

# **Planning and Operation of Hydropower Reservoir in Tekeze Basin Considering Hydrological Variability and Climate Change**

**PhD Dissertation**

**By**

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Addis Ababa Institute of Technology  
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**PLANNING AND OPERATION OF HYDROPOWER  
RESERVOIR IN TEKEZE BASIN CONSIDERING  
HYDROLOGICAL VARIABILITY AND CLIMATE CHANGE**

By  
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## **DECLARATION**

I at this moment declare that I have prepared this Doctoral dissertation independently and that only those sources, aide, and advisors that are duly noted and cited herein have been used and consulted. I had fully mentioned and referenced all materials and results that are not original to this work.

Fikru Fentaw Abera

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Signature

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Date

## DEDICATION

This work dedicated to:

- ⊕ My father, Fentaw Abera, without you, this chapter of my life would never have been written. We loved you so much.
- ⊕ The wise females that are always at my side: my wife (*Woinshet*), my little daughter (*Esetemariam*) and the soul of my mother (*Asrebeb*)

## **ABSTRACT OF THE DISSERTATION**

Reservoirs are built to manage surface water resources used to balance between water resources and demands. Water in the arid, semi-arid and other climate regions like Ethiopia has available finite, but the demand increases. Hence reservoirs should be optimally operated in this semi-arid area to use water most efficiently. This study was conducted to assess hydrological variability and climate change impacts on the operation of Tekeze hydropower reservoir in Tekeze River basin. In this basin annual and inter-annual climate variability of precipitation and climate change uncertainties are present challenges for water resources planning and management.

This study contributed to provide a scientific basis for the changing characteristics of precipitation and streamflow of Tekeze basin. The research is carried out using Mann-Kendall (MK) test and Indicators of Hydrologic Alteration (IHA) to determine the potential trends and variability of rainfall and streamflow. The trend in mean monthly precipitation data shows increasing trends in the South-eastern part of the Tekeze basin whereas decreasing trend in the North-western part of the basin. The streamflow trend analysis also showed a significant increasing trend during wet seasons, in contrast dry season showed a significant decreasing trend. Indicators of Hydrologic Alteration (IHA) used to evaluate hydrologic variables and trends generated from daily streamflow data at Embamadre due to Tekeze hydropower reservoir operation. The significant results in the streams downstream of Tekeze hydropower reservoir had increased minimum flow, decreased maximum flows, decreased rise and fall rates, reduced wet season monthly flow. All these hydro-climatological variability influence Tekeze hydropower reservoirs planning and operation. This would be valuable for the water managers and decision makers to make better decision on integrated water resources management and ecological environment assessment in the future.

Assessment of Tekeze River basin water resources undertaken through the application of bias-corrected ensemble COordinated Regional climate Downscaling Experiment in African domain (CORDEX-Africa) Regional Climate Models (RCMs) under Representative Concentration Pathway RCP4.5 and RCP8.5 climate scenarios in the 2020s, 2050s and 2080s used as an input to Soil and Water Assessment Tool (SWAT). This study compares the performance of different bias correction methods successfully, in particular, the result of both precipitation and temperature were greatly improved by the distribution mapping (DM) bias correction. Results showed that an increase in rainfall and temperature in the future would be critical to future inflow in Tekeze hydropower reservoir, with rainfall variability having a more significant impact than temperature variability. For all future time periods, both the scenarios produce moderate increases in annual and seasonal streamflow. Due to the future changes of streamflow which is an input for reservoir planning and operation, climate change scenarios should incorporate into the operation of hydropower dams and reservoirs in Tekeze basin.

US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM), a network flow based reservoir system operations optimization monthly model was used to reproduce optimum hydropower reservoir storage, release and water level on Tekeze hydropower reservoir. In current operation, HEC-ResPRM well optimized Tekeze hydropower reservoir and showed an increase in power storage, pool level and release compared to current actual hydropower reservoir operation status. Future optimized power storage in the operational Tekeze hydropower reservoir is expected to increase up to 25% and 30% under RCP4.5 and RCP8.5 climate scenarios, respectively. This result indicates that Tekeze hydropower reservoir operation affected by future climate change. Therefore, it is better to improve this reservoir operation before investing into newly planned hydropower reservoirs in the basin. This analysis shows that integrating hydrological variability and future climate

scenarios into optimal hydropower reservoir operation and other water resources planning and development are essential in Tekeze river basin and other river basins projects in Ethiopia.

Keywords: Hydrological variability, SWAT, CORDEX-Africa, RCP, Climate Change, HEC-ResPRM, Hydropower, Reservoir operation, Optimization, Tekeze Basin

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Fikru Fentaw Abera

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## PREFACE

The present thesis, entitled “Planning and Operation of Hydropower Reservoir in Tekeze Basin considering Hydrological Variability and Climate Change” has been submitted and defended as one of the requirements for the PhD Degree at the School of Civil and Environmental Engineering (Addis Ababa Institute of Technology) under the supervision of Dr.-Ing Dereje Hailu, Professor Assefa M. Melesse and Dr. Agizew Nigussie. The PhD project run from December 2013 to July 2018 and was funded by Ethiopian Ministry of Education.

The content of the PhD thesis is based on four papers published in scientific journals. In the text, the papers are referred to by their appendix number written with Arabic numbers.

1. Fikru Fentaw, Dereje Hailu, Agizew Nigussie and Assefa M. Melesse, (2018), Rainfall and Streamflow Variability in Tekeze River Basin, Ethiopia, a chapter in the book titled: Extreme Hydrology and Climate Variability: Monitoring, Modeling, Adaptation and Mitigation, Assefa M. Melesse et al. (Eds). Elsevier Publisher, (Accepted for publication)
2. Fikru Fentaw, Assefa M. Melesse, Dereje Hailu, Agizew Nigussie (2018), Impacts of Climate Changes on the Water Resources of Tekeze River Basin part of Eastern Nile, Ethiopia; Geophysical Research, *Vol.20, EGU2018-3102 Conference Paper*.
3. Fikru Fentaw, Dereje Hailu, Agizew Nigussie, Assefa M. Melesse (2018), Climate Change Impacts on the Hydrology of Tekeze Basin, Ethiopia: a projection of Rainfall-Runoff for Future Water Resources Planning, *Water Conservation Science and Engineering journal*, Springer, doi:[10.1007/s41101-018-0057-3](https://doi.org/10.1007/s41101-018-0057-3)
4. Fikru F. Abera, Dereje H. Asfaw, Agizew N. Engida and Assefa M. Melesse (2018), Optimal Operation of Hydropower Reservoir under Climate Change: the case of Tekeze Reservoir, Eastern Nile; *Water2018*, 10(3), 273; doi:[10.3390/w10030273](https://doi.org/10.3390/w10030273)

# TABLE OF CONTENTS

Content	Page
<b>ABSTRACT OF THE DISSERTATION</b> .....	<b>vi</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>ix</b>
<b>PREFACE</b> .....	<b>xi</b>
<b>TABLE OF CONTENTS</b> .....	<b>xii</b>
<b>LIST OF TABLES</b> .....	<b>xiv</b>
<b>LIST OF FIGURES</b> .....	<b>xv</b>
<b>LIST OF ACRONYMS</b> .....	<b>xviii</b>
<b>1. INTRODUCTION</b> .....	<b>1</b>
<i>1.1 Background</i> .....	<i>1</i>
<i>1.2 Statement of the Problem</i> .....	<i>9</i>
<i>1.3 Objectives and Questions of the Research</i> .....	<i>12</i>
<i>1.4 Dissertation Outline</i> .....	<i>14</i>
<b>2. DESCRIPTION OF THE STUDY AREA</b> .....	<b>16</b>
<i>2.1 Location and Topography</i> .....	<i>16</i>
<i>2.2 Climate and Hydrology</i> .....	<i>17</i>
<i>2.3 Soil and Land use</i> .....	<i>18</i>
<i>2.4 Water Resources Potential</i> .....	<i>21</i>
<b>3. RAINFALL AND STREAMFLOW VARIABILITY IN TEKEZE RIVER BASIN, ETHIOPIA<sup>1</sup></b> .....	<b>24</b>
<i>3.1 Introduction</i> .....	<i>25</i>
<i>3.2 Material and Methods</i> .....	<i>30</i>
3.2.1 Datasets used .....	30
3.2.2 Trend analysis methods .....	33
3.2.3 Indicators of Hydrologic Alteration .....	38
<i>3.3 Result and Discussion</i> .....	<i>41</i>
3.3.1 Preliminary Analysis .....	41
3.3.2 Trends of precipitation.....	42
3.3.3 Streamflow Trend and Variability .....	48
3.3.4 Influence of Tekeze reservoir operation on the streamflow regime .....	49
<i>3.4 Conclusive Remarks</i> .....	<i>58</i>

<b>4. CLIMATE CHANGE IMPACT ON THE WATER RESOURCES OF TEKEZE BASIN<sup>2,3</sup></b> .....	<b>60</b>
4.1 <i>Introduction</i> .....	61
4.2 <i>Study Area and Datasets</i> .....	66
4.2.1 Study Area.....	66
4.2.2 Dataset Used.....	69
4.3 <i>Methodology</i> .....	75
4.3.1 Bias Correction Method.....	76
4.3.2 Hydrological Modeling Using SWAT.....	84
4.4 <i>Results and Discussions</i> .....	92
4.4.1 Evaluation of bias correction methods.....	92
4.4.2 Change of Projected Precipitation and Temperature.....	97
4.4.3 SWAT Model Performance.....	102
4.4.4 Streamflow Projection.....	103
4.4.5 Climate Change Impact on Water Resources Planning.....	107
4.5 <i>Conclusive Remarks</i> .....	109
<b>5. TEKEZE HYDROPOWER RESERVOIR OPERATION UNDER CLIMATE CHANGE<sup>4</sup></b> .....	<b>111</b>
5.1 <i>Introduction</i> .....	112
5.2 <i>Material and Methods</i> .....	116
5.2.1 Study Area.....	116
5.2.2 Datasets used.....	117
5.3 <i>Methods</i> .....	118
5.3.1 HEC-ResPRM Optimization Model.....	118
5.3.2 HEC-ResPRM Model Setup.....	122
5.4 <i>Results and Discussions</i> .....	125
5.4.1 Impacts of climate change on reservoir inflow.....	125
5.4.2 Current Reservoir Operation.....	125
5.4.3 Reservoir Operation under Climate Change.....	126
5.5 <i>Conclusive Remarks</i> .....	136
<b>6 CONCLUSIONS AND RECOMMENDATIONS</b> .....	<b>138</b>
6.1 <i>Conclusions</i> .....	138
6.2 <i>Recommendations</i> .....	141
<b>REFERENCES</b> .....	<b>143</b>
<b>APPENDICES</b> .....	<b>161</b>

## LIST OF TABLES

Table	Page
Table 3.1 Location of weather stations and lengths of precipitation series used in this study.	31
<i>Table 3.2</i> Summary of hydrologic parametres used in the IHA and their charactrestics .....	40
Table 3.3 Annual precipitation time series basic statistical properties of the study area .....	42
<i>Table 3.4</i> None parametric RVA scores at Embamadre station of Tekeze River .....	53
Table 4.1 Order of sensitive parameters and their optimal value .....	89
Table 4.2 : SWAT model performance evaluation criteria(Moriasi et al., 2007).....	91
<i>Table 4.3</i> Frequency based statistics of daily observed, raw RCM simulated (raw) and bias corrected precipitation at the selected weather stations of Tekeze basin .....	93
Table 4.4 SWAT hydrological model monthly performance under validation and calibration periods in Tekeze Basin.....	102
Table 4.5 Mean annual and seasonal streamflow change (%) in Tekeze basin at Embamadre from the baseline period (1994-2008) .....	105
<i>Table 5.1</i> Mean annual optimized power storage under climate change scenarios.....	129
Table 5.2 Mean annual optimized pool level variation under RCP4.5 and RCP8.5 climate scenarios in three future time periods.....	132

