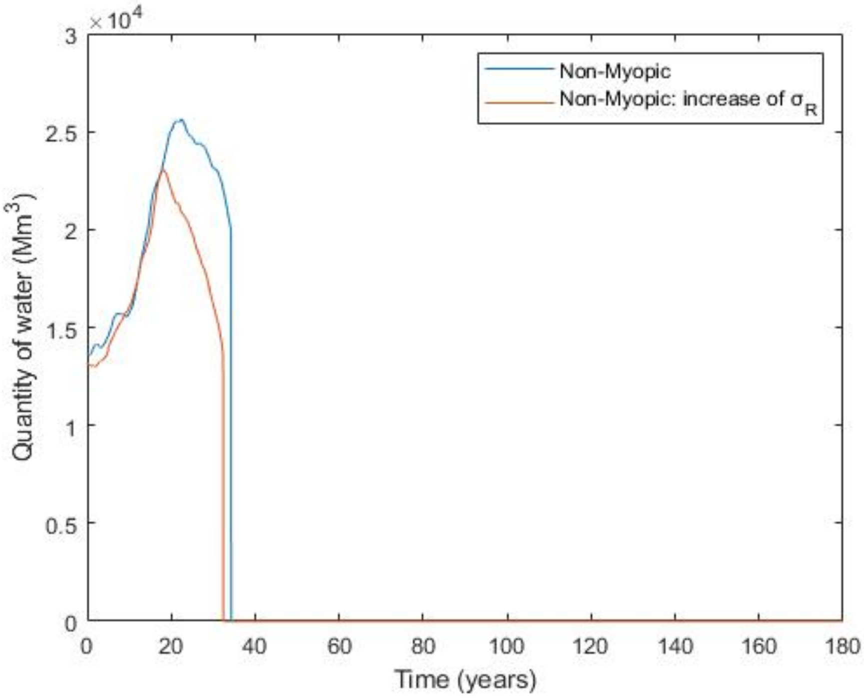

Figure 23 - Non-Myopic Case: Water Use average in Kenya with $\sigma_R = 0.431$ and $\sigma_R = 0.1$

To sum up, in this section we analyzed the net benefits of the two riparian countries under two different cases, cooperation and non-cooperation. Also, we tested the impact of different parameters associated with Climate change on our results by changing their values. The analysis showed that under any circumstances, the cooperative case is undoubtedly the most profitable one for both countries, which can incentivize them towards the liberation of the economy, as the market can lead to the optimal solutions. The existence of an international water sharing agreement could facilitate that opening and also reassure the positive collaboration between the countries. However, if no change occurs myopic and non-cooperative situations may realize, since the Government is the most dominant actor in these countries making so trade subject to Governmental decisions and not to the upcoming benefits of the free market.

Another outcome of our analysis is the dependence of the development of the economy to the water resources. As illustrated in the derived demand curves from the econometric model, all sectors are inelastic to a price change for water, with agriculture sector being the most dependent one to water. In Kenya, where the only resource of water is the Turkana lake, which is subject to the runoff coming from the Omo river, mining sector is also dependent intensively to the water and so it values higher the same quantity of water than the mining sector in Ethiopia, where there are also two dams, creating a reservoir and being used when needed. Moreover, the diagrams on the efficiency change and the productivity growth point out Ethiopia, as the fastest growing economy, which could be associated with its advantage on water resources.

4. CONCLUDING REMARKS

4.1 SUMMARY OF RESULTS

The main focus of Section 2 was to present the development of two different models of an economy that have access to the same natural resource, in this case a river basin, and explore whether they can perform sustainable transboundary water sharing for each sector taking into account the uncertainty posed by climate change. The five sectors of interest for each economic model were: Agriculture and Fishing, Residential Water Supply, Mining and Quarrying, Energy including hydropower production, and Tourism. This water distribution problem was modelled by an upstream country that has the right to unilaterally divert water away from a downstream country, which though has access to water stock reserves that provide additional agricultural (food) benefits, not enjoyed by the upstream country. We initially studied the non-cooperative case, where each country allocates water with respect to maximizing its own expected welfare without the presence of an international water sharing agreement. Employing a stochastic Stackelberg differential game via appropriate net benefit functions, our aim next was to establish an inter-sectoral cooperative water allocation trade-off between the two countries, where the downstream country offers to the upstream one agricultural exports (food) at a discount price in exchange for greater transboundary water flow, and to make the comparison with the non-cooperative framework.

Our main goal in Section 3 was to develop and study, using econometrical estimation methods, production functions per sector for the upstream and downstream countries, which appear in the mathematical model of Section 2 as the social benefit functions. Additionally, we derived the relationships and produced the corresponding graphs of the derived demand curves which represent the relationship between the price of the intermediate good, water, and the quantity demanded for a given period of time, revealing exactly how many units of water will be purchased at various prices. It is well known that as the price of a good rises, buyers will choose to buy less of it, and as its price falls, they buy more. Therefore, based on this statement, as the price of the water increases over time due to decreasing water availability, water demand for each of these economic sectors reaches zero sequentially, ending up with an ordering via their demand function for the two riparian countries.

The main outcome of Sections 2 and 3 was the remarkable opportunity for trade between Ethiopia and Kenya, which will indisputably benefit both of them. There is a number of reasons why an open economy is more preferable than a closed one. Firstly, both riparian countries become better off due to comparative advantages of each country concentrating on a specific area of production, i.e. Ethiopia in Hydropower (Energy) and Kenya in Agriculture. Secondly, they make a more valuable use of the river basin with Ethiopia recognising the upcoming benefits of trading with Kenya and so, allowing the former one have access to augmented quantity of water deriving from the river. Lastly, this collaboration has a positive footprint on the ecosystem surrounding those countries, which is based on the Turkana lake, limiting so, the negative economic and social impacts of the marine habitat destruction. Last but not least, even in extreme Climate change circumstances, where the net benefits fluctuate, trade remains the most profitable option for both countries.

4.2 ADDITIONAL REMARKS

Of particular importance at this stage is giving due consideration to the potential means of future integration of the economic model with other models from the project's WPs 3 and 4; as well as how it may be incorporated into the work of WPs 2, 3, 4 and 5 in particular. The different subtasks of WP2 provide a list of evaluation indicators and candidate actions.

As part of the DAF model, T5.1 will perform

a) a screening (scoping) of the candidate actions according to qualitative/quantitative indications coming from social-governance-economic models

b) a selection of design indicators from the large list of evaluations indicators to be used as objective in the optimization of the pathways; the design indicators which represent all the water-energy-food components of the nexus according to the characteristics of the strategic model (which will be coupled with the optimization tools)

Still in the DAF model, T5.2 will take the candidate pathways produced by the screening of the actions and the selected WEF design indicators and will run an optimization with the strategic model using observed streamflow in "entry" sections and observed irrigation demands. The DAF model will produce in outputs the optimal pathways, i.e. combinations of infrastructural (e.g., construction of new dam) and operational (e.g. reservoir operating policy) actions with timing of implementation.

The optimal pathways will be simulated by the WEF integrated model, which will produce the value of some evaluation indicators directly as output of the simulation as well as some trajectories that will be then post-processed by the social-governance-economic models to compute the value of additional evaluation indicators (e.g. indicators not directly implemented in the WEF model, for example about social aspects of the simulated pathways).

All the evaluation indicators will finally be sent to the Negotiation Simulation Lab to be discussed with the Stakeholders.

5 REFERENCES

Ackerberg, D. A., Caves, K. and G. Frazer, (2015) Identification Properties of Recent Production Function Estimators, *Econometrica*, vol. 83, 2411-2451.

Al-Saidi, M., Schellenberg, T. and E. Roach, (2016) Water, energy and food nexus in Ethiopia - Nexus Country Profile, doi:10.13140/.2.2.35554.73923.

African Development Bank Group, (2017) Data Repository. Available at: http://africaclimate.opendataforafrica.org (Accessed: 21/12/2017).

Ambec, S. and L. Ehlers, (2008) Sharing a River among Satiable Agents, *Games Econ. Behav.*, vol. 64, 35–50.

Ambec, S. and Y. Sprumont, (2002) Water and Economic Growth, *Econ. Rec.*, vol. 80, 1–16.

Andrieu, C., Doucet, A. and R. Holenstein, (2010) Particle Markov chain Monte Carlo methods, *Journal of the Royal Statistical Society: Series B*, vol. 72, 269–342.

Ansink, E. and A. Ruijs, (2008) Climate Change and the Stability of Water Allocation Agreements, *Environ. Resource Econ.*, vol. 41, 133–287.

Arnold, D., (2013) Kenya, Ethiopia Mediating Omo River Water Controversy, Voice of America (News Agency), USA. Available online: https://www.voanews.com/a/kenya-ethiopia-mediating-omo-river-water-controversy/1770973.html.

Avery, S., (2013) What Future for Lake Turkana? The Impact of Hydropower and Irrigation on the World's Largest Desert Lake, African Studies Center, University of Oxford: Oxford, UK, 2013, Available online: http://www.africanstudies.ox.ac.uk/lake-turkana-and-lower-omo-hydrological-impacts-majordam-and-irrigation-developments.

Avery, S., (2010) Assessment of hydrological impacts of Ethiopia's Omo Basin on Kenya's Lake Turkana water levels, African Development Bank as part of mediation with Friends with Lake Turkana, November 2010. Available at: http://www.AFDB.org/fileadmin/uploads/AFDB/Documents/Complience-Review/REPORT_NOV_2010_S_AVERY_TURKANA_Small_File.pdf.

Battese. G.E. and T.J. Coelli, (1995) A model for technical inefficiency effects in a stochastic frontier production function for panel data, *Empirical Economics*, vol. 20, 325-332.

Beard, R.M. and S. McDonald, (2007) Time-Consistent Fair Water Sharing Agreements, in Jorgensen S. et al., (eds), *Advances in Dynamic Game Theory and Applications Series: Annals of the International Society of Dynamic Games*, Norwell Kluwer Academic Publishing, New York, 393-410.

Bhaduri, A., Manna, U. and E. Barbier, (2011) Climate change and cooperation in transboundary water sharing: an application of stochastic Stackelberg differential game s in Volta river basin*, Natural Resource Modeling*, vol. 24(4), 409-444.

Bhaduri, A., Nicostrato, P. and L. Jens, (2008) Scope and Sustainability of Cooperation in Transboundary Water Sharing of the Volta River, *Center for Development Research*, Discussion Paper 124.

Birol, E., Hanley, N., Koundouri, P. and Y. Kountouris, (2009) Optimal management of wetlands: Quantifying trade-offs between flood risks, recreation, and biodiversity conservation, *Water Resources Research*, vol. 45, doi: 10.1029/2008WR006955.

Brauman, K.A., Van der Meulen, A. and J. Brils, (2014) Ecosystem Services and River Basin Management, in Brils, J. et al. (eds), *Risk-Informed Management of European River Basins Series: The Handbook of Environmental Chemistry*, Springer Berlin Heidelberg, vol. 29.

Brems, H*.,* (1968) *Quantitative Economic Theory*, 62–74 pp., New York: Wiley.

Blössner, M. and M. De Onis, (2005) Malnutrition: quantifying the health impact at national and local levels, Geneva: World Health Organization.

Brouwer, R., Brander, R., Kuik, O., Papyrakis, E. and I. Bateman, (2013) A synthesis of approaches to assess and value ecosystem services in the EU in the context of TEEB, Report to the European Commission.