## LIST OF FIGURES

Figure	Page
Figure 2.1 Location of Tekeze basin .....	17
Figure 2.2 Tekeze basin location, climate and streamflow stations including planned cascade hydropower reservoir.....	23
Figure 3.1 Results of Mann Kendall annual precipitation time series trend test at 95% confidence interval .....	43
<i>Figure 3.2</i> Annual precipitation trend magnitudes at different stations of Tekeze basin.....	44
Figure 3.3 Percentage annual and seasonal trend test results a) Overall negative and positive trends b) significant positive and negative trends at 95% confidence level.....	44
<i>Figure 3.4</i> Mann Kendall Z values at different Tekeze basin stations.....	46
<i>Figure 3.5</i> Results of seasonal precipitation trend magnitude at different weather stations.....	47
Figure 3.6 Annual precipitation increasing and decreasing trends in the Upper parts of Tekeze basin.....	47
<i>Figure 3.7</i> Comparison of median monthly streamflow before and after Tekeze hydropower reservoir dam construction .....	50
<i>Figure 3.8</i> November and August monthly median flow change before and after Tekeze hydropower reservoir construction in Tekeze river.....	51
<i>Figure 3.9</i> Hydrological alteration of 3-, 7-, 30-, and 90-day minimum flow before and after Tekeze hydropower reservoir construction in Tekeze river .....	56
<i>Figure 3.10</i> Hydrological alteration of 3- 7-, 30-, and 90-day maximum flow before and after Tekeze hydropower reservoir construction in Tekeze river .....	57
Figure 4.1 Location of upper Tekeze basin upstream of Embamadre gauging station .....	68
Figure 4.2 Sub-basins of Tekeze basin study area watershed delineated by SWAT.....	68

Figure 4.3 Mean monthly precipitation (mm) and maximum temperature ( $T_{max}$ ) & minimum temperature ( $T_{min}$ ) ( $^{\circ}C$ ) for <i>selected stations of Tekeze basin</i> .....	69
Figure 4.4 Major land use/land cover map of Tekeze Basin study area re-classified by SWAT .....	71
Figure 4.5 Major soil map of Tekeze Basin study area re-classified by SWAT .....	71
Figure 4.6 Conceptual diagram of the SWAT modeling process with climate change scenarios .....	75
Figure 4.7 Comparison of climate scenario data before and after bias correction with respect to observed data at (a) Lalibela, (b) Debretabor, (c) Gonder, and (d) Mekele selected meteorological stations of Tekeze basin.....	95
<i>Figure 4.8</i> Observed, raw RCP simulated and bias corrected values of precipitation at the four selected stations of Tekeze basin.....	96
Figure 4.9 Mean annual and seasonal precipitation variation over Tekeze basin under (a) RCP4.5, and (b) RCP8.5 climate scenarios .....	98
Figure 4.10 Long terms mean annual precipitation trend at Tekeze basin under RCP4.5 and RCP8.5 climate scenarios .....	98
<i>Figure 4.11</i> Change of monthly precipitation amount for the selected scenarios and projected periods. ....	99
Figure 4.12 Mean annual and seasonal temperature projection in Tekeze basin under (a) minimum temperature change at RCP4.5 (b) minimum temperature change at RCP8.5 (c) maximum temperature change at RCP4.5 (d) maximum temperature change at RCP8.5 climate scenarios.....	101
<i>Figure 4.13</i> Rates of change of monthly mean temperature for the selected scenarios and projected periods.....	101

<i>Figure 4.14 Observed and simulated monthly streamflow hydrographs during (a) Calibration and (b) validation periods.</i> .....	103
<i>Figure 4.15 Mean monthly and annual streamflow changes under RCP4.5 and RCP8.5 climate scenarios.</i> .....	106
<i>Figure 5.1 Location of Tekeze hydropower reservoir and weather stations</i> .....	117
<i>Figure 5.2 HEC-ResPRM schematization of Tekeze Hydropower reservoir operation</i> .....	123
<i>Figure 5.3 Annual Tekeze hydropower reservoir inflow trend for future time periods</i> .....	125
<i>Figure 5.4 Mean monthly reservoir inflow and optimized outflow (release) for future time periods under: (a) RCP4.5 climate scenario; (b) RCP8.5 climate scenario.</i> .....	128
<i>Figure 5.5 Monthly optimized reservoir storage variations under RCP4.5 and RCP8.5 climate scenarios for: (a) 2020s; (b) 2050s; (c) 2080s.</i> .....	130
<i>Figure 5.6 Monthly optimum pool level variations under RCP4.5 and RCP8.5 climate scenarios in three time periods: (a) 2020s; (b) 2050s; (c) 2080s.</i> .....	135

## LIST OF ACRONYMS

AR5	IPCC Fifth Assessment Report
AMMA-MIP	African Monsoon Multidisciplinary Analysis-Model Intercomparison Project
CD	Coefficient of Dispersion
CDF	Cumulative Distribution Function
CMIP3	Coupled Model Intercomparison Project phase 3
CMIP5	Coupled Model Intercomparison Project phase 5
CMIP6	Coupled Model Intercomparison Project phase 6
CN	Curve Number
CORDEX	Coordinated Regional Climate Downscaling Experiment
DEM	Digital Elevation Model
DM	Distribution Mapping
ENMSA	Ethiopian National Metrological Service Agency
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GCM	Global Climate Model
GUI	Graphical User Interface
HEC-DSS	HEC's Data Storage System
HEC-PRM	Hydrologic Engineering Center's Prescriptive Reservoir Model
HEC-ResPRM	Hydrologic Engineering Center's Reservoir Evaluation System Prescriptive Reservoir Model
HEC-ResSim	Hydrologic Engineering Center Reservoir Simulation
HRU	Hydrologic Response Unit
IHA	Indicators of Hydrologic Alteration

IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergent Zone
LH-OAT	Latin Hypercube One-factor-AT-a- Time
masl	Meter above sea level
MCM	Million Cubic Meters
MK	Mann-Kendall
MW	Mega Watt
PBIAS	Percent Bias
RVA	Range Variability Approach
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
REMO	Regional Model
SCS	Soil Conservation Service
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topographic Mapping
SWAT	Soil and Water Assessment Tool
USACE	US Army Corps of Engineer's
WAPCOS	Water and Power Consultancy Service (India) limited
WCRP	World Climate Research Program
WMA	World Meteorological Agency

# 1. INTRODUCTION

## 1.1 Background

Water is a unique natural resource essential to meeting human needs and vital to the existence of life on earth. However, water resource distribution is variable in time and space that affects the overall development of water resources infrastructure around the world. Nowadays, effective planning and management of water resources become more critical and challenging due to conflicting demands by various stakeholders, rapid population growth, industrialization, hydropower development, irrigation, urbanization and land degradation (Larson et al., 2013). The impact of climate change on the hydrological cycle may lead to further stress on the management of water resources in the future. As the water resources are inevitably linked with climate, the global climate change has severe implications for them (Bates et al., 2008) and therefore, has led to the vulnerable state of the water resources worldwide.

Therefore, it is essential to meet society's energy and water requirements by using our water resources more efficiently (Ehteram et al., 2017). In this regard, reservoirs are one of the most crucial efficient infrastructure components for integrating water resources development and management (Guo et al., 2011; Li et al., 2010; Lu et al., 2013). Reservoirs alter the spatial and temporal distribution of runoff. So Reservoir serves many purposes, such as municipal, industrial and irrigation needs, flood control, hydropower production, navigation, recreation and ecological requirements (Azizipour et al., 2016; Birhanu et al., 2014; Cheng et al., 2008; Yeh, 1985).

Management of reservoir systems from planning to operation is very challenging since the problem deals with many complex variables like inflows, storages, power production, irrigation, industrial and municipal water supply demands. These types of systems are involved because of the nonlinear storage-inflow relationship, conflicting objectives, and nonlinear constraints. The optimal operation of reservoirs is therefore vital to the efficient development of water resources in a river

basin. Reservoir inflows and water levels are the critical variables for decision making on reservoir operations, particularly during an extreme flood or drought events.

No general algorithm covers all type of reservoir operation problems (Labadie John W., 2004). The choice for techniques usually depends on the reservoir specific system characteristics, data availability, the objectives specified and the constraints imposed. Water resources reservoirs can be operated according to non-adaptive and adaptive operation approaches under climate change conditions in the future periods. In the non-adaptive operation approach the developed operational rules in the historical (base) period are used for operating the reservoir in future periods, and climate change impacts on reservoir operation are investigated. In the adaptive approach dynamic real-time operation rules are modified in future period for adapting to climate change. Different reservoir operation models have been developed and applied for planning studies to formulate and evaluate alternative plans for solving water management problems; for feasibility studies of proposed construction projects as well as for re-operation of existing reservoir systems.

Optimization and simulation are the two primary modelling approaches in system analysis of reservoir operations (Labadie John W., 2004; Wurbs Ralph A., 1993), including hydropower generation problems. Compared with simulation models that describe reservoir system performance under a given set of conditions, optimization models apply mathematical programming to determine a set of decisions that maximize reservoir system performance (Wurbs Ralph A., 1993). Optimization model expresses reservoir operation problems in standard mathematical programming forms and solves them through optimization algorithms. Operation decisions are then determined as outputs of optimization models (Labadie John W., 2004; Liu et al., 2011). This analysis typically involves optimization and simulation models which can provide the quantitative information to improve operational water management. The optimization model is used to minimize or maximize objective function under given constraints, and the simulation model is used to examine how a water system behaves under a given set of control actions. In the past, optimization problems have solved by using Linear Programming, Dynamic Programming, Quadratic Programming, Non-Linear Programming and simulation models (Labadie John W.,

2004; Lu et al., 2013; Wurbs, 2005). Nowadays combinations of simulation and optimization models are used.

Hence, for this study US Army Corps of Engineer's Hydrologic Engineering Centre Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM) Optimization model is an appropriate choice. HEC-ResPRM is a network flow programming prescriptive, optimization, or operating purpose-driven model for reservoir system operations. Prescriptive implies that the model automatically determines the best plan, as contrasted with descriptive models that demonstrate what will happen if a specified plan is adopted. The model suggests promising reservoir operation decisions, driven by quantitative descriptions of operating purpose values, called penalty functions. This represents a new, but well-tested technology, which (together with other optimization and simulation models) has become an increasingly popular tool for reservoir system studies.

Dams/reservoirs have facilitated human utilization and control of rivers by enabling water managers to convert natural flow variability in to water releases governed by human needs that have had a significant impact on freshwater ecosystem and species. Dams/ reservoirs can alter the downstream flow regime by affecting total flow quantity, water quality, magnitude, seasonal timing, duration and rate of change of specific flow events. Several merits and indicators have been proposed to assess the river hydrologic regime alterations after dam construction. The range of variability approach (RVA) based on indicators of hydrologic alteration (IHA) in terms of streamflow magnitude, timing, frequency duration and rate of change are widely used to assess river regime alteration especially the impacts of dam construction (Richter et al., 1996; Yu et al., 2016; Q. Zhang et al., 2014). The approach for assessing hydrologic alteration is based on the differences in streamflow regime characteristics between two defined time periods at a given

stream gauge, for this study at Embamadre stream gauging station in Tekeze River. RVA uses the pre-impact natural variations of IHA parameter values as a reference for defining the extent to which natural flow regime have been altered. The advantage of this method is that it rigorously evaluates changes in Tekeze river hydrological conditions before and after dam construction. By doing so, it quantifies the magnitude of impacts and yields management relevant information that can be used to modify reservoir operations for the benefits of stream biota and to guide strategies aimed at restoration of river's ecosystem.

Water resources planning based on the concept of a stationary climate is increasingly considered inadequate for sustainable water resources management (Milly et al., 2008). Hydrological cycle and water resources system are influenced by temperature and precipitation variability's and human activities. Mainly, climate variability and change will have various impacts on water-resource infrastructure (Stocker et al., 2013). Hence, it is essential to study the effects of climate variability and change on past (historical) and future water resources under different climate change scenarios and time periods. Changing patterns of rainfall and its impact on surface water resources sustainability which includes the availability, management and utilization is an important climatic problem for the societies today. Thus, understanding of the regional level of inter-annual and spatial rainfall variability from past data is of important pre-requisites for enhancing the management of water to mitigate the negative effects of floods and droughts.

Rainfall is the primary atmospheric factor that directly affects streamflow patterns, so detection of past trend, change and variability in the time series of hydro-climatic variables is very important for understanding the potential impact of future changes of the Nile basin (Tesemma et al., 2010; Tekleab et al., 2013; Zhao et al., 2015). Therefore, assessing rainfall and streamflow variability have been an integral part of water resources planning and management. There are various

parametric and non-parametric tests which were used for identifying trends and variability in hydro-climatologically time series. However, recent studies showed that non-parametric tests are mostly used for non-normally distributed and censored data, including missing values, which are frequently encountered in hydro-climatologically time series (Huang et al., 2014; Shifteh Some'e et al., 2012; Gocic and Trajkovic, 2013; Sen, 1968)). In this Tekeze basin study, the non-parametric Mann-Kendall (MK) test and Theil-Sen's approach was applied for hydro-climatic series over time on seasonal and annual scale to detect the nature and magnitude of change in trends and other fluctuations. Therefore, the detection of rainfall and streamflow trends and variability can be used for hydrological based decision making and further hydrological and climatic modeling.

The hydrologic conditions of the basin need to be adequately understood through solid hydrologic modeling to investigate the long-term availability of water resources under climate change and varying land use patterns (Kim and Kaluarachchi, 2009). The use of hydrological models in planning and management of water resources (Schuol et al., 2008) and analyses of the impact of climate change on water components (Uniyal et al., 2015) has become a norm recently. Climate change effect on water resources analyzed using a combination of hydrologic models and climate change scenarios (Fowler et al., 2007; Xu, 2000; Xu et al., 2005). These hydrologic models provide a link between climate changes and water yields through simulation of hydrologic processes within watersheds. Hydrologic models then allow various simulations to be performed based on user needs. Confidence in the results varies greatly and largely depends on the methods and structure of the climate scenario and the hydrologic model. Climate change impact studies usually consist of forcing hydrologic models with Global Climate Model (GCM) projections. However, there exist many critical challenges in the application of GCMs and hydrological models (Chen et al., 2012; Fowler et al., 2007).

The impact of climate change has been widely studied using GCMs, the most effective tools for exploring the physical processes of the earth's surface-atmosphere system which can provide very credible information regarding historical and future climate. The World Climate Research Programmer's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) and Coupled Model Intercomparison Project phase 5 (CMIP5) datasets have many GCM outputs to advance understanding of past, present, and future climate variability and change. Both datasets use different scenarios describing the amount of greenhouse gas in the atmosphere in the future. CMIP3 uses climate scenarios from the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES). Whereas CMIP5 having higher spatial resolution compared than CMIP3 which built up on CMIP3 and included more idealized process and feedback oriented experiments and output to facilitate understanding of the climate system and has higher spatial resolution uses new established Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011; Taylor et al., 2011), which can depict a wide variety of possible future climate scenarios recommended in the IPCC Fifth Assessment Report (AR5). Thus, RCP scenarios represent an attractive potential approach for further research and assessment, including emissions mitigation and impact analysis (Riahi et al., 2011; Thomson et al., 2011; Vuuren et al., 2011). Another benefit of RCPs' is its better resolution that helps in performing regional and local comparative studies.

Climate change impacts estimated from the use of a single GCM need to be interpreted cautiously because GCM introduced uncertainties. Hence, multi-model ensemble climate simulations have been used in many of the recent studies (Gbobaniyi et al., 2014; Nikulin et al., 2012). The multi-model mean has been found to be giving a better simulation of the climate variables compared to the individual models. However, GCMs are limited to regional studies because their spatial

resolution is too coarse (approximately 100–250 km) to be compatible with hydrological models (Fowler et al., 2007) and require downscaling to an appropriate scale to represent the catchment characteristics.

Progress in regional climate models (RCMs) has recently made to transfer the large-scale information from GCMs to scales (25–50 km), which are closer to the catchment scale. RCMs simulate hydrological components such as runoff in addition to climate variables. But these simulations do not often agree with streamflow observations (Teutschbein and Seibert, 2010) and, thus, might not be directly useful for assessing hydrological impacts at the catchment scale (Graham et al., 2007; Teutschbein and Seibert, 2012). Hence, hydrological variables rarely used directly from RCMs for impact assessment studies.

However, also RCM simulations of temperature and precipitation must be handled with caution as they often show significant biases (Christensen et al., 2008; Teutschbein and Seibert, 2010). These preferences need to be considered carefully before applying these data for future projections. Otherwise, the projections could be misleading. The reasons for such biases include systematic model errors caused by imperfect conceptualization, discretization and spatial averaging within grid cells. The bias makes the use of RCM simulations as direct input data for hydrological impact studies more complicated. One recommendation is to use an ensemble of RCM simulations (Teutschbein and Seibert, 2010) together with bias correction methods. Bias correction methods are applied to help remedy the various problems with biased RCM output. Typical biases are the occurrence of too many wet days with low-intensity rain or incorrect estimation of extreme temperatures (Ines and Hansen, 2006), but also include under or overestimation and inaccurate seasonal variations of precipitation (Christensen et al., 2008; Teutschbein and Seibert, 2010). Several bias correction methods have been developed to downscale climate variables from climate

models (Chen et al., 2011). These plans range from simple scaling approaches to rather sophisticated methods employing probability mapping or weather generators. They were initially designed to downscale GCM data, but can also be applied to adjust RCM-simulated temperature and precipitation (Teutschbein and Seibert, 2012).

Several researchers in the Eastern Nile tried to investigate climate change impacts on water resources by the trend analysis of historical data (Abteu et al., 2009; Conway and Hulme, 1993; Tabari et al., 2015) and future climate projections (Kim and Kaluarachchi, 2009; Setegn et al., 2011). Most of the studies focused on the influence of climate variability, and change in the Eastern Nile has been based on a limited number of GCMs downscaled (dynamic, statistical) RCMs. These studies used different SRES relied on CMIP3 models for all time windows. However, nowadays those scenarios have become outdated and needs to be updated and expanded in scope. Recently the new CMIP5 models typically have more excellent resolution processes, incorporation of additional physics, and better-developed or well-integrated earth system components used. CMIP5 downscaled as ensemble means at COordinated Regional Climate Downscaling Experiment-Africa domain (CORDEX-Africa) with new emission scenario called Representative Concentration Pathways (RCP) which overcomes the shortcoming of SRES scenarios for climate change impact studies in Africa. A Semi distributed continuous hydrological model Soil and Water Assessment Tool (SWAT) is increasingly used for climate change assessment applications in the Eastern Nile basins (Mengistu and Sorteberg, 2012; van Griensven et al., 2012). Hence, SWAT is a suitable hydrologic model to assess impacts of climate change on the water resources of the Eastern Nile basin.

Translating the impacts of climate change affected runoff on hydropower reservoir operation requires coupling of hydrological models and reservoir optimization models. This study integrates

these types of models to provide insight into the impacts of climate change on hydropower reservoir operation. So, this study aims to present a regional overview of Ethiopia's hydropower reservoir operation at Tekeze Hydropower dam project under future climate change by using the projections from SWAT model under ensembles of CORDEX-Africa RCMs outputs for future climate scenarios of RCP4.5 and RCP8.5. Therefore, the US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM) used future inflow generated using calibrated SWAT model to optimally operate Tekeze hydropower reservoir in the face of climate change.

## **1.2 Statement of the Problem**

Water resources problems worldwide in the future are found to become more complex due to population growth, climate variability, regulatory requirements, project planning horizons, temporal and spatial scales, social and environmental considerations, trans-boundary considerations, etc. Water resources planning and management is going to face difficult challenges mainly due to the growing water demand from increasingly populated and complex societies which requires a shift towards an integrated approach; and climate variability and change from a hydrological point of view assumes of stationarity in long term weather conditions not valid anymore; and requires seeking for new approaches, strategies and tools. It has been established that climate variability and change will have impacts on the availability of water resources as well as on the operating policies for water resources systems.

Today, water resources planning under the paradigm of climate change includes a wide range of projected climate scenarios, great variability in future supply projections, temperature-driven increases in water demand, and many other sources of uncertainty. Additionally, the projections are coarse in nature (i.e., produced at a low resolution) compared with the scale of information

utilities directly feed into the water resources planning models. It is then challenging for utilities to incorporate highly uncertain, low-resolution climate change information into water resources planning and management decisions. The uncertainties of climate projections depend on the uncertainties of the scenarios of future emissions, GCMs, downscaling methods and hydrologic modeling used to study the impacts of climate change on watersheds. Therefore, uncertainties of climate change and the future non-stationarity of hydrological regimes require the use of the multi-model ensemble of climate projections in water resources system optimization. A typical method of evaluating effects of climate change on flow regime is to use an ensemble of GCMs, scenarios and statistical downscaling/regional climate models to provide inputs to a hydrological model, and examine the range of effects on statistics of the modeled flows.

Ethiopian government is pursuing plans and programs to use the water resource potential of the 12 river basins of the country for sustainable economic growth and poverty reduction. To alleviate electricity problem, poverty and food insecurity, it is widely recognized to utilize water resources such as Tekeze basin and improve water management practices which was one of the least planned and managed sub-basins of the Nile. Owing to such rapidly developing water resource projects in the basin, there is an increasing need for the management of the available water resources to boost agricultural production and to meet the demand for hydro electrical power production. It needs to be understood when, where and how much water is available and how an intervention plan will be suitable based on historical and future climate variables with the expected changing climate. Despite the importance of precipitation and streamflow to insure sustainable water resource planning and management, long term trends and variability of flow regime and their association with climate change in Tekeze basin are not yet well understood. Therefore, it is necessary to identify the presence of hydro-climatic trends and variability in Tekeze basin as it is a prerequisite

step to understand the cause and effect of trends and the links to water resources and use in the basin.

Climate change will cause changes in the patterns of water cycle and geographical distribution of water resources in the future where impacts will see in climatic factors such as precipitation and temperature. The impact of interest here is on streamflow which is the sources for reservoir operation for hydropower reservoir planning and operations. The resulting flow effects could be in the form of changes in average flows (amount), variability of flow or seasonal variability. Even though there is marked progress in climate research in recent years, the climate of many parts of Nile basin particularly Tekeze basin is still not fully understood. Further derived climate scenarios are very coarse and do not usually adequately capture important regional variations that exist in Tekeze basin's climate.

Regarding research gaps and priorities, there is very little detailed information on the impacts and vulnerabilities of the hydropower reservoir operation in Blue Nile particularly in Tekeze basin specific to climate change and variability by applying ensemble scenarios and outputs of GCMs and RCMs. The greatest challenge is that hydropower reservoir operation is depending on magnitude and timing of streamflow, which in turn is dependent on precipitation. Precipitation makes hydropower reservoir operation one of the most vulnerable to changing climate. Currently, Tekeze hydropower reservoir has not been optimally operated and sometimes not fully functional during dry periods of the year due to fluctuations of the inflow to the reservoirs. To overcome this problem, the reservoir can be operated optimally to get optimum level of release and optimal volumes of storage considering future inflows and needs in the face of climate change. In recent years, combinations of simulation and optimization models are applied in reservoir operation. In

this research, US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Models (HEC-ResPRM), a combination of simulation and optimization model was used.

### **1.3 Objectives and Questions of the Research**

#### ***1.3.1 Objectives of the Research***

The main objective of this PhD research is to predict and assess the potential impact of climate variability and change on the hydrology and hydropower reservoir operation in the Tekeze River basin, Northwest of Ethiopia. This research focuses on the following specific objectives:

- ❖ Investigate the change and variability of long term historical records of precipitation, and streamflow in the Tekeze river basin
- ❖ Quantifying Tekeze river hydrological alterations associated with Tekeze hydropower reservoir dam operation by comparing the hydrological regimes from pre- and post-impact period
- ❖ Investigate the possible effect of climate change on hydro-climatological variables and water resources availability under bias corrected new ensembles of CORDEX-Africa RCMs outputs for future climate scenarios under RCP4.5 and RCP8.5.
- ❖ Apply HEC-ResPRM optimization model to get Tekeze hydropower operation optimal reservoir level and storage for optimal power production including in the face of climate change.

### ***1.3.2 Questions of the Research***

To assess and address the above-mentioned problems and objectives, a number of hypothetical questions can be formulated. Among those:

- ❖ What are the nature of the historical trends and variability in precipitation and streamflow in the Tekeze river basin?
- ❖ How Tekeze hydropower reservoir dam operation can affect downstream river flow?
- ❖ What is the likely trend in precipitation and temperature for the future period under recent RCP climate scenarios compared to the historical periods?
- ❖ How will climate change impact water resources in the Tekeze River Basin?
- ❖ How optimal reservoir operation could be achieved in Tekeze reservoir system in the face of climate change?

## **1.4 Dissertation Outline**

This dissertation includes six chapters as described below. The general flow follows the research process from the introduction and main body of the thesis through to conclusions and recommendations. Each chapter that contains a methodology and analysis also gives the results at the end of that chapter. In conclusion, which is the final chapter a summary made for all the results obtained. Each chapter is self-sustained and includes its conclusive remarks.