Buffavand, L., (2016) The land does not like them: Contesting dispossession in cosmological terms in Mela, south-west Ethiopia, *J. East. Afr. Stud*., vol. 10, 476–493.

Carr, C.J., (2017) *River Basin Development and Human Rights in Eastern Africa: A Policy Crossroads*, 157-189 pp., Springer Cham, ISBN 978-3-319-50469-8.

Casarin, R. and J.M. Marin, (2007) Online data processing: Comparison of Bayesian regularized particle filters. University of Brescia, Department of Economics, Working Paper n. 0704.

Caudill, S.B., Ford, J.M. and D.M. Gropper, (1993) Frontier estimation and firm-specific inefficiency measures in the presence of heteroskedasticity, *Journal of Business Economic Statistics*, vol. 13, 105-111.

Cira, D. A., Kamunyori, S. W. and R.M. Babijes, (2016) Kenya urbanization review. Washington, DC: World Bank, Available at: http://documents.worldbank.org/curated/en/639231468043512906/Kenya-urbanization-review.

Cuesta-Fernández, I., (2015) Mammoth dams, lean neighbours: Assessing the bid to turn Ethiopia into East Africa's regional powerhouse, in Scholvin, S. (eds), *A New Scramble for Africa? The Rush for Energy Resources in Sub-Saharan Africa*, 93-110.

Danaher, P.J. and M.S. Smith, (2011) Modeling multivariate distributions using copulas: Applications in marketing, *Marketing Science*, vol.30 (1), 4-21.

De Groot, R. S., Wilson, M. A. and R. M. J. Boumans, (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services, *Ecological Economics*, vol. 41, 393-408, doi:10.1016/S0921-8009(02)00089-7.

Dinar, A., (2009) Climate Change and International Water: The Role of Strategic Alliances in Resource Allocation, in Dinar A. et al. (eds), *Policy and Strategic Behaviour in Water Resource Management*, 301–324.

Dinar, A., Blankespoorb, B., Dinarc, S. and P. Kurukulasuriya, (2010) Does Precipitation and Runoff Variability Affect Treaty Cooperation between States Sharing International Bilateral Rivers?, *Ecol. Econ*., vol. 69, 2568–2581.

Doucet, A., N., de Freitas and N. Gordon, (2001) *Sequential Monte Carlo Methods in Practice*, New York: Springer.

Engelbert, D., Jorgensen, S., Long, N. V. and G. Sorger, (2000) *Differential Games in Economics and Management Science,* Cambridge University Press, New York, ISBN 978-0521637329.

Eora, (2017) The Eora MRIO Database, Available at: http://www.worldmrio.com/country (Accessed: 21/12/2017).

FAO, (2017) AQUASTAT: Main Database, Food and Agriculture Organization of the United Nations (FAO), Available at: http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en.

FAO, (2017) FAOSTAT: Food and Agriculture Data, Available at: http://www.fao.org/faostat/en/#data (Accessed: 21/12/2017).

FAO, (2018a) AQUASTAT: Main Database, Food and Agriculture Organization of the United Nations (FAO), Available at: http://www.fao.org/nr/water/aquastat/countries_regions/ETH/.

FAO, (2018b) AQUASTAT: Main Database, Food and Agriculture Organization of the United Nations (FAO), Available at http://www.fao.org/nr/water/aquastat/countries_regions/KEN/.

Fearnhead, P. (2007) Computational methods for complex stochastic systems: a review of some alternatives to MCMC, *Statistics and Computing*, vol. 18(2), 151-171.

Flury, T. and N. Shephard, (2011) Bayesian inference based only on simulated likelihood: particle filter analysis of dynamic economic models, *Econometric Theory,* vol. 27, 933-956.

Gebresenbet, S. T., (2015) Modelling of Cascade Dams and Reservoirs Operation for Optimal Water Use: Application to Omo Gibe River Basin, Ethiopia, PhD Dissertation, Available at: https://www.hydrologie.bgu.tum.de/fileadmin/w00bpg/www/Christiane1/Dissertations/Omo_Gibe_River_Basin_Dissertation_Teshome_Seyoum_new.pdf

Giodarno, M.A. and A. Wolf, (2003) Impact of Climate Change on Transboundary Water Sharing, *CEPR Discussion Paper*, vol.27(2), 163–171.

Gleick, P.H. (1992). Effects of Climate Change on Shared Fresh Water Resources. in I.M. Mintzer, (Eds.), Confronting Climate Change; Risks, Implication and Responses, (Chapter 9, pp. 127–141). Cambridge University Press, Sweden.

Gordon, N.J., Salmond, D.J. and A.F.M. Smith, (1993) Novel approach to nonlinear/non-Gaussian Bayesian state estimation, *IEEE-Proceedings-F,* vol. 140, 107–113.

Gordon, N.J. (1997) A hybrid bootstrap filter for target tracking in clutter, *IEEE Transactions on Aerospace and Electronic Systems*, vol. 33, 353– 358.

Gownaris, N.J., Pikitch, E.K., Aller, J.Y., Kaufman, L.S., Kolding, J., Lwiza, K.M.M., Obiero, K.O., Ojwang, W.O., Malala, J.O. and K.J. Rountos, (2017). Fisheries and water level fluctuations in the world's largest desert lake, *Ecohydrology*, vol.10, e1769.

Hailu, S.S., (1998) Hydropower of Ethiopia: Status, Potential and Prospects, *Ethiopian Association of Civil Engineers Bulletin*, vol.1, No.1.

Hall, J., Pitt, M.K. and R. Kohn, (2014) Bayesian inference for nonlinear structural time series models*, Journal of Econometrics*, vol. 179 (2), 99–111.

Human Rights Watch, (2017) Ethiopia: Dams, Plantations a Threat to Kenyans, Available at: https://www.hrw.org/news/2017/02/14/ethiopia-dams-plantations-threat-kenyans.

ILO, (2017) ILOSTAT: Key Indicators of the Labour Market., Available at https://www.ilo.org/ilostat/faces/wcnav_defaultSelection?_afrLoop=466209758859045&_afrWindowMode=0&_afrWindowId=null#!%40%40%3F_afrWindowId%3Dnull%26_afrLoop%3D466209758859045%26_afrWindowMode%3D0%26_adf.ctrl-state%3Dhsk7m0x7f_4.

IPCC, (2007) *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report*, Cambridge University Press, Cambridge, UK, ISBN 978 0521 88010-7.

Janmatt, J. and A. Ruijs, (2007) Sharing the Load? Floods, Droughts and Managing International Rivers. Environ Dev. *Econ*., vol. 4, 573–592.

Jondrow, J., Lovell, C.A.K., Materov, I.S. and P. Schmidt, (1982) On the estimation of technical inefficiency in the stochastic frontier production function model*, Journal of Econometrics,* vol. 19 (2/3), 233-238.

Kim, C. S., Moore, M. R. and J. J. Hanchar, (1989) A Dynamic Model of Adaptation to Resource Depletion: Theory and an Application to Groundwater Mining, *Journal of Environmental Economics and Management*, vol. 17, 66-82.

Koundouri, P., Akinsete, E., and S. Tsani, (2019) *Socio-Economic and Policy Implications of Multi-Stressed Rivers: A European Perspective. In Multiple Stressors in River Ecosystems*, 335-351pp., Elsevier, doi: https://doi.org/10.1016/B978-0-12-811713-2.00019-4

Koundouri, P. and C. Christou (2006) Dynamic Adaptation to Resource Scarcity and Backstop Availability: Theory and Application to Groundwater, *The Australian Journal of Agricultural and Resources Economics*, vol. 50, 227-245.

Koundouri, P., and O. G., Davila, (2015) The use of the ecosystem services approach in guiding water valuation and management: Inland and coastal waters, *Handbook of Water Economics*, 126-149. Available at: https://books.google.gr/books?hl=el&lr=&id=166CCgAAQBAJ&oi=fnd&pg=PA126&dq=).+The+Use+of+E

cosys-tem+Services+Approach+in+Guiding+Water+Valuation+and+Management:+Inland+and+Coastal+Waters.+&ots=OdzKug90oF&sig=KURKJHv24pXg1or8wjYDhSYvwxQ&redir_esc=y#v=onepage&q&f=false.

Kumar, P. (2012), The economics of ecosystems and biodiversity: ecological and economic foundations, Routledge, Available at: https://www.taylorfrancis.com/books/9781136538803.

Kumbhakar, S., Parmeter, C.F. and E.G. Tsionas, (2013) A zero inefficiency stochastic frontier model, *Journal of Econometrics*, vol. 172, 66-76.

Lenzen, M., Kanemoto, K., Moran, D. and A. Geschke, (2012) Mapping the Structure of the World Economy, *Env. Sci. Tech.*, vol. 46(15), 8374-8381, doi: https://doi.org/10.1021/es300171x.

Lenzen, M., Moran, D., Kanemoto, K. and A. Geschke, (2013). Building Eora: A Global Multi-Regional Input-Output Database at High Country and Sector Resolution, *Economic Systems Research*, vol. 25(1), 20-49, doi: https://doi.org/10.1080/09535314.2013.769 938 .

Levinsohn, J. and A. Petrin, (2003) Estimating production functions using inputs to control for unobservables, *The Review of Economic Studies*, vol. 70 (2), 317-341.

Liu, J. and M. West, (2001) Combined parameter and state estimation in simulation-based filtering, in Doucet, A. et al. (eds.), *Sequential Monte Carlo Methods in Practice*, Springer-Verlag.

Moroney, J. R., (1967) Cobb-Douglass production functions and returns to scale in US manufacturing industry, *Western Economic Journal*, vol. 6(1), 39–51, doi: https://doi.org/:10.1111/j.14657295.1967.tb01174.x.

Mutambo, A., (2017) Ethiopia Denies Forcing through Gibe Dams Project, Daily Nation (Newspaper), Kenya, Available at: http://www.nation.co.ke/news/Gibe-Dams-project-on-Kenya-and-Ethiopia/1056-3816882-10d7oky/index.html.

Nelsen, R.B. (2006) *An Introduction to Copula*, Vol. 139 of Springer Series in Statistics, Springer.

Nemeth, C. and P. Fearnhead, (2014) Particle Metropolis adjusted Langevin algorithms for state-space models, Pre-print arXiv:1402.0694v1.

Oduor, A., Cherogony, K., Mutune, J., Maimbo, M. Karuma, A., Nyolei, D., Kandagor, J. and D. Onyango, (2012) Food Security Master Plan for Turkana County, Trócaire International, Diocese of Lodwar, ProWater International, World Agroforestry Centre (ICRAF), Ministry of Agriculture – Lodwar and Ministry of Livestock Development – Lodwar.

Olley, S. and A. Pakes, (1996) The dynamics of productivity in the telecommunications equipment industry, *Econometrica*, vol. 64, 1263-1297.

Park, S. and S. Gupta (2012) Handling endogenous regressors by joint estimation using Copulas, *Marketing Science*, vol. 31 (4), 567-586.

Pistocchi, A., Udias, A., Grizzetti, B., Gelati, E., Koundouri, P., Ludwig, R., Papandreou A. and I. Souliotis, (2017) An integrated assessment framework for the analysis of multiple pressures in aquatic ecosystems and the appraisal of management options, *Science of the Total Environment*, vol. 575, 1477-1488, doi: https://doi.org/10.1016/j.scitotenv.2016.10.020

Pitt, M.K. and N. Shephard, (1999) Filtering via simulation based on auxiliary particle filters, *Journal of the American Statistical Association,* vol. 94 (446), 590-599.