**Chapter 1** Introduction: gives a general introduction to climate change and hydrological variability that affect the water resources of the watershed and reservoir operation. This chapter also includes statement of the problem, research objectives, research questions and structure of the dissertation.

**Chapter 2** Description of the Study Area: In this chapter, the description of the study area, topography, climate, hydrology, land use, soil and water resources potential of Tekeze basin was presented.

**Chapter 3** Rainfall & Stream Flow Variability in Tekeze River Basin, Ethiopia: This chapter presents the assessment of long-term changes in the critical hydro-climatic parameters (precipitation and streamflow). The chapter aims to establish if there have been significant trends in hydro-meteorological data. The investigation implemented in Embamadre streamflow and different precipitation gauging stations of the basin. Rainfall data are used to detect patterns in climatic variables. Trends and change points were investigated and summarized in this chapter. Also, the streamflow variability in the watershed and the impact of Tekeze Arch dam hydropower dam/reservoir operation on streamflow regime using indicators of hydrological alteration were analyzed.

**Chapter 4** Climate Change Impacts on the Water Resources of Tekeze basin: describes hydrological modeling in the context of climate change and description of the hydrological model and hydrological processes in the model elaborated. This chapter deals with the description of hydrological and meteorological data used for this study, the methodology that has been employed for bias correction of ensemble CORDEX-Africa RCMs under RCP4.5 and RCP8.5 climate scenarios meteorological data sets, their results and discussion elaborated in detail. This chapter also focuses on setup and calibration of SWAT hydrological model at Tekeze hydropower reservoir watershed, mainly to investigate the effects of climate change on Tekeze hydropower reservoir inflows for the coming 90 years (2011-2100). This chapter focuses on different future climate bias correction methods and modeling of the basin under bias-corrected climate change scenarios and analysis of future time flow carried out.

**Chapter 5** Tekeze Hydropower Reservoir Operation under Climate Change: This chapter describes hydropower reservoir optimal operation using HEC-ResPRM optimization network flow monthly model. This chapter highlights the results of current hydropower reservoir optimal operation and the impacts of climate change on reservoir storage, release and pool level for the future time periods.

Finally, **Chapter 6** summarizes the findings of this dissertation, concluding remarks, recommendation and directions for further studies in the basin.

## **2. DESCRIPTION OF THE STUDY AREA**

### **2.1 Location and Topography**

The Tekeze-Setit-Atbara sub-basin (covers about 227,128 km<sup>2</sup>) is one of the three major sub-basins in the Eastern Nile Basin originate on the Ethiopian plateau (Blue Nile, the Tekeze-Setit-Atbara, and the Baro-Akobo (Sobat) Rivers), and is located at most north-eastern portion of the Eastern Nile Basin. The Tekeze-Setit-Atbara sub-basin consists of the Tekeze river (known as the Setit in Sudan), and its tributaries, the Goang (Atbara in Sudan) and Angereb, all of which originates from the central north and north western highland plateaus of Ethiopia at an altitude of above 3,000 masl and descends to Humera less than an altitude of 800 masl at the Ethio-Sudan border, which also goes down to less than 500 masl at its mouth in the Sudan. Water availability in this sub basin is erratic but it contributes 13% of the Nile flow (Arsano and Tamrat, 2005; Mengistu and Sorteberg, 2012). This study focuses on the Ethiopian portion of Tekeze basin (Figure 2.1) up to Ethio-Sudan border with geographic location 11°40' to 15°12' N, and 36°30' to 39°50'E covers an area of 86,510 square kilometers of which 82,350 Km<sup>2</sup> (95.19%) in Ethiopia and relatively small part of the basin 4,160 km<sup>2</sup> (4.81%) is situated in Eritrea. From its source, a spring around Lalibela in North Wollo, the Tekeze River traverses about 750 km to the Ethio-Sudan border. The topography of Tekeze basin is complex, characterized by rugged topography consisting of mountainous and terrains of gentle slopes, about 70% of the area lies in the highland (above 1,500 masl) and some 40% of its watershed has an altitude of above 2,000 masl. The Tekeze River has the Ras Dashen mountain chain (4,620 masl) in its watershed and Metema low lands at Sudan Border (589masl). Tekeze basin is bordered by the Mereb River basin and Eritrea in the north, Atbara River plains in Sudan in the west, Abay River basin in the south and Danakil basin in the east.

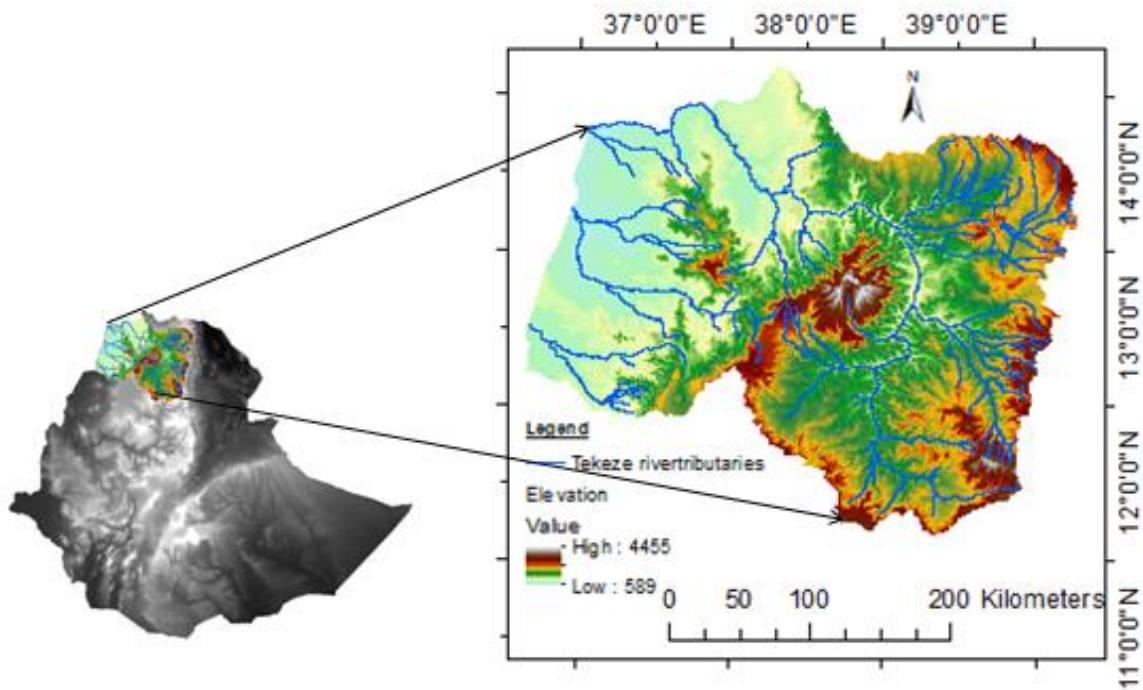


Figure 2.1 Location of Tekeze basin

## 2.2 Climate and Hydrology

The climate of Tekeze basin is a tropical type with semi-arid in the East and North, and partly humid in the South. There are three seasons in Tekeze basin; *Kiremt* (wet) season, *Belg* (minor rainy) season and *Bega* (dry) season. The basin's rainy seasons are, the main rainy season locally known as *Kiremt*, main rainfall season for almost all parts of the basin where more than 70% of the total annual rainfall falling within three-month periods beginning in the late June and lasting until September, and a minor rainy season locally known as *Belg* between February to May in which most parts of the basin receive considerable amount of rainfall. *Bega* season from October to January is mostly a dry season for most parts of the basin. Wide variation in rainfall from year to year is characteristics of the basin. The variations of rainfall over the basin are mainly associated with the seasonal migration of the inter-tropical convergent zone (ITCZ) (Seleshi and Zanke, 2004)

and complex topography. The mean annual rainfall is 600mm in the lowlands and 1,300mm in the Semein Mountains which is increased from North to South parts of the basin.

The spatial distribution of temperature value in Tekeze basin is strongly related to altitude. The area located in the highlands of the basin is characterized by lowest mean monthly temperatures that occur between December and February, in contrary, low land areas near Sudanese border characterized hottest temperature. The temperature characteristics in this basin have large variations in a limited elevation range. The mean monthly temperatures in the basin vary from 10<sup>0</sup>C in the Semein Mountains of Ethiopian highlands to 22<sup>0</sup>C in the highlands and to 26<sup>0</sup>C in the lowlands. Also, the minimum and maximum temperature ranges from 3-21<sup>0</sup>C in the Semein Mountains and 19-43<sup>0</sup>C in the lowlands areas.

The river flow pattern of Tekeze basin typically follows that of rainfall. Maximum discharge occurs in August while it ceases completely during the dry season from October to January. The flows in this basin are highly variable (compared to the Blue Nile and Baro-Akobo-Sobat basins) especially in the crucial low flow months. Seasonal distribution is highly erratic and variable affecting agricultural production and water resources projects of the basin significantly. At Embamadre stream gauging station between 1994 and 2008, the mean annual flow was 190m<sup>3</sup>/s, and the monthly low and high flow periods were the months of May (15 m<sup>3</sup>/s) and August (2187 m<sup>3</sup>/s), respectively.

### **2.3 Soil and Land use**

Soils in the Tekeze basin are classified by the FAO soil classification system (FAO, 1995). There are four major soil types in the Tekeze basin: Vertisols, Cambisols, Leptosols and Alisols. The major soils locations on the basin are Eutric Vertisols on the level lands; Eutric Leptosols, Eutric Vertisols, Eutric Cambisols and Haplic Alisol on the sloping lands; Eutric Leptosols on the steep

lands; and Leptosols on composite landforms. Eutric Vertisols is difficult to cultivate. Eutric Vertisols with soil depths of more than 50 cm are dominant on the level lands while Leptosols are the most common soils on the sloping lands. Soils in the mountains and hilly-land areas are very shallow whereas normally deep in the valleys and lowland areas. The Tekeze river basin highlands support most of the population as they offer a favorable environment for human settlement. Moreover, the volcanic parent material supplies a rich diversity of nutrients that makes the soils more suitable for agriculture (Sonneveld and Keyzer, 2003) but in current agricultural production techniques, this largely exceeds the lands carrying capacity. This is due to loss of topsoil by sheet, rill and gully erosion as well as on land sliding as a result of continued intense land degradation and deforestation (Nyssen et al., 2004).

Tekeze basin dominant land use includes cultivated land, open grass land, sparsely grown wood land, bushes, shrubs and exposed rocks. Recently trees such as Eucalyptus globules and acacia species have been planted in the protected areas. Apart from forests and bushes, other land use types include widely grown rain fed annual crops in the basin area were Tef (*Eragrostis tef*), wheat (*Tritium* species), Barely (*Hordeum vulagaris*), sorghum (*Sorghum bicolor*), beans (*Phaseolus vulgaris*) and Pulses (e.g., *Vacia faba*). From this annual crops *Eragrostis tef* covered large proportion of the cultivated land. Most people in the Tekeze basin lead to a subsistence agrarian life with agricultural crop production has the oldest history in this area. Environmental deterioration caused a declining in production which together with the population increase that created a shortage of land. These processes further led to an expansion of agricultural and grazing activities in to marginal and steep slopes, which accelerated environmental degradation.

This basin characterized by severs land degradation due to population growth, deforestation, repeated drought, over grazing and cultivation on the rugged topography. This region has virtually

lost its forest cover, and left with only remnant vegetation. The present natural vegetation cover comprises of sparse woodland of thorny acacia bushes and scrubs interspersed between cultivated areas. The combination of rugged terrain which is sensitive to erosion as well as difficult for utilization and management, poor surface cover and the prominent gullies have led the region to be considered one of the most degraded and degrading.

Cultivated land is the main dominant land use over the basin, where there is agricultural land expansion due to human economic activities and population pressure. In response to the increasing demands for food production, agricultural lands are expanding at the expense of natural vegetation and grass lands. The natural forest resource of the basin is over exploited and most of the climax vegetation of the basin has disappeared and only little of the original vegetation is evident while only little of the lowland woodlands and bush lands in the Western and Northern parts of the basin are nearer to climax. However, the Afro-alpine and sub-afro-alpine heath vegetation lies above 3,700 to 3,900 masl around Semein Mountains. Rehabilitation activities are under way through area closures, afforestation, plantation programmers and community mobilization only on the North-eastern part of the basin (Gebremedhin et al., 2003). In this basin, the common agricultural land use system is a mixed crop-livestock smallholder farming system with agricultural production in small parcels for subsistence purpose with no external inputs. These changes in land use/land cover system have great impact among others like agro-biodiversity, soil degradation and sustainability of agricultural production.