Pitt, M.K., Silva, R.S., Giordani, P. and R. Kohn, (2012). On some properties of Markov chain Monte Carlo simulation methods based on the particle filter, *J. Econom*., vol. 171(2), 134–151.

Ristic, B., Arulampalam, S. and N. Gordon, (2004) *Beyond Kalman Filters: Particle Filters for Applications*, Norwood, MA: Artech House.

Saari, S., (2006) Productivity. Theory and Measurement in Business. Espoo, Finland: European Productivity Conference.

Saari, S., (2011). Production and Productivity as Sources of Well-being, *MIDO OY*, vol. 25, 1-25.

Shephard, R., (1970) *Theory of Cost and Production Functions. Princeton, NJ: Princeton University Press.*

Salini Impregilo, (2016) Ethiopia inaugurates tallest RCC dam in world built by Salini Impregilo. Accessed: 8th February 2017.

Sennoga, E. B. and A. W. Zerihun, (2018) 2018 African Economic Outlook Country Note: Ethiopia, African Development Bank Group, 1-11 pp.

Sklar, A. (1959) Functions de repartition a n dimensions et leurs marges, *Publications de l'Institut de Statistique de l'Uinversite de Paris,* vol. 8, 229-231.

SOGREAH Consultants, (2010) Independent review and studies regarding the Environmental & Social Impact Assessments for the Gibe III Hydropower Project, European Investment Bank.

Song, P.X.K. (2000) Multivariate dispersion models generated from Gaussian copula, *Scandinavian Journal of Statistics*, vol. 27 (2), 305-320.

Stephen, D.E. and J. E. Kundell, (2008) Sharing Waters: Post-Rio International Water Management, *J. Water Resour. Plan. Manag.*, vol.133(5), 405–415.

Stevenson, E.G.J., (2018) Plantation Development in the Turkana Basin: The Making of a New Desert? *Land*, vol. 7, 1-16.

The East African, (2013) Find could reshape Kenya's fortunes as water emerges top geopolitical issue, Available at: http://www.theeastafrican.co.ke/news/Water-emerges-top-East-Africa-geopolitical-issue/2558-1992668-b9eusaz/index.html.

The International Trade Administration (2017) *Ethiopia – Agriculture* (Online) Available: https://www.export.gov/apex/article2?id=Ethiopia-Agriculture (Accessed: 30/08/18)

Thuo, S., Schreiner, B. and S. Byakika, (2017) The water-energy-food nexus and poverty eradication in Kenya, Pegasys Institute.

Tsionas, M.G. and M. Izzeldin, (2018a) Smooth approximations to monotone concave functions in production analysis: An alternative to nonparametric concave least squares, *European Journal of Operational Research*, vol. 271, 797-807, doi: https://doi.org/10.1016/j.ejor.2018.05.053.

Tsionas, M.G. and M. Izzeldin, (2018b) A novel model of costly technical efficiency, *European Journal of Operational Research*, vol. 268, 653-664, doi: https://doi.org/10.1016/j.ejor.2018.01.016.

Tsionas, M.G., Malikov, E. and S. C. Kumbhakar, (2018) An internally consistent approach to the estimation of market power and cost efficiency with an application to U.S. banking, *European Journal of Operational Research*, vol. 270, 747-760, doi: https://doi.org/10.1016/j.ejor.2018.04.012.

Tsionas, M.G., and S. K. Mallick, (2019) A Bayesian semiparametric approach to stochastic frontiers and productivity, *European Journal of Operational Research*, vol. 274, 391-402, doi: https://doi.org/10.1016/j.ejor.2018.10.026.

Tsionas, M.G. and E. Mamatzakis, (2018) Further results on estimating inefficiency effects in stochastic frontier models, *European Journal of Operational Research*, in press.

Turton, D., (2015) Hydropower and irrigation development in the Omo valley: Development for whom? In Proceedings of the International Conference on Ethiopian Studies, Warsaw, Poland, 28 August.

Turton, D., (1985) Mursi Response to Drought: Some Lessons for Relief and Rehabilitation, *Afr. Aff.*, vol. 84, 331–346.

Vorosmarty, C.J., (2002) Global Water Assessment and Potential Contributions from Earth Systems Science, *Aquat. Sci.*, vol. 64, 328–351.

World Bank (2016). World Development Indicators. Available at: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators. Accessed on 01/12/2016.

World Bank Group (2017). Climate Change Knowledge Portal For Development Practitioners and Policy Makers. Available at: http://sdwebx.worldbank.org/climateportal/ (Accessed: 21/12/2017).

World Bank (2018). World Bank Open Data. Free and open access to global development data. Available at: https://data.worldbank.org

World Tourism Organization (2017) Yearbook of Tourism Statistics: Compendium of Tourism Statistics and data files https://www.e-unwto.org/toc/unwtotfb/current (Accessed: 21/12/2017).

Woodroof, R. and Associates Ltd. Mascott, (1996) Omo-Gibe River Basin Integrated Development Master Plan Study, Final Report for the Ministry of Water Resources of the Federal Democratic Republic of Ethiopia.

WWAP (United Nations World Water Assessment Program), (2015). The United Nations World Water Development Report 2015: Water for a Sustainable World, Paris: UNESCO.

Young, R.A., (1996) Measuring Economic benefits for water investments and policies, World Bank Technical Paper No. 338.

APPENDIX 1 – ECOSYSTEM SERVICES INDICES

Table 18 - Description of Indices of Ecosystem Services

ES Services	Indicator	Description	Units	Source
	GVA per sector	Represents the contribution of labor and capital to the production process. Gross value added at basic prices is defined as output valued at basic prices less intermediate consumption valued at purchasers' prices. Although the outputs and inputs are valued using different sets of prices, for brevity the value added is described by the prices used to value the outputs. From the point of view of the producer, purchasers' prices for inputs and basic prices for outputs represent the prices actually paid and received. Their use leads to a measure of gross value added that is particularly relevant for the producer. Net value added is defined as the value of output less the values of both intermediate consumption and consumption of fixed capital.	$	Input-OutputTables http://www.worldmrio.com/country
	Gross Fixed Capital Formation per sector	Gross fixed capital formation is measured by the total value of a producer's acquisitions, less disposals, of fixed assets during the accounting period plus certain additions to the value of non-produced assets (such as subsoil assets or major improvements in the quantity, quality or productivity of land) realized by the productive activity of institutional units.	$	Input-Output Tables http://www.worldmrio.com/country
	Employment Per sector	Persons in employment are defined as all those of working age who, during a short reference period, were engaged in any activity to produce goods or provide services for pay or profit. They comprise employed persons "at work", i.e. who worked in a job for at least one hour; and employed persons "not at work" due to temporary absence from a job, or to working-time arrangements (such as shift work, flexitime and compensatory leave for overtime).	Abs. Value	ILO (International LABOR Organization)
Provis. services	**WFN: Total Water Footprint per sector**	Total water use which includes: – WFN: Total water footprint - Green – WFN: Total water footprint - Blue – WFN: Total water footprint - Grey	Mm^3/yr	Input-Output Tables http://www.worldmrio.com
	Energy Use (Total) per sector	Natural Gas, Coal, Petroleum, Nuclear Electricity, Hydroelectric Electricity, Geothermal Electricity, Wind Electricity, Solar, Tide and Wave Electricity, Biomass and Waste Electricity	TJ	Input-Output Tables http://www.worldmrio.com/country
Regul. Services	**Water Quality**	Nitrogen Emissions exportable to water bodies from agriculture and household waste water	Gg	Input-Output Tables http://www.worldmrio.com/country
	Fertilizers:	Proportions of consumption of fertilizers (by nutrient	kg/ha	Food and

	Total Nitrogen and Phosphate (N and P2O5)	group) per unit of agricultural land area are calculated by UNSD using available consumption and land use data from FAOSTAT.		Agriculture Organization of United Nations (FAOSTAT)
Provis. services	**Agricultural Area**	Agricultural area, this category is the sum of areas under “Arable land”, “Permanent crops” and “Permanent pastures”	10^3ha	Food and Agriculture Organization of United Nations (FAOSTAT)
Provis. services	**Raw Materials per Sector**	For agriculture total biomass and for mining-quarries total construction material and total fossil fuel	t	Input-Output Tables http://www.worldmrio.com/country
Provis. services	**Permanent Crops**	Permanent crops is the land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee); land under trees and shrubs producing flowers, such as roses and jasmine; and nurseries (except those for forest trees, which should be classified under "forest"). Permanent meadows and pastures are excluded from land under permanent crops.	10^3ha	Food and Agriculture Organization of United Nations (FAOSTAT)
Provis. services	**Arable Land**	Arable land is the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for “Arable land” are not meant to indicate the amount of land that is potentially cultivable.	10^3ha	Food and Agriculture Organization of United Nations (FAOSTAT)
Provis. services	**Crop Production**	Crop statistics are recorded for 173 products, covering the following categories: Crops Primary, Fibre Crops Crop statistics are recorded for 173 products, covering the following categories: Crops Primary, Fibre Crops Primary, Cereals, Coarse Grain, Citrus Fruit, Fruit, Jute & Jute-like Fibres, Oilcakes Equivalent, Oil crops Primary, Pulses, Roots and Tubers, Treenuts and Vegetables and Melons. Data are expressed in terms of area harvested, production quantity, yield and seed quantity. The objective is to comprehensively cover production of all primary crops for all countries and regions in the world.	t	Input-Output Tables http://www.worldmrio.com/country
Regul. Services	**Forest**	Forest area is the land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 metres (m) in situ. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 percent and a tree height of 5 m are included, as are temporarily unstocked	10^3ha	Food and Agriculture Organization of United Nations (FAOSTAT)

		areas, resulting from human intervention or natural causes, which are expected to regenerate. Includes: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, fire-breaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m; plantations primarily used for forestry or protective purposes, such as: rubber-wood plantations and cork, oak stands. Excludes: tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens.		
Provis. services	**Total Area Equipped For Irrigation**	Area equipped with irrigation infrastructure to provide water to the crops. This includes areas equipped for full and partial control irrigation, spate irrigation areas, and equipped wetland or inland valley bottoms.	10^3ha	Food and Agriculture Organization of United Nations (FAOSTAT)
Provis. services	**Total Fisheries Production**	Total fisheries production measures the volume of aquatic species caught by a country for all commercial, industrial, recreational and subsistence purposes. The harvest from mariculture, aquaculture and other kinds of fish farming is also included.	t	Food and Agriculture Organization of United Nations (FAOSTAT)
	Temperature	The yearly mean historical rainfall and temperature data can be mapped to show the baseline climate and seasonality yearly, and for rainfall and temperature.	°C	The World Bank Group Climate Change Knowledge PortalFor Development Practitioners and Policy Makers
	Rainfall	Yearly Mean historical rainfall	mm	The World Bank Group Climate Change Knowledge PortalFor Development Practitioners and Policy Makers
Habitat services	**Biodiversity and Habitats**	A “proximity-to-target methodology” is used to assess how close each country is to an identified policy target. Country scores are determined by how close or far countries are to targets. Scores are standardized (i.e., on a scale of 0 to 100) for comparability, weighting, and aggregation. The Environmental Performance Index (EPI) is constructed through the calculation and aggregation of 20 indicators reflecting national-level environmental	%	Environment and Climate Change Data Portal

		data. These indicators are combined into nine issue categories, each of which fit under one of two over-arching objectives. The two objectives that provide the overarching structure of the EPI are Environmental Health and Ecosystem Vitality. Biodiversity & Habitats belongs to the Ecosystem Vitality which measures ecosystem protection and resource management. These two objectives are further divided into nine issue categories that span high-priority environmental policy issues, including air quality, forests, fisheries, and climate and energy, among others. The issue categories are extensive but not comprehensive. Underlying the nine issue categories, 20 indicators are calculated from country-level data and statistics. In this case the Biodiversity and Habitat category includes four indicators: Critical Habitat Protection, Terrestrial Protected Areas (National Biome Weight), Terrestrial Protected Areas (Global Biome Weight), and Marine Protected Areas. The targets are: 100% for Critical Habitat Protection; 17% for Terrestrial Protected Areas (National Biome Weights); 17% for Terrestrial Protected Areas (Global Biome Weights); 10% for Marine Protected Areas. (c.f. http://archive.epi.yale.edu/our-methods/biodiversity-and-habitat)		
Regul. Services	**Terrestrial Protected Areas**	The definition of a "protected area", as adopted by the International Union for Conservation of Nature (IUCN), is "an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means". (IUCN 1994. Guidelines for Protected Areas Management Categories. IUCN; Gland; Switzerland and Cambridge; UK). Protected areas increase with time and are not deleted from subsequent years. Only protected areas that are "nationally designated" are included in this indicator. The status "designated" is attributed to a protected area when the authority that corresponds, according to national legislation or common practice (e.g. by means of an executive decree), officially endorses a document of designation. The designation must be for conservation of biodiversity, not single species and not fortuitous de facto protection arising because of some other activity (e.g. military). Hence, a number of United States Marine Managed Areas as well as permanent fisheries closures are excluded. Data are adjusted to account for transboundary protected areas (protected areas that transcend international boundaries) to ensure that the appropriate area/extent from the total area for that site is attributed to the country in which it is contained. Similar adjustments have been made where a protected area transcends both marine and terrestrial environments. The size of the protected area (its "extent") is the officially documented total area provided by the national authority or as listed by the World Database on Protected Areas and may be generated from spatial	Km^2	World Database on Protected Areas (WDPA) website at: www.wdpa.org/.

		(GIS) boundary data (see source for details). Many protected areas can contain proportions of both the marine and terrestrial environment, and the size of the protected area extent that falls into each environment is not always available. The table also includes some protected areas for which the year (date of establishment/designation) is unavailable. If no update is received for a given year, the total number and size of the protected area is assumed to be equal to the previous year's values.		
	Access to Electricity	Access to electricity is the percentage of population with access to electricity. Electrification data are collected from industry, national surveys and international sources.	% of population	World Bank, Sustainable Energy for All (SE4ALL) database
	People Using Basic Drinking Water Services	The percentage of people using at least basic water services. This indicator encompasses both people using basic water services as well as those using safely managed water services. Basic drinking water services is defined as drinking water from an improved source, provided collection time is not more than 30 minutes for a round trip. Improved water sources include piped water, boreholes or tubewells, protected dug wells, protected springs, and packaged or delivered water.	% of population	World Bank, from WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene (washdata.org).
	International Tourism, Number of Arrivals	International inbound tourists (overnight visitors) are the number of tourists who travel to a country other than that in which they have their usual residence, but outside their usual environment, for a period not exceeding 12 months and whose main purpose in visiting is other than an activity remunerated from within the country visited. When data on number of tourists are not available, the number of visitors, which includes tourists, same-day visitors, cruise passengers, and crew members, is shown instead. Sources and collection methods for arrivals differ across countries. In some cases data are from border statistics (police, immigration, and the like) and supplemented by border surveys. In other cases data are from tourism accommodation establishments. For some countries number of arrivals is limited to arrivals by air and for others to arrivals staying in hotels. Some countries include arrivals of nationals residing abroad while others do not. Caution should thus be used in comparing arrivals across countries. The data on inbound tourists refer to the number of arrivals, not to the number of people traveling. Thus a person who makes several trips to a country during a given period is counted each time as a new arrival.	Abs. Value	World Bank, World Tourism Organization, Yearbook of Tourism Statistics, Compendium of Tourism Statistics and data files
Regul. Services	**Renewable Electricity Production**	Electricity production refers to gross production, which is the sum of the electrical energy production by all the generating units/installations concerned (including pumped storage) measured at the output terminals of the main generators. Renewable electricity production (%) refers to the proportion of total electricity produced that comes from a renewable origin. Electricity production refers to gross electricity	%	United Nations Statistics Division, Energy Statistics http://unstats.un.org/unsd/ener-

		production, which is the sum of the electrical energy production by all the generating units/installations concerned (including pumped storage) measured at the output terminals of the main generators. This includes the consumption by station auxiliaries and any losses in the transformers that are considered integral parts of the station. Renewable electricity production was calculated as the sum of electricity produced from hydro, geothermal, solar, wind, tide, wave and ocean sources. All electricity production from combustible fuels is considered non-renewable; therefore electricity produced from burning biomass or renewable waste is not included as renewable electricity in this table. However, this has been observed to be a relatively negligible proportion of electricity production in most cases.		gy/yearbook/default.htm.
Regul. Services	**CO_2**	Public electricity and heat production Other Energy Industries Manufacturing Industries and Construction Domestic aviation Road transportation Rail transportation Inland navigation Other transportation Residential and other sectors Fugitive emissions from solid fuels Fugitive emissions from oil and gas International aviation International navigation Production of minerals Cement production Lime production Production of chemicals Production of metals Production of pulp/paper/food/drink Production of halocarbons and SF6 Refrigeration and Air Conditioning Foam Blowing Fire Extinguishers Aerosols F-gas as Solvent Semiconductor/Electronics Manufacture Electrical Equipment Other F-gas use Non-energy use of lubricants/waxes (CO_2) Solvent and other product use: paint Solvent and other product use: degrease Solvent and other product use: chemicals Solvent and other product use: other Enteric fermentation Manure management Rice cultivation Direct soil emissions Manure in pasture/range/paddock Indirect N_2O from agriculture Other direct soil emissions Savanna burning Agricultural waste burning Forest fires	Gg	Input-Output Tables http://www.worldmrio.com/country

		Grassland fires Decay of wetlands/peatlands Other vegetation fires Forest Fires-Post burn decay Solid waste disposal on land Wastewater handling Waste incineration Other waste handling Fossil fuel fires Indirect N_2O from non-agricultural NO_x Indirect N_2O from non-agricultural NH_3 Other sources		
Regul. Services	**NO_2**	Public electricity and heat production Other Energy Industries Manufacturing Industries and Construction Domestic aviation Road transportation Rail transportation Inland navigation Other transportation Residential and other sectors Fugitive emissions from solid fuels Fugitive emissions from oil and gas Memo: International aviation Memo: International navigation Production of minerals Cement production Lime production Production of chemicals Production of metals Production of pulp/paper/food/drink Production of halocarbons and SF6 Refrigeration and Air Conditioning Foam Blowing Fire Extinguishers Aerosols F-gas as Solvent Semiconductor/Electronics Manufacture Electrical Equipment Other F-gas use Non-energy use of lubricants/waxes (CO_2) Solvent and other product use: paint Solvent and other product use: degrease Solvent and other product use: chemicals Solvent and other product use: other Enteric fermentation Manure management Rice cultivation Direct soil emissions Manure in pasture/range/paddock Indirect N_2O from agriculture Other direct soil emissions Savanna burning Agricultural waste burning Forest fires Grassland fires Decay of wetlands/peatlands Other vegetation fires Forest Fires-Post burn decay		

		Solid waste disposal on land Wastewater handling Waste incineration Other waste handling Fossil fuel fires Indirect NO_2 from non-agricultural NO_x Indirect NO_2 from non-agricultural NH_3 Other sources		
Regul. Services	**Total Annual Freshwater Withdrawals**	Annual freshwater withdrawals refer to total water withdrawals, not counting evaporation losses from storage basins. Withdrawals also include water from desalination plants in countries where they are a significant source. Withdrawals can exceed 100 percent of total renewable resources where extraction from non-renewable aquifers or desalination plants is considerable or where there is significant water reuse. Withdrawals for agriculture and industry are total withdrawals for irrigation and livestock production and for direct industrial use (including withdrawals for cooling thermoelectric plants). Withdrawals for domestic uses include drinking water, municipal use or supply, and use for public services, commercial establishments, and homes. Data are for the most recent year available for 1987-2002.	$10^9 m^3$	Food and Agriculture Organization, AQUASTAT data.
Regul. Services	**Floods and Droughts**	Number of floods/droughts events.	[-]	The Emergency Events Database - Université catholique de Louvain (UCL) - CRED, D. Guha-Sapir, www.emdat.be, Brussels, Belgium. http://emdat.be/emdat_db/
Cultural and amenity services	**Cultural-Natural-Mixed Heritage Sites**	To be included on the World Heritage List, sites must be of outstanding universal value and meet at least one out of ten selection criteria. These criteria are explained in the Operational Guidelines for the Implementation of the World Heritage Convention which, besides the text of the Convention, is the main working tool on World Heritage. The criteria are regularly revised by the Committee to reflect the evolution of the World Heritage concept itself. Access to an improved water source refers to the percentage of the population with reasonable access to an adequate amount of water from an improved source, such as a household connection, public standpipe, borehole, protected well or spring, and rainwater collection. Unimproved sources include vendors, tanker trucks, and unprotected wells and springs. Reasonable access is defined as the availability of at least 20 liters a person a day from a source within one kilometer of the dwelling.	[-]	UNESCO World Heritage Centre – World Heritage List

APPENDIX 2 – DECOUPLING METHOD

In this appendix we derive analytical solutions for the stochastic optimization problems presented in Section 2.2 by making use of a decoupling method for linear FBSDEs.