## **2.4 Water Resources Potential**

Water resources availability is often the most vital factor controlling the economic growth in developing countries like Ethiopia, which depend on agriculture. Ethiopia is endowed with a substantial amount of water resources. The country has adequate average annual rainfall, several major rivers and lakes, and significant hydropower potential sites and groundwater resources. The total renewable surface water resources are estimated at 122 billion cubic meters per year from 12 major river basins and 22 lakes. Renewable groundwater resources are estimated to be about 2.6 billion cubic meters while gross hydro-electric potential about 45,000 MW (160,000GWh/year) with in 299 potential sites and the potentially irrigable land in the country has been estimated at 3.7 million hectares. From these adequate water resources of the country Tekeze basin has a capacity of surface water potential of 8.2 billion cubic meters per year, ground water potential about 0.20 billion cubic meters, gross hydro-electric potential 5980Gwh/year with in 15 potential sites and potential irrigable land from three large scale irrigation projects 83,368 hectares (Awulachew et al., 2007). The surface water resource potential as runoff is impressive all of which disappears without being used and the basin is little developed.

Tekeze river basin study not yet well developed even if preliminary water resources assessment carried out by different water resources researchers and agencies which show different hydropower and irrigation potential of the basin. The Ethiopian valley development studies authority commissioned Water and Power Consultancy Service (India) limited (WAPCOS, 1990) undertake the preliminary water resources development master plan for 14 basins of Ethiopia covering all aspects of water resources development including domestic, agricultural and industrial use, hydropower navigation, flood control, environmental aspects and fisheries that identifies ten potential hydropower sites of Tekeze river basin with technical energy potential of 5588 Gwh/year.

According to NEDECO investigation hydropower potential of the basin is quite large, the river is quite steep and some sites have deep gorges which make ideal dam construction sites easier. However, the draw backs are steep drops and high flows for the short rainy season and the presence of high variability over the year. Tekeze basin has a technical hydropower potential of 5980Gwh/year with in 15 potential sites. This study also estimates the potential for irrigable land to be 45,000hectare for small scale and 207,781 hectare for medium and large scale with most irrigable land found in the lower part of the basin (NEDECO, 1998). Such irrigation scheme would get its water from reservoir dams to be built for hydropower generation. According to Tekeze river basin master plan studies by NEDECO, from 15 potential hydropower sites 10 were selected and made ground checking, and feasibility study carried out for the three cascade TK04, TK05 and TK07 hydropower dam sites (NEDECO, 1998). From these potential sites three planned and operational dam cascades found upstream of Embamadre stream gauged station which includes from upstream to downstream, TK04 (in planning; 133 MW), Tekeze hydropower reservoir or TK05 (completed in 2009; 300 MW), and TK07 (in planning; 321 MW) (Figure 2.2). This study focused only on the operational (TK05) Tekeze arch dam hydropower reservoir. Tekeze hydropower reservoir (TK05) detail characteristics have shown in chapter 5 and in the annex.

The high surface water potential of Tekeze basin also leads to development of small scale irrigation systems. The possibility of using about fifty percent of this potential could irrigate half a million hectares, which could feed three times the population of the region. In order to exploit this potential an ambitious plan of the regional government of Tigray in 1994 established a Commission for Sustainable Agriculture and Environmental Rehabilitation for the Tigray region (Co-SAERT) targeted to bring food self-sufficiency in the region through irrigation agriculture by planning, design and construction of up to 500 small dams to irrigate 50,000 hectares, but up to

2003, around 54 small dams have been built (Haregeweyn et al., 2008), which increase the area of potentially irrigable land by about 2000 hectares in Tigray region (Behailu, 2002) but only small number of small dams built in the portion of Amhara region. A socio-economic impact assessment study conducted for some built small reservoirs/dams indicated that farmers were able to increase crop yields 3 to 7 fold by using irrigation from the water harvesting schemes (Behailu, 2002). This is due to people and livestock have been able to get enough water easily even during drought periods. The reservoirs constructed in the Tekeze basin also contributed greatly to the reduction in soil losses and the off-site effects such as rapid siltation of downstream planned and operational dams and river. This construction of dams for irrigation and hydropower purpose resulted in various economic, hydrologic and ecologic benefits.

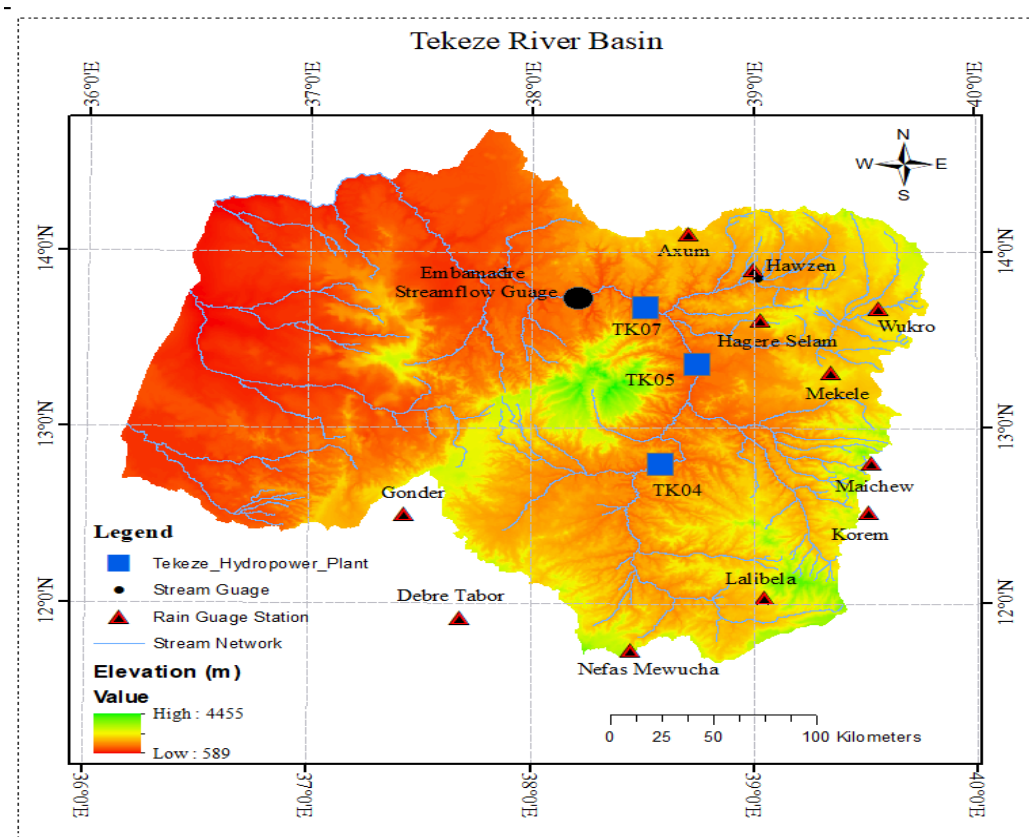


Figure 2.2 Tekeze basin location, climate and streamflow stations including planned cascade hydropower reservoir

### **3. RAINFALL AND STREAMFLOW VARIABILITY IN TEKEZE RIVER BASIN, ETHIOPIA<sup>1</sup>**

**Abstract:** This research was carried out using non-parametric Mann-Kendall test and Indicators of Hydrologic Alteration (IHA) to determine the potential trend and variability of rainfall and streamflow variability in Tekeze River Basin. In this study monthly, seasonal and annual precipitation and streamflow has been analyzed to determine the trends and variability. Precipitation trend analysis result showed many significant trends, increasing trends for Annual, Kiremt and Belg seasons from 1953-2013 throughout the basin. Streamflow trends analysis also showed a decreasing trend in dry season (October to January), in contrary increasing trend observed in the annual, small and high rainy season months over Tekeze basin. The indicators of hydrologic alteration and range variability approach (RVA) methods were used to evaluate the pre- and post-impact hydrologic regimes of Tekeze River due to dam construction. The result showed that Tekeze hydropower reservoir significantly changed the hydrological regime downstream of the dam i.e. the 1-, 3-, 7-, 30-, and 90-day intervals minimum streamflow increased, the 1-, 3-, 7-, 30-, and 90-day intervals maximum streamflow reduced, high pulse count decreased, fall and rise rates decreased, increased in number of annual hydrograph reversals, the number and duration of high and low pulses increased. Hence, investigation of trends in the hydro-climatic variables of Tekeze River basin revealed many significant trends, both increasing and decreasing. The findings may assist water managers in better planning and management of water resources under climate variability and change.

**Keywords:** Hydro-climatic Variability, Hydrologic alteration, Trend Analysis, Rainfall, Streamflow, Tekeze Basin

### **3.1 Introduction**

Water resources problems are found to become more challenging and complex worldwide for future. The complexity of water resources planning, and management is due to the contribution of climate variability, social and environmental considerations, trans-boundary nature of the rivers and population growth. The stress on water resources diversely increased due to the rapid increase in population (Wu et al., 2013). Further, water managers have been concerned about the anticipated impacts of climate variability and change on water resources (Dawadi and Ahmad, 2013; Vedwan et al., 2008). Changes in climate variability enhance the uncertainties in the availability of fresh water for the future (Middelkoop et al., 2001). As a result water resources managers face challenges to meet future water demands on existing water infrastructure that may be inadequate in the future and stress is increasing to meet environmental flow requirements and provide water for the energy needs (McCartney and Menker Girma, 2012; Qaiser et al., 2011). Changes in the hydrological cycle can result from both climate variability and anthropogenic interference. These changes may be gradual (trend) or abrupt (shift). Changing hydrology may lead to under-designed or over-designed projects (Mosquera-Machado and Ahmad, 2007), which may not meet long-term needs; thus, the traditional assumption of stationarity for hydraulic designs requires review (Milly et al., 2008).

Rainfall and river flow in Africa display high levels of variability across a range of spatial and temporal scales, with significant consequences for the management of water resource systems (Conway et al., 2009). Throughout Africa, this variability brings significant implications for society and causes widespread acute human suffering and economic damage. Examples of variability include prolonged periods of high flows for rivers draining large parts of East and central Africa (Conway, 2002). Most parts of East Africa covered with Nile river basin watersheds are sensitive to climate variations as shown in previous studies (Beyene et al., 2010; Kim and

Kaluarachchi, 2009; Setegn et al., 2011) implying that climate change will have a considerable impact on the resource. About 70% of the Nile flow is from the three major sub-basins in the Eastern Nile Basin (the Blue Nile, the Tekeze-Setit-Atbara, and the Baro-Akobo (Sobat) Rivers), and located at the North-eastern portion of the Eastern Nile Basin (Arsano and Tamrat, 2005; Swain, 1997). As the vast majority of agriculture is rain-fed in the Eastern Nile, precipitation plays a pivotal role (Block et al., 2008). Precipitation also plays another equally important role in the Ethiopian highlands, feeding the headwaters of the Blue Nile and Atbara Rivers, which eventually supply the mighty Nile River. Policy and planning tools, including water management, economic, hydropower, and irrigation models for Ethiopia and other downstream countries, rely heavily on precipitation and streamflow as critical parameters. Any rise or fall in the annual and seasonal rainfall in this region leads to stress on average yearly runoff flow in the area with consequent implication on the planning of water resource, water allocation and overall integrated development of the watershed. Changes in precipitation directly affect water resources management, hydrology, agriculture, natural ecosystem, food security, water quality and quantity, and human health. For this reason, it is vital to understanding and predicting the trends and variability of precipitation and streamflow to improve water resources management strategies (Block et al., 2008; Cannarozzo et al., 2006).

Many studies conducted to characterize trends and variability's of rainfall and streamflow time series at various locations across the globe (Casanueva et al., 2013; Melesse et al., 2011; Moges et al., 2014). These studies have adopted several statistical techniques to quantify increasing or decreasing trends in annual and monthly rainfall.

Most studies used trend detection techniques like Mann-Kendal, Spearman rho, and linear regression tests to understand rainfall and streamflow trend and variability in the Eastern Nile

Basin. Many studies on Blue Nile basin have been conducted to detect changing pattern and amounts of rainfall and streamflow in the last decades (Conway and Hulme, 1993; Mengistu et al., 2014; Tabari et al., 2015; Taye and Willems, 2012). All these studies on rainfall, on the other hand, do not show any consistent pattern or trends. Conway and Hulme (1993) reported declining annual rainfall over the Blue Nile, and Tekeze-Atbara basins resulting in a reduction of river flows between the years of 1945 and 1984. In contrast, recent investigations by Tabari et al. (2015) agreed that rainfall over the Upper Blue Nile basin did not show a statistically significant trend. Whereas streamflow showed both statistically significant increasing and decreasing trends in annual and seasonal time scale at the different Blue Nile gauging stations for the last 40 years (1964- 2005). Mengistu et al. (2014) showed that annual and seasonal rainfall for 1981-2010 in the Upper Blue Nile River basin statistically non-significant increasing trends except spring season that shows declining trend in the Northeastern part of the basin.

In Tekeze river basin part of Eastern Nile, there are little local level studies about rainfall and streamflow trends. The long-term trend analysis of rainfall in some stations covering a small part of Tekeze basin was studied various researchers (Gidey et al., 2013; Kiros et al., 2017; Seleshi and Zanke, 2004; Tesfaye et al., 2017). Seleshi and Zanke (2004) attempted to investigate the pattern of rainfall over the upper part of Tekeze River basin by considering only one climatic station. Their output demonstrated that the amount of rainfall remained constant for the past 40 years (1962–2002). Kiros et al. (2017) investigated a decline of rainfall at Geba catchment a tributary of Tekeze River using Mann Kendall trend for the last 40 years. Gidey et al. (2013) indicate that there was a slight decrease in rainfall of upper Tekeze basin considering only part of Tigray region in the year of 1954-2008. However, all the above studies are specific to catchment level not included the

rainfall stations founding in the sources of Tekeze river in the South and Southwest parts of Tekeze basin.

In pursuit of detecting the trend and the shift of trend in hydro-meteorological variables, various statistical methods have been developed and used over the years in Ethiopia (Cheung et al., 2008; David et al., 1999; Tabari et al., 2015; Tesemma et al., 2010). There are various parametric and non-parametric tests which used for identifying trends in hydro-meteorological time series. However, from recent studies, it is found that non-parametric tests mostly used for non-normally distributed and censored data, including missing values, which frequently encountered in hydro-climatologically time series. The non-parametric Mann–Kendall statistical test (Kendal, 1975; Mann, 1945) has commonly been used to quantify the significance of monotonic trends in hydro-meteorological time series (Huang et al., 2014; Shifteh Some'e et al., 2012). The Mann-Kendall test does not provide an estimate of the magnitude of the trend itself. For this purpose, another nonparametric method referred to as the Sen's slope estimate or approach is very popular by the researchers to quantify slope of the pattern (magnitude) (Gocic and Trajkovic, 2013; Sen, 1968). Sen's slope estimator used more robust slope estimate than least-square method because it is insensitive to outliers or extreme values and competes well against simple least squares even for normally distributed data in the time series. However, these cited trend detection methods are not designed to detect the duration or timing of changes. The timing of a shift and change-point tests have been performed in association with a trend test, using the various methods, such as the nonparametric Pettitt test (Pettitt, 1979). The Pettitt test able to detect potential change points in the mean of time series; it has been widely used with precipitation and streamflow data (Mu et al., 2007; Villarini et al., 2011). Change-point tests are also performed separately from trend tests to provide information on both the significance and timing of the change. However, there is no means

for those studies to differentiate between abrupt (a step change) and gradual (a trend) changes rigorously and consistently unless the nature of the shift is visually obvious.

The natural streamflow's of rivers also worldwide have significantly altered due to construction of reservoirs, weirs and other hydraulic structures for the purpose of irrigation, hydropower, industry and/or domestic uses (Wang et al., 2016). Reservoir operation has significant impacts on river hydrology, primarily through changing the magnitude, frequency, duration, and timing of flow regime. Indicators of hydrologic alteration (IHA) widely used to assess river regime streamflow alteration due to dam construction (Richter et al., 1997). IHA is statistical software developed by US Nature of Conservancy to assess the change in hydrologic conditions (e.g., River flows, lake levels) over time including changes caused by water management activities (dams, diversions, ground water pumping), climate shifts and land use change due to human activities (Maingi and Marsh, 2002). The IHA method embodies the range of variability approach (RVA) proposed by Richter et al. (1997), which has successfully used to evaluate hydrological disturbance in many regulated rivers around the world (Jiang et al., 2014). The RVA assess the extent to which flow conditions after dam construction (disturbance) lies within a user defined target range of flow conditions that typified the hydrological regime in pre-impact periods. The IHA assess hydrological alterations based on 33 parameters characterized by streamflow magnitude, timing, frequency, duration and rate of change which is essential for understanding and predicting the impact of altered flow regimes in the river.

The objective of this study was to investigate the change and variability of long term historical records of precipitation and hydrological data in the Tekeze basin and to evaluate Tekeze river streamflow regime change caused by Tekeze hydropower reservoir dam construction.

## **3.2 Material and Methods**

### **3.2.1 Datasets used**

The basic datasets that are required by the trend analysis test and indicators of hydrologic alteration for trend, change point detection and streamflow regime change at Tekeze basin are precipitation and streamflow data's.

#### ***3.2.1.1 Rainfall/precipitation data***

Examination of climate trends and variability needs long and high-quality records of climatic variables. There are now many precipitations recording stations located in Tekeze Basin. However, only a few stations have continuous records which are found in the South and North-Eastern part of the basin essential to hydro-climatic studies. In this study, long periods of daily, monthly and annual precipitation recorded data corresponding to eleven selected gauging station sites out of the more gauging stations available for Tekeze River Basin collected from the Ethiopian National Metrological Service Agency (ENMSA) used. The data were analyzed to determine whether there is evidence of specific trends in the characteristics of inter-annually and annually rainfall events in the upper parts of the basin. The period of record was from 1953 to 2013 with varying record length. The length of recording varies due to differences in site establishment and data gaps. To check on the spatial coherence of the variability results across the study area. Some potential data problems, for instance missing values, data entry errors, outliers, etc., were solved by careful inspection. Due to lack of continuous available data this study focused on the middle and higher latitude of half part of Tekeze basin. Location of the study area and spatial distributions of the 11 stations are shown in Figure 2.2, and their characteristics and data availability are presented in Table 3.1.

Table 3.1 Location of weather stations and lengths of precipitation series used in this study

Station	Lat. (o)	Long. (o)	Altitude (masl)	P <sub>mean</sub> (mm)	Period of record
Axum	14.12	38.73	2105	723.94	1992-2012
Debre Tabor	11.53	38.02	2690	1439.04	1988-2013
Gonder	12.33	38.02	1967	1175.18	1953-2004
Hager Selam	13.39	39.09	2000	692.49	1994-2012
Hawzen	13.58	39.26	2242	531.90	1971-2012
Korem	12.31	39.31	3000	980.50	1985-2012
Lalibela	12.31	39.03	2500	799.07	1976-2004
Maichew	12.48	39.32	2400	733.03	1971-2012
Mekele	13.3	39.29	2070	603.68	1980-2012
Nefas Mewucha	11.44	38.27	3000	1103.41	1986-2004
Wukro	13.46	39.36	2070	581.29	1992-2012

P<sub>mean</sub> is mean annual precipitation

### 3.2.1.2 River flow record at Tekeze Basin

There are more than 20 streamflow gauging stations in Tekeze Basin covering small tributaries obtained from the Department of Hydrology – Ethiopian Ministry of Water, Irrigation and Electricity. But all stations except Embamadre station cannot be used for the analysis because of massive data gaps during civil war particularly at the end of 1970s up to mid-1980s and after that most stations were not in operation for long periods of time. The remaining station which was operational after 1990 has unreliable discharge data mainly due to the short period of record and high missing data. The minimum length of streamflow record is 21 years (1994-2014) at Embamadre which is impacted by hydropower reservoir operation since 2009 and less than 15 years (1998-2014) for the remaining stations. A longer period of recorded historical flow data at Embamadre gauging stations increases the visibility of trends and the reliability of results from trend analysis than shorter period records of flow in other stations found in the small tributary of Tekeze basin even if they enhance spatial coverage on different parts of the basin. Based on the quality of the data, time series length and influence of infrastructure (Tekeze hydropower

reservoir) Embamadre station (Figure 2.2) was selected for detailed analysis. The temporal resolution of data available is daily.

### ***3.2.1.3 Data Quality Check and Analysis***

The hydro-climatic data of Tekeze basin is scanty and have many data gaps. Therefore, it is essential to devote careful screening and quality check for all data before use in any hydro-climatological analysis. The quality of collected data sets was checked in several ways, mainly depending on the type of the data set and perceived uncertainties. The three steps visualization, comparison to the nearest station with in the same zone and regression were taken for verifying the hydro-climatic data used in this research. The climatic data was sorted and arranged in excel and checked the homogeneity of it using the standard normal homogeneity test and Von Neumann ratio test. The data series from these eleven weather stations that was used in this study were found to be homogeneous. Visual inspection and regression relations between neighboring stations have been used to detect outliers and fill in the missing gaps in the data series. For precipitation and temperature data the regression coefficient ( $r^2$ ) ranges between values of 0.77 to 0.89. Large data gaps of each weather station for the duration of one year and above, where excluded from the analysis. Also, according to World Meteorological Agency (WMA) standards, it is not recommended to fill more than 10% of missing data. Missing values less than 8% for daily stream flow at Embamadre gauging stations and less than 10% of the eleven selected stations precipitation and temperature data have been used over the considered period. According to the result all the selected eleven stations were consistent and have been used for climate variability and change studies and simulation purposes as discussed in the next chapter.

### **3.2.2 Trend analysis methods**

There are various parametric and non-parametric tests available such as moving average, Bayesian procedures, Mann-Kendall test, filtering technology, Pearson correlation coefficient, etc. which were used to detect trends and variability in hydro-meteorological time series. However, from recent studies it is found that non-parametric Mann-Kendall test are most frequently used for non-normally distributed and censored data, including missing values, which are frequently encountered in hydro-climatic time series. Non-parametric trend analysis is preferred by various researchers recently due to several advantages over parametric method. (i) Non-parametric tests do not require the assumption of normality or homogeneity of variance which are frequently violated by hydro-climatic data or are difficult to verify; (ii) It compares medians rather than means and, as a result, if the data have one or two outliers, their influence is negated; (iii) Prior transformations are not required, even when approximate normality could be achieved; (iv) greater powers is achieved for the sketching distribution and (v) data below the detection limit can be incorporated without fabrication of values or biases. The statistical significance trend detected using a non-parametric model such as Mann-Kendal test can be complemented with Theil–Sen’s slope estimation to determine the magnitude of the trend and the Pettit test to determine the change point detection. Brief explanations of these methods are discussed as follows:

#### **3.2.2.1 Mann–Kendall test**

The non-parametric Mann–Kendall test (Kendal, 1975; Mann, 1945) is widely used to evaluate statistically significant trends in hydro-meteorological time series (Gocic and Trajkovic, 2013; Shifteh Some’e et al., 2012). Like many other trend methods, the Mann–Kendall test assumes that the time series under research are stable, independent and random with equal probability distributions. It has the advantage of being a simple calculation that assumes no special data

distribution. The Mann-Kendall test, used to detect a trend in a time series, yields an incorrect (too large) rejection rate when applied to an auto correlated series with no trend. Pre-whitening corrects this situation, but reduces the power of the test when a trend exists. Pre-whitening is the most commonly used procedure to eliminate the effect of serial correlation in trend analysis. It efficiently removes the possibility of finding a significant trend in the Mann-Kendall test when actually there is no trend. But pre-whitening has the disadvantage of accepting the hypothesis of no trend with a high probability when a trend exists.