Non-Cooperative Approach: Upstream Case

For the *j*-exit stage, the Hamiltonian of the optimization problem **Error! Reference source not found.** is formulated as follows:

$$H_j^U\left(W_{jt}^U, w_{jt}^U, \dots, w_{5t}^U, \lambda_{jt}^U\right) \triangleq \sum_{i=j}^{5}\left[\frac{a_i^U}{b_i^U} w_{it}^U - \frac{1}{2b_i^U}\cdot (w_{it}^U)^2 - (k_2^U - k_1^U W_{jt}^U) w_{it}^U\right] + \lambda_{jt}^U\left[W_t - \sum_{i=j}^{5} w_{it}^U\right], \quad j=1,2,\dots,5, \tag{41}$$

where $\lambda_{j\cdot}^U$ is the *j*-exit stage adjoint variable that represents water scarcity rents for the upstream area. Making use of (41), the necessary conditions for optimality are given as follows:

$$\frac{\partial H_j^U}{\partial w_{it}^U} = \frac{a_i^U}{b_i^U} - \frac{1}{b_i^U}\cdot w_{it}^U - (k_2^U - k_1^U W_{jt}^U) - \lambda_{jt}^U = 0, \quad i=j,\dots,5, \quad j=1,2,\dots,5, \tag{42}$$

$$d\lambda_{jt}^U = \left[-\frac{\partial H_j^U}{\partial W_{jt}^U} + r\lambda_{jt}^U\right]dt \quad \Leftrightarrow \quad d\lambda_{jt}^U = \left[-k_1^U \sum_{i=j}^{5} w_{it}^U + r\lambda_{jt}^U\right]dt, \quad i=j,\dots,5, \quad j=1,2,\dots,5. \tag{43}$$

From (42) we have that:

$$w_{it}^U = a_i^U - b_i^U (k_2^U - k_1^U W_{jt}^U) - b_i^U \lambda_{jt}^U, \quad i=j,\dots,5, \quad j=1,2,\dots,5. \tag{44}$$

Setting

$$A_j^U \triangleq \sum_{i=j}^{5} a_i^U \quad \text{and} \quad B_j^U \triangleq \sum_{i=j}^{5} b_i^U, \quad j=1,2,\dots,5, \tag{45}$$

the state equation of (3) and the adjoint equation of (43) form the FBSDEs system:

$$\begin{aligned} dW_{jt}^U &= \left[-k_1^U B_j^U W_{jt}^U + B_j^U \lambda_{jt}^U + W_t - A_j^U + k_2^U B_j^U\right]dt, \\ d\lambda_{jt}^U &= \left[-\left(k_1^U\right)^2 B_j^U W_{jt}^U + \left(k_1^U B_j^U + r\right)\lambda_{jt}^U - k_1^U A_j^U + k_1^U k_2^U B_j^U\right]dt, \\ W_{00}^U &= wr_0, \quad \lim_{t\to\infty} \lambda_{jt}^U = 0, \quad j=1,2,\dots,5. \end{aligned} \tag{46}$$

To solve the above system of FBSDEs we impose a solution $\left(W_{j\cdot}^U, \lambda_{j\cdot}^U\right)$, $j=1,2,\dots,5,$ of the form:

$$\lambda_{jt}^U = N_{jt}^U W_{jt}^U + M_{jt}^U, \quad j=1,2,\dots,5, \tag{47}$$

where N_{jt}^U and M_{jt}^U are stochastic processes to be determined. Taking differentials in (47) and using the forward equation of (46) we have that

$$d\lambda_{jt}^{U} = W_{jt}^{U} dN_{jt}^{U} + N_{jt}^{U} dW_{jt}^{U} + dM_{jt}^{U}$$
$$= W_{jt}^{U} dN_{jt}^{U} + dM_{jt}^{U} + \left\{ \left[B_{j}^{U} \left(N_{jt}^{U} \right)^{2} - k_{1}^{U} B_{j}^{U} N_{jt}^{U} \right] W_{jt}^{U} + B_{j}^{U} N_{jt}^{U} M_{jt}^{U} + \left[W_{t} - A_{j}^{U} + k_{2}^{U} B_{j}^{U} \right] N_{jt}^{U} \right\} dt,$$

while from the backward equation of system (46) we get:

$$d\lambda_{jt}^{U} = \left\{ \left[\left(k_{1}^{U} B_{j}^{U} + r \right) N_{jt}^{U} - \left(k_{1}^{U} \right)^{2} B_{j}^{U} \right] W_{jt}^{U} + \left(k_{1}^{U} B_{j}^{U} + r \right) M_{jt}^{U} - k_{1}^{U} A_{j}^{U} + k_{1}^{U} k_{2}^{U} B_{j}^{U} \right\} dt.$$

Sufficient conditions for the last two relationships to be equivalent are given by

$$dN_{jt}^{U} = \left[-B_{j}^{U} \left(N_{j}^{U} \right)^{2} + \left(2k_{1}^{U} B_{j}^{U} + r \right) N_{jt}^{U} - \left(k_{1}^{U} \right)^{2} B_{j}^{U} \right] dt,$$
$$\lim_{t\to\infty} N_{jt}^{U} = 0, \quad j = 1,2,...,5,$$

which is a backward Riccati equation (RE) that can be solved numerically for $N_{j\bullet}^{U}, \; j = 1,2,...,5,$

and by

$$dM_{jt}^{U} = \left[\left(-B_{j}^{U} N_{j}^{U} + k_{1}^{U} B_{j}^{U} + r \right) M_{jt}^{U} - \left(W_{t} - A_{j}^{U} + k_{2}^{U} B_{j}^{U} \right) N_{j}^{U} - k_{1}^{U} A_{j}^{U} + k_{1}^{U} k_{2}^{U} B_{j}^{U} \right] dt,$$
$$\lim_{t\to\infty} M_{jt}^{U} = 0, \quad j = 1,2,...,5,$$

which given the above solution is a backward linear first-order stochastic differential equation (SDE) that can be easily solved for $M_{j\bullet}^{U}, \; j = 1,2,...,5.$

Substituting the linear solution form of (47) to the forward equation of the FBSDEs system (46), we obtain that

$$dW_{jt}^{U} = \left[\left(-k_{1}^{U} + N_{jt}^{U} \right) B_{jt}^{U} W_{jt}^{U} + B_{j}^{U} M_{j}^{U} + W_{t} - A_{j}^{U} + k_{2}^{U} B_{j}^{U} \right] dt,$$
$$W_{00}^{U} = wr_{0}, \quad j = 1,2,...,5,$$

which is a forward linear SDE that can be solved for $W_{j\bullet}^{U}, \; j = 1,2,...,5$. Then the backward adjoint variable $\lambda_{j\bullet}^{U}, \; j = 1,2,...,5,$ follows from (47) and the optimal water use $w_{i\bullet}^{U}, \; i = 1,2,...,5,$ follows from the optimality condition (44).

Non-Cooperative Approach: Downstream Case

For the (*j,k*)-th exit-stage the Hamiltonian of the optimization problem (14) is formulated by

$$H_{jk}^{D}\left(S_{jk}, w_{jkt}^{D}, ..., w_{j5t}^{D}, \lambda_{jkt}^{D} \right) \triangleq \sum_{l=k}^{5} \left[\frac{a_{l}^{D}}{b_{l}^{D}} w_{jlt}^{D} - \frac{1}{2b_{l}^{D}} \cdot (w_{jlt}^{D})^{2} \right] - (k_{2}^{D} - k_{1}^{D} S_{jkt}) \sum_{l=k}^{5} w_{jlt}^{D}$$
$$+ \lambda_{jkt}^{D} \left[W_{t} - \sum_{i=j}^{5} w_{it}^{U} - \sum_{l=k}^{5} w_{jlt}^{D} + R_{t} - O_{t} \right], \qquad j,k = 1,2,...,5, \tag{48}$$

where $\lambda_{jk\bullet}^{D}$ is the (*j,k*)-th exit stage adjoint variable that represents water scarcity rents for the downstream area. Thanks to (48) the necessary conditions for optimality are given as follows:

$$\frac{\partial H_{jk}^{D}}{\partial w_{jlt}^{D}} = \frac{a_{l}^{D}}{b_{l}^{D}} - \frac{1}{b_{l}^{D}} \cdot w_{jlt}^{D} - (k_{2}^{D} - k_{1}^{D} S_{jkt}) - \lambda_{jkt}^{D} = 0, \quad l = k,...,5, \qquad j,k = 1,2,...,5, \tag{49}$$

$$d\lambda_{jkt}^D = \left[-\frac{\partial H_{jk}^D}{\partial S_{jkt}} + r\lambda_{jkt}^D \right] dt \quad \Leftrightarrow \quad d\lambda_{jkt}^D = \left[-k_1^D \sum_{l=k}^{5} w_{jlt}^D + r\lambda_{jkt}^D \right] dt, \quad j,k = 1,2,...,5. \tag{50}$$

From (49) we have the optimal water abstraction policy:

$$w_{jlt}^D = a_l^D - b_l^D (k_2^D - k_1^D S_{jkt}) - b_l^D \lambda_{jkt}^D, \quad l = k,...,5, \quad j,k = 1,2,...,5. \tag{51}$$

Then making use the notation of (45), we may reformulate the state equation (5) and the adjoint equation (50) to obtain the system of FBDEs:

$$\begin{aligned} dS_{jkt} &= \left[-k_1^D B_k^D S_{jkt} + B_k^D \lambda_{jkt}^D + W_t - \sum_{i=j}^{5} w_{it}^U + R_t - O_t - A_k^D + k_2^D B_k^D \right] dt, \\ d\lambda_{jkt}^D &= \left[-\left(k_1^D\right)^2 B_k^D S_{jkt} + \left(k_1^D B_k^D + r\right) \lambda_{jkt}^D - k_1^D A_k^D + k_1^D k_2^D B_k^D \right] dt, \\ S_{000} &= s_0, \quad \lim_{t\to\infty} \lambda_{jkt}^D = 0, \quad j,k = 1,2,...,5. \end{aligned} \tag{52}$$

To solve the above system of FBDEs we impose a solution $\left(S_{jk\bullet}, \lambda_{jk\bullet}^D\right)$, $j,k = 1,2,...,5$, of the form:

$$\lambda_{jkt}^D = N_{jkt}^D S_{jkt} + M_{jkt}^D, \quad j,k = 1,2,...,5, \tag{53}$$

where $N_{jk\bullet}^D$ and $M_{jk\bullet}^D$ are stochastic processes to be determined. Taking differentials in (53) we have that

$$\begin{aligned} d\lambda_{jkt}^D &= S_{jkt} dN_{jkt}^D + N_{jkt}^D dS_{jkt} + dM_{jkt}^D \\ &= S_{jkt} dN_{jkt}^D + dM_{jkt}^D \\ &+ \left\{ \left[B_k^D \left(N_{jkt}^D\right)^2 - k_1^D B_k^D N_{jkt}^D \right] S_{jkt} + B_k^D N_{jkt}^D M_{jkt}^D + \left[W_t - \sum_{i=j}^{5} w_{it}^U + R_t - O_t - A_k^D + k_2^D B_k^D \right] N_{jkt}^D \right\} dt, \end{aligned}$$

while the backward equation of the FBSDEs system (52) becomes:

$$d\lambda_{jkt}^D = \left\{ \left[\left(k_1^D B_k^D + r\right) N_{jkt}^D - \left(k_1^D\right)^2 B_k^D \right] S_{jkt} + \left(k_1^D B_k^D + r\right) M_{jkt}^D - k_1^D A_k^D + k_1^D k_2^D B_k^D \right\} dt.$$

The latter are equivalent under the following sufficient conditions:

$$\begin{aligned} dN_{jkt}^D &= \left[-B_k^D \left(N_{jkt}^D\right)^2 + \left(2k_1^D B_k^D + r\right) N_{jkt}^D - \left(k_1^D\right)^2 B_k^D \right] dt, \\ \lim_{t\to\infty} N_{jkt}^D &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which is a backward RE that can be solved numerically for $N_{jk\bullet}^D$, $j,k = 1,2,...,5$, and

$$\begin{aligned} dM_{jkt}^D &= \begin{bmatrix} \left(-B_k^D N_{jkt}^D + k_1^D B_k^D + r\right) M_{jkt}^D - \left(W_t - \sum_{i=j}^{5} w_{it}^U + R_t - O_t - A_k^D + k_2^D B_k^D \right) N_{jkt}^D \\ -k_1^D A_k^D + k_1^D k_2^D B_k^D \end{bmatrix} dt, \\ \lim_{t\to\infty} M_{jkt}^D &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which given the above solution is a backward linear first-order SDE that can be easily solved for $M_{jk\bullet}^D$, $j,k = 1,2,...,5$.