In the Mann–Kendall test, the null hypothesis  $H_0$  states that the data  $x_1; x_2; \dots; x_n$  is a sample of  $n$  random variable independent and distributed identically without considering seasonal changes. The alternative hypothesis  $H_1$  of a two-sided test is that the distributions of  $x_k$  and  $x_j$  are not identical for all  $k, j \leq n$  with  $k \neq j$ . The test statistic  $S$  is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (3.1)$$

in which  $n$  is number of data points,  $x_i$  and  $x_j$  are the data values in time series  $i$  and  $j$  ( $j > i$ ), respectively and  $\text{sgn}(x_j - x_i)$  is the sign function as

$$\text{sgn}(x_j - x_k) = \begin{cases} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases} \quad (3.2)$$

The variance is computed as

$$\text{Var}(S) = \frac{\left[ n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5) \right] b}{18} \quad (3.3)$$

Where  $n$  is number of data points;  $m$  is the number of tied groups which has a set of sample data with same value and  $t_i$  is the number of ties for the  $i$  value. When the sample size  $n > 10$ , the standard normal variable,  $Z$ , is computed from the following equation(Douglas et al., 2000):

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases} \quad (3.4)$$

A hypothesis test based on normalized Kendall's statistics for a significance level of  $\alpha$  is used to analyze all variables in the Mann– Kendall test. The null hypothesis,  $H_0$ , is accepted at the significance level of  $\alpha$  in the two-sided trend test if  $-Z_{\alpha/2} < Z < Z_{\alpha/2}$ , where  $\pm Z_{\alpha/2}$  are standard normal deviates. Alternatively,  $H_0$  is rejected or  $Z$  is statistically significant if  $Z > Z_{\alpha/2}$  or if  $Z < -Z_{\alpha/2}$ . Moreover, positive values of  $Z$  indicate an increasing trend while a negative  $Z$  reflects a decreasing trend. In most of the researches around the globe, changing trends tested at 0.01, 0.05 and 0.1 significance levels. The null hypothesis of no trend is rejected if  $[Z] > 1.65$ ,  $[Z] > 1.96$  and  $[Z] > 2.57$  at the 10%, 5% and 1% significance levels, respectively.

In this study, significance level  $\alpha=0.05$  which usually used in the Nile Basin hydro-climatic trend analysis were used (Tabari et al., 2015). The  $Z$  values are approximately normally distributed, and a positive  $Z$  value larger than 1.96 (based on normal probability tables) denotes a significant increasing trend at the significance level of 0.05, whereas a negative  $Z$  value lower than -1.96 shows a significant decreasing trend.

### 3.2.2.2 Sen's slope estimator

The Sen's slope method is a nonparametric, linear slope estimator that works most effectively on monotonic data. Sen's slope method (Sen, 1968) used to determine the magnitude of the trend line. Sen's slope proceeds by calculating the slope as a change in measurement per change in time. The slope of trend in the sample of  $N$  pairs of data estimated as:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, \dots, N \quad (3.5)$$

Where  $Q_i$  is slope between data points,  $x_j$  and  $x_k$  are the data values at times  $j$  and  $k$  ( $j > k$ ), respectively.

If there is only one datum in each time period, then  $N = \frac{n(n-1)}{2}$ ; where  $n$  is the number of time periods. If there are multiple observations in one or more-time periods, then  $N < \frac{n(n-1)}{2}$ ; where  $n$  is the total number of observations.

The  $N$  values of  $Q_i$  are ranked from smallest to largest, and the median of slope or Sen's slope estimator calculated as:

$$Q_{\text{med}} = \begin{cases} Q_{\left(\frac{N+1}{2}\right)} & \text{if } N \text{ is odd} \\ \frac{Q_{\left(\frac{N}{2}\right)} + Q_{\left(\frac{N+2}{2}\right)}}{2} & \text{if } N \text{ is even} \end{cases} \quad (3.6)$$

The  $Q_{\text{med}}$  sign reflects data trend reflection, while its value indicates the steepness of the trend. To determine whether the median slope is statistically different than zero, one should obtain the confidence interval of  $Q_{\text{med}}$  at specific probability.

The confidence interval about the time slope can be computed as follows:

$$C_{\alpha} = Z_{1-\alpha/2} \sqrt{\text{Var}(S)} \quad (3.7)$$

Where  $\text{Var}(S)$  defined in Equation (3.3) and  $Z_{1-\alpha/2}$  is obtained from the standard normal distribution table. In this study, the confidence interval was computed at significance level  $\alpha=0.05$ .

Then  $M_1 = \frac{N - C_{\alpha}}{2}$  and  $M_2 = \frac{N + C_{\alpha}}{2}$  are computed. The lower and upper limits of the confidence

interval,  $Q_{\text{min}}$ , and  $Q_{\text{max}}$  are the  $M_1^{\text{th}}$  largest and the  $(M_2+1)^{\text{th}}$  largest of the  $N$  ordered slope estimates. The slope  $Q_{\text{med}}$  is statistically different than zero if the two limits ( $Q_{\text{min}}$  and  $Q_{\text{max}}$ ) have a similar sign. When hypothesis of no trend is rejected by Mann Kendall test, the Sen's slope is

used to quantify the trend. Sen's slope estimator widely used in hydro-meteorological time series (Huang et al., 2014; Shifteh Some'e et al., 2012).

### 3.2.2.3 Pettit's test for change-point detection

This test, developed by Pettitt (Pettitt, 1979) is a nonparametric test, which is useful for evaluating the occurrence of abrupt changes in hydrological and climatic records with continuous data. One of the reasons for using this test is that it is more sensitive to breaks in the middle of the time series and mostly used change point detection in climatic records (Smadi et al., 2006). This method detects a significant change in the mean of a time series when the exact time of the change is unknown. The test uses a version of the Mann-Whitney statistic  $U_{t,N}$ , that tests whether two sample sets  $X_1, \dots, X_t$  and  $X_{t+1}, \dots, X_N$  are from the same population. The test statistic  $U_{t,N}$  is given by:

$$U_{t,N} = U_{t-1,N} + \sum_{j=1}^N \text{sgn}(X_t - X_j) \quad (3.8)$$

Where  $t = 2, 3, \dots, N$  and

$$\begin{aligned} \text{if } (X_t - X_j) > 0, \quad \text{sgn}(X_t - X_j) &= 1 \\ \text{if } (X_t - X_j) = 0, \quad \text{sgn}(X_t - X_j) &= 0 \\ \text{if } (X_t - X_j) < 0, \quad \text{sgn}(X_t - X_j) &= -1 \end{aligned} \quad (3.9)$$

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The test statistic  $K_N$  and the associated probability ( $P$ ) used in the test given as:

$$K_N = \max_{1 \leq t \leq N} |U_{t,N}| \quad (3.10)$$

$$P \cong 2 \exp\left\{ \frac{-6(K_N)^2}{(N^3 + N^2)} \right\} \quad (3.11)$$

The significance probability of  $K_N$  approximated for  $p \leq 0.05$ .

### 3.2.3 Indicators of Hydrologic Alteration

The Nature Conservancy developed Indicators of hydrologic alteration (IHA) method to enable rapid processing of daily hydrologic records to characterise natural flow conditions and facilitate evaluations of human induced changes to flow regimes (Richter et al., 1996; Yu et al., 2016; Q. Zhang et al., 2014). IHA is one of the most common and widely accepted methods for assessing the extent to which human disturbance has altered the hydrological regime of river systems. The program was designed to calculate the value of thirty three hydrologic parameters that characterize the daily, monthly and annual flow regime by five hydrologic features: (i) magnitude of monthly discharge, (ii) magnitude and duration of annual extreme flows, (iii) timing of annual extreme discharge (iv) frequency and duration of high and low pulses, and (v) rate and frequency of discharge change (Table 3.2). Range variability approach (RVA) method used to assess the hydrological regime alterations for regulated rivers based on IHA (Yu et al., 2016). In the RVA analysis, hydrological parameters were calculated using parametric (mean and standard deviation) or non-parametric (median and percentile) statistics. For most situations, non-parametric statistics are a better choice, because of the skewed nature of many hydrologic datasets. But parametric statistics may be preferable for certain situations such as flood frequency or average monthly flow volumes. IHA detail description can be found in Richter et al. (Richter et al., 1998, 1997, 1996). It is recommended to use long years of daily record streamflow data to obtain reliable pre- vs. post impact comparison, as well as for trend analysis (Richter et al., 1997), while twenty years should be considered as good baseline requirement for the amount of data needed. In this study, a twenty-one years daily streamflow data at Embamadre gauge records were analyzed using the IHA methods to determine hydrologic shifts of Tekeze river basin streamflow in response to Tekeze hydropower reservoir dam construction and operation. Analysis were conducted on mean daily

discharges for the water year (June-May) for the period of record prior to Tekeze hydropower dam construction (reference) and then again after dam construction completed (disturbance). For the case of Tekeze river the historical (1994-2008) and post-dam construction (2009-2014) hydrologic conditions were evaluated. As the analysis focused on two time intervals of dams pre-impact and post-impact periods, the range variability approach (RVA) was used to evaluate hydrological change (Gao et al., 2013; Richter et al., 1997; Wang et al., 2016). The RVA uses the pre-impact variation of IHA parameter values as references for defining the extent to which the flow regime has been altered by dam construction (Richter et al., 1998). Based on these references, RVA analysis generates a series of hydrologic alteration factors, which quantify the degree of alteration of 33 IHA parameters.

The hydrological alterations in the RVA analysis are evaluated by comparing the frequency with which pre-impact and post-impact variables (usually the IHA) fall within the three categories. Richter et al. (1998) divide the range of hydrologic alterations into three classes of equal ranges with a distinct pattern as no alteration (0-33%), moderate alteration (34-67%), and high degree of alteration (68-100%). Hydrologic alteration (HA) assumed to occur if the number of post-impact values falling in the central interval (34<sup>th</sup> to 67<sup>th</sup> percentile) differ from the expected ones i.e. the number of the pre-impact values. The RVA target range for each parameter is bracketed by 25<sup>th</sup> and 75<sup>th</sup> percentail values of the pre-impact daily flow. The deviation of the post-impact flow regime from the pre-impact period quantified using hydrologic alteration of Tekeze river. The degree of hydrologic alteration, HA, is calculated for each variable as:

$$HA = \left[ \frac{N_o - N_e}{N_e} \right] \times 100 \quad (3.12)$$

$$N_e = p \times N_T \quad (3.13)$$

Where  $N_O$  is observed number of post-impact years for which the values of hydrologic parameters falls within the RVA target range,  $N_e$  is expected number of post-impact years for which the values of hydrologic parameters falls within the RVA target range, and  $p$  is percentage of post-impact years for which the values of hydrologic parameters falls within the RVA target range, and  $N_T$  is total number of post-impact years. When the observed frequency of post-impact annual values falling within the RVA target range equals the expected frequency, HA is equal to zero. A positive HA factor means that the frequency of values in the category has increased from the pre-impact to post-impact period (maximum: 2), while a negative value means that the frequency of values has decreased (minimum: -1). The coefficient of dispersion was a commonly used indicator used to evaluate the variability of daily streamflow. It is calculated as: the coefficient of dispersion (CD) = (75<sup>th</sup> percentile - 25<sup>th</sup> percentile) / 50<sup>th</sup> percentile.

*Table 3.2* Summary of hydrologic parameters used in the IHA and their characteristics

IHA statistics group	Hydrologic characteristics	Parameters used in Tekeze basin streamflow	Total No. of parameters
1. Magnitude of monthly discharge condition	Magnitude, timing	Median discharge for each calendar month	12 parameters
2. Magnitude and duration of annual extremes discharge condition	Magnitude, duration	Annual maxima 1-, 3-, 7-, 30-, and 90-day means Annual minima 1-, 3-, 7-, 30-, and 90-day means Number of zero days, base flow index	12 parameters
3. Timing of annual extremes discharge condition	Timing	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	2 parameters
4. Frequency and duration of high and low pulses	Magnitude, frequency Duration	Number of high pulses each year Number of low pulses each year Median duration of high pulses each year Median duration of low pulses each year	4 parameters
5. Rate and frequency of hydrograph changes	Frequency, rate of change	Number of rises and falls Number of reversals	3 parameters

### **3.3 Result and Discussion**

#### **3.3.1 Preliminary Analysis**

The rainfall data screened and comparisons between stations were made using the statistical metrics mean, standard deviation (STD), the coefficient of variation (CV), skewness (Cs), and actual excess kurtosis (Ku). The mean annual rainfall varied between 581.29mm in the Northern part of the Tekeze River basin (Wukro station) and 1439.04mm in the Southwest part (Nefas Mewucha station) of this basin. The skewness (Cs), which is a measure of asymmetry in a frequency distribution around the mean, varied between 1.47 and 2.41, positive skewness indicating that annual precipitation during the period is asymmetric and it lies to the right of the mean over all the stations. Kurtosis (Ku) is a statistic describing the peakedness of a symmetrical frequency distribution, for Tekeze basin it varied from 0.65 to 5.44 (Table 3.3). For time series data to be considered normally distributed, the coefficient of skewness and kurtosis must be equal to 0 and 3, respectively. Table 3.3 indicates, therefore, that the data in Tekeze basins precipitation stations are positively skewed and not normally distributed. The coefficient of variation (CV), a statistical measure of the dispersion of data points in a data series around the mean, was computed for all stations to investigate spatial pattern of inter-annual variability of annual precipitation over the study area. The coefficient of variation varied between 1.18 (Maichew station) and 1.86 (Wukro station). Table 3.3 shows that stations found in the Northern part of Tekeze basin (Wukro, Mekele, Hawzen, and Axum stations) have a more inter-annual variability of precipitation than the stations observed in the South and Southwest part of the basin. It can be concluded from the results that the areas of usually heavy precipitation are the zone of least variability and areas of lowest precipitation are the zone of highest variability.