Substituting the linear solution form of (53) to the forward equation of the FBSDEs system (52), we get that

$$dS_{jkt} = \left[\left(-k_1^D + N_{jkt}^D \right) S_{jkt} + B_k^D M_{jkt}^D + W_t - \sum_{i=j}^{5} w_{it}^U + R_t - O_t - A_k^D + k_2^D B_k^D \right] dt,$$
$$S_{000} = s_0, \quad j,k = 1,2,...,5,$$

which is a forward linear SDE that can be solved for $S_{jk\bullet}$, $j,k = 1,2,...,5.$. Thus, the backward adjoint variable $\lambda_{jk\bullet}^D$, $j,k = 1,2,...,5,$ follows from the linear transformation of (53) and the optimal water use $w_{il\bullet}^D$, $i,l = 1,2,...,5,$ follows from the optimality condition (51).

Cooperative Approach: Upstream Case

For the (j,k)-th exit stage the optimization problem (17) admits the augmented Hamiltonian:

$$\begin{aligned} \bar{H}_{jk}^U \left(W_{jt}^U, S_{jkt}, \lambda_{jkt}^D, w_{jkt}^U, ..., w_{5kt}^U, \mu_{j\kappa t}, \nu_{j\kappa t}, \xi_{j\kappa t} \right) &\triangleq \sum_{i=j}^{5} \left[\frac{a_i^U}{b_i^U} w_{ikt}^U - \frac{1}{2b_i^U} \cdot (w_{ikt}^U)^2 - (k_2^U - k_1^U W_{jt}^U) w_{ikt}^U \right] \\ &+ \eta_1^U S_{jkt} + \eta_2^U + \mu_{jkt} \left[W_t - \sum_{i=j}^{5} w_{ikt}^U \right] \\ &+ \nu_{jkt} \left[W_t - \sum_{i=j}^{5} w_{ikt}^U + R_t - O_t - A_k^D + B_k^D (k_2^D - k_1^D S_{jkt}) + B_k^D \lambda_{jkt}^D \right] \\ &+ \xi_{jkt} \left\{ -k_1^D \left[A_k^D - B_k^D (k_2^D - k_1^D S_{jkt}) \right] + \left(r + k_1^D B_k^D \right) \lambda_{jkt}^D \right\}, \quad j,k = 1,2,...,5, \end{aligned} \tag{54}$$

where $\left(\mu_{j\kappa\bullet}, \nu_{j\kappa\bullet}, \xi_{j\kappa\bullet} \right)$ is the vector of the associated adjoint variables. Due to (54), the necessary optimality conditions are given below:

$$\frac{\partial \bar{H}_{jk}^U}{\partial w_{ikt}^U} = \frac{a_i^U}{b_i^U} - \frac{1}{b_i^U} \cdot w_{ikt}^U - (k_2^U - k_1^U W_{jt}^U) - \mu_{jkt} - \nu_{jkt} = 0, \quad i = j,...,5, \quad j,k = 1,2,...,5, \tag{55}$$

$$d\mu_{jkt} = \left[-\frac{\partial \bar{H}_{j\kappa}^U}{\partial W_{jt}^U} + r\mu_{jkt} \right] dt \quad \Leftrightarrow \quad d\mu_{jkt} = \left[-k_1^U \sum_{i=j}^{5} w_{ikt}^U + r\mu_{jkt} \right] dt, \quad j,k = 1,2,...,5, \tag{56}$$

$$d\nu_{jkt} = \left[-\frac{\partial \bar{H}_{j\kappa}^U}{\partial S_{jkt}} + r\nu_{jkt} \right] dt \;\Leftrightarrow\; d\nu_{jkt} = \left[-\eta_1^U + k_1^D B_k^D \nu_{jkt} + \left(k_1^D \right)^2 B_k^D \xi_{jkt} + r\nu_{jkt} \right] dt, \; j,k = 1,2,...,5, \tag{57}$$

$$d\xi_{jkt} = \left[-\frac{\partial \bar{H}_{j\kappa}^U}{\partial \lambda_{jt}^D} + r\xi_{jkt} \right] dt \quad \Leftrightarrow \quad d\xi_{jkt} = \left[-B_k^D \nu_{jkt} - k_1^D B_k^D \xi_{jkt} \right] dt, \quad \xi_{000} = 0, \quad j,k = 1,2,...,5. \tag{58}$$

From (55) we have that the optimal water consumption strategy is given by

$$w_{ikt}^U = a_i^U - b_i^U (k_2^U - k_1^U W_{jt}^U) - b_i^U \mu_{jkt} - b_i^U \nu_{jkt}, \quad i = j,...,5, \quad j,k = 1,2,...,5. \tag{59}$$

Then, recalling also the notation of (45), it is easily seen that the adjoint variables of both (57) and (58) satisfy the system of FBSDEs:

$$\begin{aligned} d\xi_{jkt} &= -\left[k_1^D B_k^D \xi_{jkt} + B_k^D \nu_{jkt} \right] dt, \\ d\nu_{jkt} &= \left[\left(k_1^D \right)^2 B_k^D \xi_{jkt} + \left(r + k_1^D B_k^D \right) \nu_{jkt} - \eta_1^U \right] dt, \\ \xi_{000} &= 0, \quad \lim_{t \to \infty} \nu_{jkt} = 0, \quad j,k = 1,2,...,5. \end{aligned} \tag{60}$$

In order to solve this FBSDEs system we are looking for solutions $\left(\xi_{jk\bullet}, \nu_{jk\bullet}\right)$, $j,k = 1,2,...,5,$ that satisfy the linear transformation:

$$\nu_{jkt} = N_{jkt}\xi_{jkt} + M_{jkt}, \quad j,k = 1,2,...,5, \tag{61}$$

where $N_{jk\bullet}$ and $M_{jk\bullet}$ are stochastic processes to be determined. Taking differentials in (61) we get

$$\begin{aligned} d\nu_{jkt} &= N_{jkt}d\xi_{jkt} + \xi_{jkt}dN_{jkt} + dM_{jkt} \\ &= \xi_{jkt}dN_{jkt} + dM_{jkt} - \left[\left(B_k^D N_{jkt}^2 + k_1^D B_k^D N_{jkt}\right)\xi_{jkt} + B_k^D N_{jkt} M_{jkt}\right]dt, \end{aligned}$$

while the backward equation of (60) may be written as

$$d\nu_{jkt} = \left\{\left[\left(r + k_1^D B_k^D\right)N_{jkt} + \left(k_1^D\right)^2 B_k^D\right]\xi_{jkt} + \left(r + k_1^D B_k^D\right)M_{jkt} - \eta_1^U\right\}dt.$$

Sufficient conditions for the latter to be equivalent are provided by

$$\begin{aligned} dN_{jkt} &= \left[B_k^D N_{jk}^2 + \left(2k_1^D B_k^D + r\right)N_{jkt} + \left(k_1^D\right)^2 B_k^D\right]dt, \\ \lim_{t\to\infty} N_{jkt} &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which is a backward RE that can be solved numerically for $N_{jk\bullet}^D$, $j,k = 1,2,...,5,$ and by

$$\begin{aligned} dM_{jkt} &= \left[\left(B_k^D N_{jk}^U + r + k_1^D B_k^D\right)M_{jkt} - \eta_1^U\right]dt, \\ \lim_{t\to\infty} M_{jkt} &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which given the above solution is a backward linear first-order SDE that can be easily solved for $M_{jk\bullet}^D$, $j,k = 1,2,...,5.$

Substituting the linear solution form of (61) to the forward equation of the FBSDEs system (60), we obtain

$$\begin{aligned} d\xi_{jkt} &= \left[-B_k^D\left(N_{jkt} + k_1^D\right)\xi_{jkt} - B_k^D M_{jkt}\right]dt, \\ \xi_{000} &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which is a forward linear SDE that can be solved for $\xi_{jk\bullet}$, $j,k = 1,2,...,5.$ Then the backward adjoint variable $\nu_{jk\bullet}$, $j,k = 1,2,...,5,$ follows from the linear transformation of (61).

Given the obtained solution $\left(\xi_{jk}, \nu_{jk}\right)$, $j,k = 1,2,...,5,$ of the FBSDEs system, as described above, we may put in use (45) and (59) to derive that the upstream country water resources state equation of (3) and the adjoint variable of (56) form the subsequent system of FBSDEs:

$$\begin{aligned} dW_{jt}^U &= \left[-k_1^U B_j^U W_{jt}^U + B_j^U \mu_{jkt} + B_j^U \nu_{jkt} + W_t - A_j^U + k_2^U B_j^U\right]dt, \\ d\mu_{jkt} &= \left[-\left(k_1^U\right)^2 B_j^U W_{jt}^U + \left(k_1^U B_j^U + r\right)\mu_{jkt} + k_1^U B_j^U \nu_{jkt} - k_1^U A_j^U + k_1^U k_2^U B_j^U\right]dt, \\ W_{00}^U &= wr_0, \quad \lim_{t\to\infty}\mu_{jkt} = 0, \quad j,k = 1,2,...,5. \end{aligned} \tag{62}$$

To find a solution process pair $\left(W_{j\bullet}^U, \mu_{jk\bullet}\right)$, $j,k = 1,2,...,5,$ for this system of FBSDEs, we impose the linear transformation:

$$\mu_{jkt} = \Lambda_{jkt} W_{jt}^{U} + \Xi_{jkt}, \quad j,k = 1,2,...,5, \tag{63}$$

where $\Lambda_{jk\bullet}$ and $\Xi_{jk\bullet}$ are stochastic processes to be determined. Taking differentials in (63) we have that

$$\begin{aligned} d\mu_{jkt} &= \Lambda_{jkt} dW_{jt}^{U} + W_{jt}^{U} d\Lambda_{jkt} + d\Xi_{jkt} \\ &= W_{jt}^{U} d\Lambda_{jkt} + d\Xi_{jkt} \\ &+ \left\{ \left[B_j^U \Lambda_{jkt}^2 - k_1^U B_j^U \Lambda_{jkt} \right] W_{jt}^U + B_j^U \Lambda_{jkt} \Xi_{jkt} + B_j^U \nu_{jkt} \Lambda_{jkt} + \left[W_t - A_j^U + k_2^U B_j^U \right] \Lambda_{jkt} \right\} dt, \end{aligned}$$

while the backward equation of (62) may be reformulated as

$$d\mu_{jkt} = \left\{ \left[-\left(k_1^U\right)^2 B_j^U + \left(k_1^U B_j^U + r\right) \Lambda_{jkt} \right] W_{jt}^U + \left(k_1^U B_j^U + r\right) \Xi_{jkt} + k_1^U B_j^U \nu_{jkt} - k_1^U A_j^U + k_1^U k_2^U B_j^U \right\} dt .$$

Sufficient conditions for the latter to be equivalent are given as follows:

$$\begin{aligned} d\Lambda_{jkt} &= \left[-B_j^U \Lambda_{jkt}^2 + \left(2k_1^U B_j^U + r\right) \Lambda_{jkt} - \left(k_1^U\right)^2 B_j^U \right] dt, \\ \lim_{t\to\infty} \Lambda_{jkt} &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which is a backward RE that can be solved numerically for $\Lambda_{jk\bullet},\ j,k = 1,2,...,5,$ and

$$\begin{aligned} d\Xi_{jkt} &= \left\{ \begin{aligned} &\left[-B_j^U \Lambda_{jkt} + \left(k_1^U B_j^U + r\right) \right] \Xi_{jkt} - B_j^U \nu_{jkt} \Lambda_{jkt} - \left[W_t - A_j^U + k_2^U B_j^U \right] \Lambda_{jkt} \\ &+ k_1^U B_j^U \nu_{jkt} - k_1^U A_j^U + k_1^U k_2^U B_j^U \end{aligned} \right\} dt, \\ \lim_{t\to\infty} \Xi_{jkt} &= 0, \quad j,k = 1,2,...,5, \end{aligned}$$

which given the above solution is a backward linear first-order SDE that can be easily solved for $\Xi_{jk\bullet},\ j,k = 1,2,...,5.$

Substituting the linear transformation of (63) to the forward equation of the FBSDEs system (62), we deduce that

$$\begin{aligned} dW_{jt}^U &= \left\{ \left[-k_1^U B_j^U + B_j^U \Lambda_{jkt} \right] W_{jt}^U + B_j^U \Xi_{jkt} + B_j^U \nu_{jkt} + W_t - A_j^U + k_2^U B_j^U \right\} dt, \\ W_{00}^U &= w_0^U, \quad j,k = 1,2,...,5, \end{aligned}$$

which is a forward linear SDE that can be solved for $W_{j\bullet}^U,\ j = 1,2,...,5.$ Then the backward adjoint variable $\mu_{jk\bullet},\ j,k = 1,2,...,5$ follows readily from the linear transformation of (63).

Given now the solutions $\left(\xi_{jk}, \nu_{jk}\right),\ \left(W_{j\bullet}^U, \mu_{jk\bullet}\right),\ j,k = 1,2,...,5,$ of the FBSDES systems (60) and (62), respectively, we may combine (45) and (59) to write equivalently the Hamiltonian FBSDEs state system of the downstream country as

$$\begin{aligned} dS_{jkt} &= \begin{bmatrix} -k_1^U B_j^U W_{jt}^U - k_1^D B_k^D S_{jkt} + B_k^D \lambda_{jkt}^D + B_j^U \mu_{jkt} + B_j^U \nu_{jkt} + W_t - A_j^U + k_2^U B_j^U \\ +R_t - O_t - A_k^D + k_2^D B_k^D \end{bmatrix} dt, \\ d\lambda_{jkt}^D &= \left[-\left(k_1^D\right)^2 B_k^D S_{jkt} + \left(r + k_1^D B_k^D\right) \lambda_{jkt}^D - k_1^D A_k^D + k_1^D k_2^D B_k^D - \eta_1^D \right] dt, \\ S_{000} &= s_0, \quad \lim_{t\to\infty} \lambda_{jkt}^D = 0, \quad j,k = 1,2,...,5. \end{aligned} \tag{64}$$

Imposing once again a solution $\left(S_{jk\bullet}, \lambda_{jk\bullet}^U\right),\ j,k = 1,2,...,5,$ that satisfies the linear transformation:

$$\lambda_{jkt}^{D} = \Pi_{jkt} S_{jkt} + \Sigma_{jkt}, \quad j,k = 1,2,...,5, \tag{65}$$

we will determine in what follows the stochastic processes $\Pi_{jk\bullet}$ and $\Sigma_{jk\bullet}$. Taking differentials in (65) we have that

$$\begin{aligned} d\lambda_{jkt}^{D} &= \Pi_{jkt} dS_{jkt} + S_{jkt} d\Pi_{jkt} + d\Sigma_{jkt} \\ &= S_{jkt} d\Pi_{jkt} + d\Sigma_{jkt} + \left\{ \begin{aligned} &\left[B_k^D \Pi_{jkt}^2 - k_1^D B_k^D \Pi_{jkt} \right] S_{jkt} + B_k^D \Pi_{jkt} \Sigma_{jkt} - k_1^U B_j^U W_j^U \Pi_{jkt} \\ &+ \left[B_j^U \mu_{jkt} + B_j^U \nu_{jkt} + W_t - A_j^U + k_2^U B_j^U + R_t - O_t - A_k^D + k_2^D B_k^D \right] \Pi_{jkt} \end{aligned} \right\} dt, \end{aligned}$$

while the backward equation of (64) may be written equivalently as

$$d\lambda_{jkt}^{D} = \left\{ \left[-\left(k_1^D\right)^2 B_k^D + \left(r + k_1^D B_k^D\right) \Pi_{jkt} \right] S_{jkt} + \left(r + k_1^D B_k^D\right) \Sigma_{jkt} - k_1^D A_k^D + k_1^D k_2^D B_k^D \right\} dt..$$

Sufficient conditions for the latter to be equivalent are provided by

$$d\Pi_{jkt} = \left[-B_k^D \left(\Pi_{jk}^U\right)^2 + \left(2k_1^D B_k^D + r\right) \Pi_{jkt}^U - \left(k_1^D\right)^2 B_k^D \right] dt,$$

$$\lim_{t\to\infty} \Pi_{jkt} = 0, \quad j,k = 1,2,...,5,$$

which is a backward RE that can be solved numerically for $\Pi_{jk\bullet}, \ j,k = 1,2,...,5,$ and by

$$d\Sigma_{jkt} = \left\{ \begin{aligned} &\left[-B_k^D \Pi_{jkt} + \left(k_1^D B_k^D + r\right) \right] \Sigma_{jkt} \\ &- \left[-k_1^U B_j^U W_j^U + B_j^U \mu_{jkt} + B_j^U \nu_{jkt} + W_t - A_j^U + k_2^U B_j^U + R_t - O_t - A_k^D + k_2^D B_k^D \right] \Pi_{jkt} \\ &- k_1^D A_k^D + k_1^D k_2^D B_k^D \end{aligned} \right\} dt,$$

$$\lim_{t\to\infty} \Sigma_{jkt} = 0, \quad j,k = 1,2,...,5,$$

which given the above solution is a backward linear first-order SDE that can be easily solved for $\Sigma_{jk\bullet}, \ j,k = 1,2,...,5.$

Substituting the linear transformation (65) to the forward equation of the FBSDEs system (64) we obtain

$$dS_{jkt} = \left\{ \begin{aligned} &B_k^D \left[\Pi_{jkt} - k_1^D \right] S_{jkt} + B_k^D \Sigma_{jkt} - k_1^U B_j^U W_{jt}^U + B_j^U \mu_{jkt} + B_j^U \nu_{jkt} \\ &+ W_t - A_j^U + k_2^U B_j^U + R_t - O_t - A_k^D + k_2^D B_k^D \end{aligned} \right\} dt,$$

$$S_{000} = s_0, \quad j,k = 1,2,...,5,$$

which is a forward linear SDE that can be solved for $S_{jk\bullet}, \ j,k = 1,2,...,5.$ Then the backward adjoint variable $\lambda_{jk\bullet}^D, \ j,k = 1,2,...,5,$ follows immediately from the linear transformation of (65). Clearly, the optimal water abstraction policies $w_{jk\bullet}^U, w_{jk\bullet}^D, \ j,k = 1,2,...,5,$ of the upstream and downstream countries follow from (59) and (51), respectively.

APPENDIX 3 – SEQUENTIAL MONTE CARLO

The particle filter methodology can be applied to state space models of the general form:

$$y_T \sim p(y_t \mid x_t), s_t \sim p(s_t \mid s_{t-1}), \tag{66}$$

where s_t is a state variable. For general introductions see *Gordon* (1997), *Gordon et al.* (1993), *Doucet et al.* (2001) and *Ristic et al.* (2004).

Given the data Y_t the posterior distribution $p(s_t \mid Y_t)$ can be approximated by a set of (auxiliary) particles $\left\{s_t^{(i)}, i = 1,...,N\right\}$ with probability weights $\left\{w_t^{(i)}, i = 1,...,N\right\}$ where $\sum_{i=1}^{N} w_t^{(i)} = 1$. The predictive density can be approximated by:

$$p(s_{t+1} \mid Y_t) = \int p(s_{t+1} \mid s_t) p(s_t \mid Y_t) ds_t \simeq \sum_{i=1}^{N} p(s_{t+1} \mid s_t^{(i)}) w_t^{(i)}, \tag{67}$$

and the final approximation for the filtering density is:

$$p(s_{t+1} \mid Y_t) \propto p(y_{t+1} \mid s_{t+1}) p(s_{t+1} \mid Y_t) \simeq p(y_{t+1} \mid s_{t+1}) \sum_{i=1}^{N} p(s_{t+1} \mid s_t^{(i)}) w_t^{(i)}. \tag{68}$$

The basic mechanism of particle filtering rests on propagating $\left\{s_t^{(i)}, w_t^{(i)}, i = 1,\ldots,N\right\}$ to the next step, viz. $\left\{s_{t+1}^{(i)}, w_{t+1}^{(i)}, i = 1,\ldots,N\right\}$ but this often suffers from the weight degeneracy problem. If parameters $\theta \in \Theta \in \Re^k$ are available, as is often the case, we follow *Liu and West* (2001) parameter learning takes place via a mixture of multivariate normals:

$$p(\theta \mid Y_t) \simeq \sum_{i=1}^{N} w_t^{(i)} N\left(\theta \mid a\theta_t^{(i)} + (1-a)\overline{\theta}_t, b^2 V\right)_t, \tag{69}$$

where $\overline{\theta}_t = \sum_{i=1}^{N} w_t^{(i)} \theta_t^{(i)}$, and $V_t = \sum_{i=1}^{N} w_t^{(i)} (\theta_t^{(i)} - \overline{\theta}_t)(\theta_t^{(i)} - \overline{\theta}_t)'$. The constants a and b are related to shrinkage and are determined via a discount factor $\delta \in (0,1)$ as $a = (1-b^2)^{1/2}$ and $b^2 = 1 - [(3\delta - 1)/2\delta]^2$. See also *Casarin and Marin* (2007).

Andrieu and Roberts (2009), *Flury and Shephard* (2011) and *Pitt et al.* (2012) provide the Particle Metropolis-Hastimgs (PMCMC) technique which uses an unbiased estimator of the likelihood function $\hat{p}_N(Y \mid \theta)$ as $p(Y \mid \theta)$ is often not available in closed form.

Given the current state of the parameter $\theta^{(j)}$ and the current estimate of the likelihood, say $L^j = \hat{p}_N(Y \mid \theta^{(j)})$, a candidate θ^c is drawn from $q(\theta^c \mid \theta^{(j)})$ yielding $L^c = \hat{p}_N(Y \mid \theta^c)$. Then, we set $\theta^{(j+1)} = \theta^c$ with the Metropolis - Hastings probability:

$$A = \min\left\{1, \frac{p(\theta^c) L^c}{p(\theta^{(j)}) L^j} \frac{q(\theta^{(j)} \mid \theta^c}{q(\theta^c \mid \theta^{(j)})}\right\}, \tag{70}$$

otherwise we repeat the current draws: $\left\{\theta^{(j+1)}, L^{j+1}\right\} = \left\{\theta^{(j)}, L^j\right\}$.

Hall, Pitt and Kohn (2014) propose an auxiliary particle filter which rests upon the idea that adaptive particle filtering (*Pitt et al*., 2012) used within PMCMC requires far fewer particles that the standard particle filtering algorithm to approximate $p(Y \mid \theta)$. From *Pitt and Shephard* (1999) we know that auxiliary particle filtering can be implemented easily once we can evaluate the state transition density $p(s_t \mid s_{t-1})$. When this is not possible, *Hall et al.* (2014) present a new approach when, for instance, $s_t = g(s_{t-1}, u_t)$ for a certain disturbance. In this case we have:

$$p(y_t \mid s_{t-1}) = \int p(y_t \mid s_t) p(s_t \mid s_{t-1}) ds_t, \tag{71}$$

$$p(u_t \mid s_{t-1}; y_t) = p(y_t \mid s_{t-1}, u_t) p(u_t \mid s_{t-1}) / p(y_t \mid s_{t-1}). \tag{72}$$

If one can evaluate $p(y_t \mid s_{t-1})$ and simulate from $p(u_t \mid s_{t-1}; y_t)$ the filter would be fully adaptable (*Pitt and Shephard*, 1999). One can use a Gaussian approximation for the first-stage proposal $g(y_t \mid s_{t-1})$ by matching the first two moments of $p(y_t \mid s_{t-1})$. So, in some way we find that the approximating density $p(y_t \mid s_{t-1}) = N\left(E(y_t \mid s_{t-1}), V(y_t \mid s_{t-1})\right)$. In the second stage, we know that $p(u_t \mid y_t, s_{t-1}) \propto p(y_t \mid s_{t-1}, u_t) p(u_t)$. For $p(u_t \mid y_t, s_{t-1})$ we know it is multimodal so suppose it has M modes are $\hat{u}_t^m$, for $m = 1, ..., M$. For each mode we can use a Laplace approximation. Let $l(u_t) = log\left[p(y_t \mid s_{t-1}, u_t) p(u_t)\right]$. From the Laplace approximation we obtain:

$$l(u_t) \simeq l(\hat{u}_t^m) + \tfrac{1}{2}(u_t - \hat{u}_t^m)' \nabla^2 l(\hat{u}_t^m)(u_t - \hat{u}_t^m). \tag{73}$$

Then we can construct a mixture approximation:

$$g(u_t \mid x_t, s_{t-1}) = \sum_{m=1}^{M} \lambda_m (2\pi)^{-d/2} \mid \Sigma_m \mid^{-1/2} \exp\left\{\tfrac{1}{2}(u_t - \hat{u}_t^m)' \Sigma_m^{-1} (u_t - \hat{u}_t^m\right\}, \tag{74}$$

where $\Sigma_m = -\left[\nabla^2 l(\hat{u}_t^m)\right]^{-1}$ and $\lambda_m \propto \exp\left\{l(u_t^m)\right\}$ with $\sum_{m=1}^{M} = 1$. This is done for each particle s_t^i. This is known as the Auxiliary Disturbance Particle Filter (ADPF).

An alternative is the independent particle filter (IPF) of *Lin et al.* (2005). The IPF forms a proposal for s_t directly from the measurement density $p(y_t \mid s_t)$ although *Hall et al*. (2014) are quite right in pointing out that the state equation can be very informative.

In the standard particle filter of *Gordon et al.* (1993) particles are simulated through the state density $p(s_t^i \mid s_{t-1}^i)$ and they are re-sampled with weights determined by the measurement density evaluated at the resulting particle, viz. $p(y_t \mid s_t^i)$.

The ADPF is simple to construct and rests upon the following steps:

For $t = 0, ..., T-1$ given samples $s_t^k \sim p(s_t \mid Y_{1:t})$ with mass π_t^k for $k = 1, ..., N$.

1) For $k = 1, ..., N$ compute $\omega_{t|t+1}^k = g(y_{t+1} \mid s_t^k)\pi_t^k$, $\pi_{t|t+1}^k = \omega_{t|t+1}^k / \sum_{i=1}^{N} \omega_{t|t+1}^i$.

2) For $k = 1, ..., N$ draw $\tilde{s}_t^k \sim \sum_{i=1}^{N} \pi_{t|t+1}^i \delta_{s_t}^i (ds_t)$.

3) For $k = 1, ..., N$ draw $u_{t+1}^k \sim g(u_{t+1} \mid \tilde{s}_t^k, y_{t+1})$ and set $s_{t+1}^k = h(s_t^k; u_{t+1}^k)$.

4) For $k = 1, ..., N$ compute

$$\omega_{t+1}^k = \frac{p(y_{t+1} \mid s_{t+1}^k) p(u_{t+1}^k)}{g(y_{t+1} \mid s_t^k) g(u_{t+1}^k \mid \tilde{s}_t^k, y_{t+1})}, \qquad \pi_{t+1}^k = \frac{\omega_{t+1}^k}{\sum_{i=1}^{N} \omega_{t+1}^i}. \tag{75}$$

It should be mentioned that the estimate of likelihood from ADPF is:

$$p(Y_{1:T}) = \prod_{t=1}^{T}\left(\sum_{i=1}^{N}\omega_{t-1|t}^{i}\right)\left(N^{-1}\sum_{i=1}^{N}\omega_{t}^{i}\right). \quad (76)$$

Particle Metropolis Adjusted Langevin Filters

Nemeth et al. (2014) provide a particle version of a Metropolis Adjusted Langevin algorithm (MALA). In Sequential Monte Carlo we are interested in approximating $p\left(s_t \mid Y_{1:t},\theta\right)$. Given that:

$$p\left(s_t \mid Y_{1:t},\theta\right) \propto g\left(y_t \mid x_t,\theta\right)\int f\left(s_t \mid s_{t-1},\theta\right) p\left(s_{t-1} \mid y_{1:t-1},\theta\right) ds_{t-1}, \quad (77)$$

where $p\left(s_{t-1} \mid y_{1:t-1},\theta\right)$ is the posterior as of time $t-1$. If at time $t-1$ we have a set of particles $\left\{s_{t-1}^{i},\ i=1,\ldots,N\right\}$ and weights $\left\{w_{t-1}^{i},\ i=1,\ldots.N\right\}$ which form a discrete approximation for $p(s_{t-1} \mid y_{1:t-1},\theta)$ then we have the approximation:

$$\hat{p}\left(s_{t-1} \mid y_{1:t-1},\theta\right) \propto \sum_{i=1}^{N} w_{t-1}^{i} f\left(s_t \mid s_{t-1}^{i},\theta\right). \quad (78)$$

See *Andrieu et al*. (2010) and *Cappe at al.* (2005) for reviews. From (78) *Fernhead* (2007) makes the important observation that the joint probability of sampling particle s_{t-1}^{i} and state s_t is:

$$\omega_t = \frac{w_{t-1}^{i} g\left(y_t \mid s_t,\theta\right) f\left(s \mid s_{t-1}^{i},\theta\right)}{\xi_t^{i} q\left(s_t \mid s_{t-1}^{i}, y_t,\theta\right)}, \quad (79)$$

where $q\left(s_t \mid s_{t-1}^{i}, y_t,\theta\right)$ is a density function amenable to simulation and

$$\xi_t^{i} q\left(s_t \mid s_{t-1}^{i}, y_t,\theta\right) \simeq c g\left(y_t \mid s_t,\theta\right) f\left(s_t \mid s_{t-1}^{i},\theta\right), \quad (80)$$

and c is the normalizing constant in (77).

In the MALA algorithm of Roberts and Rosenthal (1998)[10] we form a proposal:

$$\theta^{c} = \theta^{(s)} + \lambda z + \tfrac{\lambda^2}{2}\nabla \log\, p(\theta^{(s)} \mid Y_{1:T}), \quad (81)$$

where $z \sim N(0,I)$ which should result in larger jumps and better mixing properties, plus lower autocorrelations for a certain scale parameter λ . Acceptance probabilities are:

$$a\left(\theta^{c} \mid \theta^{(s)}\right) = \min\left\{1, \frac{p\left(Y_{1:T} \mid \theta^{c}\right) q\left(\theta^{(s)} \mid \theta^{c}\right)}{p\left(Y_{1:T} \mid \theta^{(s)}\right) q\left(\theta^{c} \mid \theta^{(s)}\right)}\right\}. \quad (82)$$

Using particle filtering it is possible to create an approximation of the score vector using Fisher's identity:

$$\nabla \log p\left(Y_{1:T} \mid \theta\right) = E\left[\nabla \log p\left(s_{1:T}, Y_{1:T} \mid \theta\right) \mid Y_{1:T},\theta\right], \quad (83)$$

which corresponds to the expectation of:

[10]The benefit of MALA over Random-Walk-Metropolis arises when the number of parameters n is large. This happens because the scaling parameter λ is $O(n^{-1/2})$ for Random-Walk-Metropolis but it is $O(n^{-1/6})$ for MALA, see Roberts et al. (1997) and Roberts and Rosenthal (1998)

$$\nabla \log p\left(s_{1:T}, Y_{1:T} \mid \theta\right) = \nabla \log p\left(\mid s_{1:T-1}, Y_{1:T-1} \mid \theta\right) + \nabla \log g\left(y_T \mid s_T, \theta\right) + \nabla \log f\left(s_T \mid s|_{T-1}, \theta\right),$$

over the path $s_{1:T}$. The particle approximation to the score vector results from replacing $p\left(s_{1:T} \mid Y_{1:T}, \theta\right)$ with a particle approximation $\hat{p}\left(s_{1:T} \mid Y_{1:T}, \theta\right)$. With particle i at time $t-1$ we can associate a value $\alpha_{t-1}^i = \nabla \log p\left(s_{1:t-1}^i, Y_{1:t-1} \mid \theta\right)$ which can be updated recursively. As we sample κ_i in the APF (the index of particle at time $t-1$ that is propagated to produce the i-th particle at time t) we have the update:

$$\alpha_t^i = a_{t-1}^{\kappa_i} + \nabla \log g\left(y_t \mid s_t^i, \theta\right) + \nabla \log f\left(s_t^i \mid s_{t-1}^i, \theta\right). \tag{84}$$

To avoid problems with increasing variance of the score estimate $\nabla \log p(Y_{1:t} \mid \theta)$ we can use the approximation:

$$\alpha_{t-1}^i \sim N(m_{t-1}^i, V_{t-1}). \tag{85}$$

The mean is obtained by shrinking α_{t-1}^i towards the mean of α_{t-1} as follows:

$$m_{t-1}^i = \delta \alpha_{t-1}^i + (1-\delta) \sum_{i=1}^{N} w_{t-1}^i \alpha_{t-1}^i, \tag{86}$$

where $\delta \in (0,1)$ is a shrinkage parameter. Using Rao-Blackwellization one can avoid sampling α_t^i and instead use the following recursion for the means:

$$m_t^i = \delta m_{t-1}^{\kappa_i} + (1-\delta) \sum_{i=1}^{N} w_{t-1}^i m_{t-1}^i + \nabla \log g\left(y_t \mid s_t^i, \theta\right) + \nabla \log f\left(s_t^i \mid s_{t-1}^{\kappa_i}, \theta\right), \tag{87}$$

which yields the final score estimate:

$$\nabla \log \hat{p}\left(Y_{1:t} \mid \theta\right) = \sum_{i=1}^{N} w_t^i m_t^i. \tag{88}$$

As a rule of thumb *Nemeth et al.* (2014) suggest taking $\delta = 0.95$. Furthermore, they show the important result that the algorithm should be tuned to the asymptotically optimal acceptance rate of 15.47% and the number of particles must be selected so that the variance of the estimated log-posterior is about 3. Additionally, if measures are not taken to control the error in the variance of the score vector, there is no gain over a simple random walk proposal.

Of course, the marginal likelihood is:

$$p\left(Y_{1:T} \mid \theta\right) = p\left(y_1 \mid \theta\right) \prod_{t=2}^{T} p\left(y_t \mid Y_{1:t-1}, \theta\right), \tag{89}$$

where

$$p\left(y_t \mid Y_{1:t-1}, \theta\right) = \int g(y_t \mid s_t) \int f\left(s_t \mid s_{t-1}, \theta\right) p\left(s_{t-1} \mid Y_{1:T-1}, \theta\right) ds_{t-1} ds_t, \tag{90}$$

provides, in explicit form, the predictive likelihood.