The highest mean annual precipitation recorded at Debre Tabor station (1439.04 mm) and the lowest registered in Hawzen station (531.90mm) according to the analysis of the present datasets. These two rainfall stations also recorded the maximum (148.15 mm) and minimum (66.91 mm) standard deviations respectively. However, 1998.40mm is seen for Debre Tabor station while minimum (757.81 mm) indicated for Wukro station compared to other stations. The annual rainfall series are positively skewed for all the eleven stations and the coefficient of variation shows no significant differences among the stations. Mean annual rainfall at the stations varied from 531.90 mm /year to 1439.04 mm/year.

Table 3.3 Annual precipitation time series basic statistical properties of the study area

Station	P <sub>mean</sub> (mm)	P <sub>max</sub> (mm)	STD	CV	Cs	Ku
Axum	723.94	1067.20	88.24	1.46	1.91	3.47
Debre Tabor	1439.04	1998.40	148.15	1.24	1.32	0.65
Gonder	1175.18	1772.80	120.62	1.23	1.41	1.26
Hager Selam	692.49	900.00	82.41	1.43	1.90	3.50
Hawzen	531.90	768.50	66.91	1.51	2.07	3.90
Korem	980.50	1272.20	103.00	1.26	1.68	2.14
Lalibela	799.07	1100.10	96.12	1.44	1.93	3.47
Maichew	733.03	1051.00	72.05	1.18	1.47	1.58
Mekele	603.68	917.90	84.18	1.67	2.21	4.47
Nefas Mewucha	1103.41	1105.70	113.82	1.24	1.90	4.13
Wukro	581.29	757.81	90.07	1.86	2.41	5.44

P<sub>mean</sub>: mean annual precipitation; P<sub>max</sub>: maximum annual precipitation

### 3.3.2 Trends of precipitation

#### 3.3.2.1 Annual trends of precipitation

Analysis of the Tekeze basin annual precipitation time-series using non-parametric Mann-Kendall test found that 64% of the stations with a positive trend and the rest with a negative trend (Figure 3.3). Annual precipitation trend magnitude, direction and significance in the Tekeze river basin are shown in Figure 3.1 through Figure 3.3. In the Tekeze basin selected stations, the level of significance using Z value identified as positive and negative non-significant trends.

The Theil Sen's Slope estimator (Q mm/year) summarizes the results of change per unit time of the trends detected in the basin. The highest decreasing trend detected in the Northern part (Axum, Hawzen, and Hager Selam stations) whereas an increasing trend identified in the other stations found in Southern (Lalibela, Nefas Mewucha, Debre Tabor and Korem stations) and Eastern (Maichew and Mekele stations) part of Tekeze basin (Figure 3.6). Sen's slope indicates that the magnitudes of the non-significant positive trends at 95% confident level varies in the range of 8.12 mm/year at Lalibela station to 2.32 mm/year at Nefas Mewucha station. A negative non-significant trend also predicted in the basin and varies from  $-1.26$  mm/year at Gonder station to  $-6.22$  mm/year at Axum station. Positive trends mostly happened in the Eastern part of Tekeze basin whereas the negative trends occurred in the Northern and Southwestern parts of the basin. Mann-Kendal test results in all selected stations of Tekeze basin shows a non-significant increasing and decreasing annual precipitation trend observed at the 5% significance level which is similar to other studies done in the Eastern Nile (Bewket and Conway, 2007; Conway, 2000; Gebremicael et al., 2013; Mengistu et al., 2014; Tabari et al., 2015).

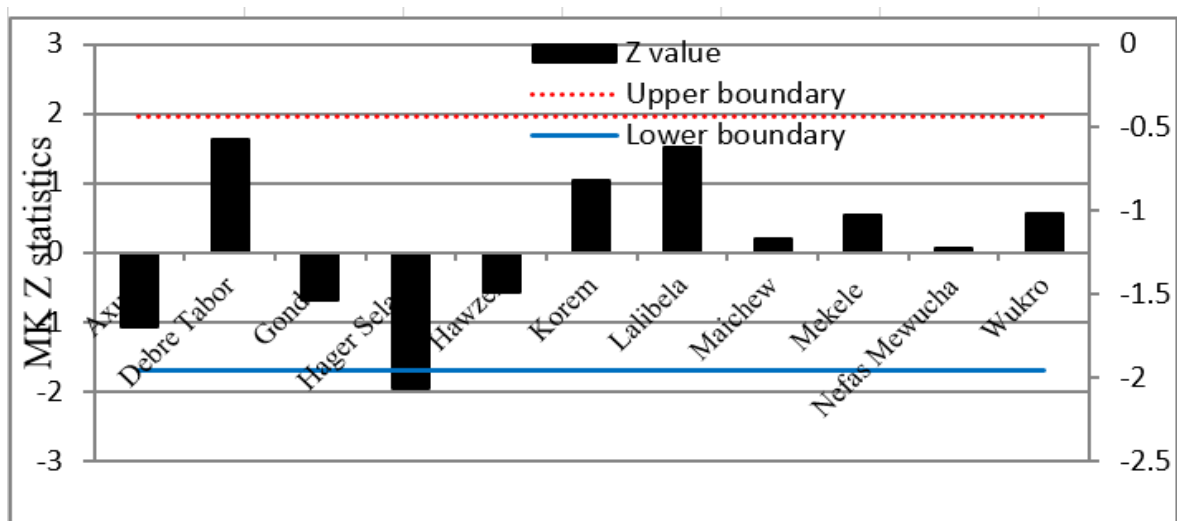


Figure 3.1 Results of Mann Kendall annual precipitation time series trend test at 95% confidence interval

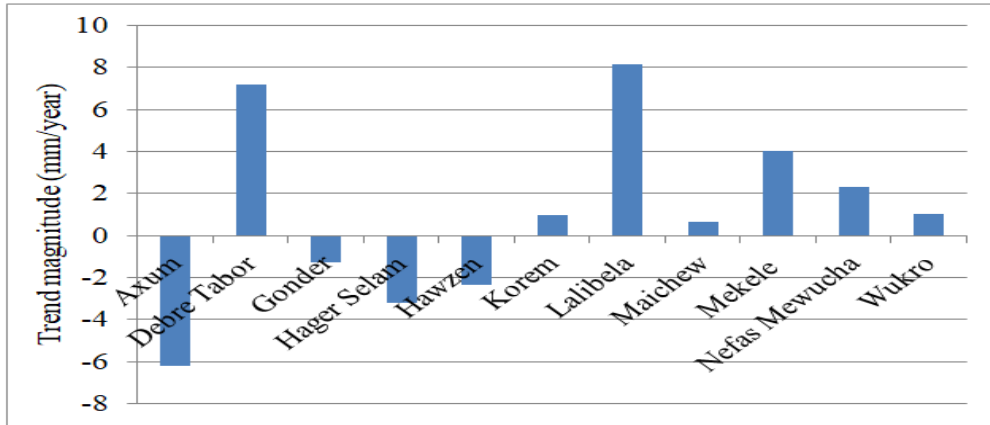


Figure 3.2 Annual precipitation trend magnitudes at different stations of Tekeze basin

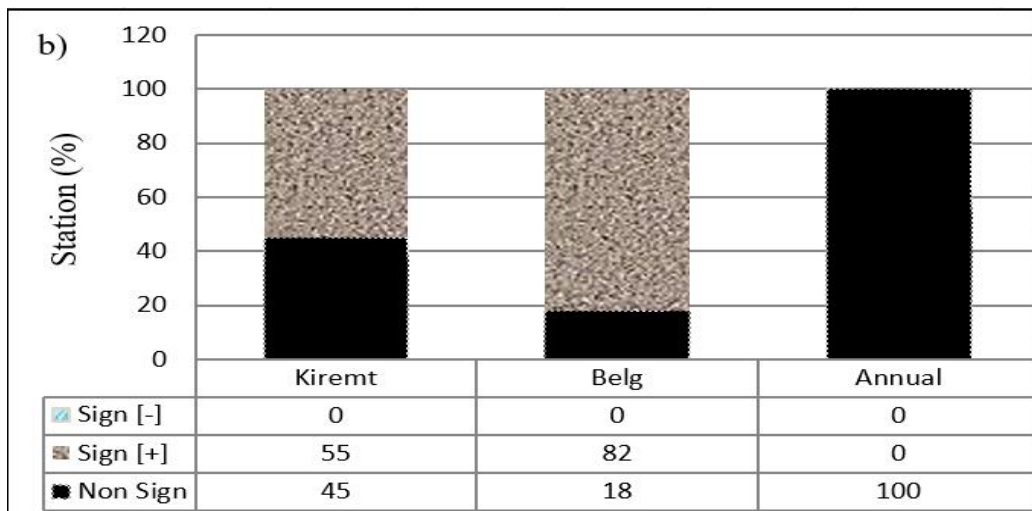
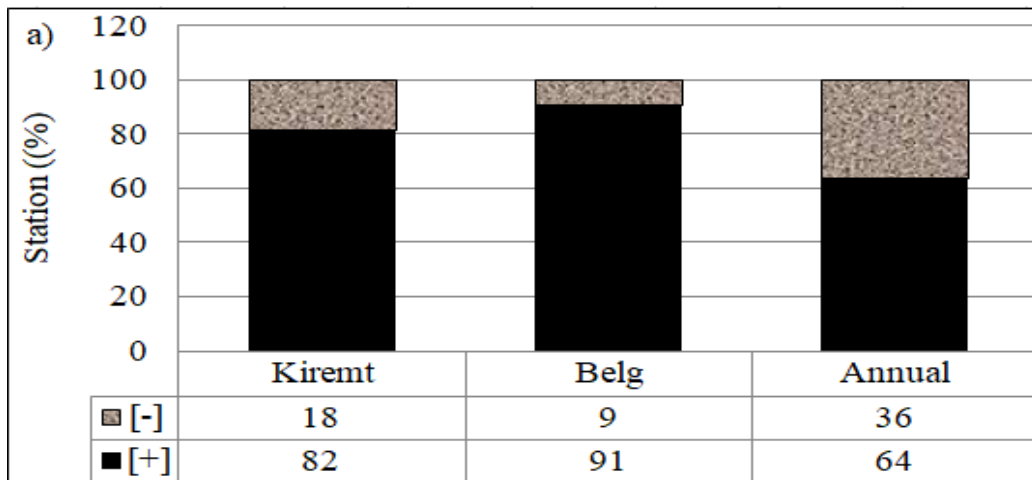


Figure 3.3 Percentage annual and seasonal trend test results a) Overall negative and positive trends b) significant positive and negative trends at 95% confidence level

### 3.3.2.2 Seasonal precipitation Trend

For all selected stations of Tekeze basin, Mann Kendall test and Sen's slope estimator method were also applied to detect the temporal trends of seasonal precipitation time series during 1953-2013. Pre-whitening did not change the results of the seasonal MK test, implying that the trend was strong enough not to be missed, even after pre-whitening. Like the annual precipitation series, the seasonal time series in the Tekeze basin showed a mix of positive and negative trends but significant trends (Figure 3.3 and Figure 3.4).

In Kiremt main rainy season (Wet season: June-September) precipitation, 82% of the stations and 18% of the stations show positive and negative trends, respectively (Figure 3.3a). Only 55% (6 stations) found with significant positive trends and none with significant negative trends (Figure 3.3b). These significant positive trends are mostly observed to exist in the sources of Tekeze basin at stations Debre Tabor, Lalibela, Nefas Mewucha in the southern mountainous areas and stations like Maichew and Korem in the eastern part of the basin. Kiremt precipitation trend magnitude varied between  $-1.19$  and  $6.4$  mm/year. In general, it can be stated that the Kiremt season has been experiencing mild increasing precipitation trends over the past 50 years. Kiremt season trend was like the annual precipitation trend, which indicates that Kiremt precipitation has high contribution for annual precipitation in Tekeze basin.

The Belg (Small rainy season: February-March) precipitation trends showed a similar trend to the Kiremt season time series. Most of the trends in the Belg precipitation time series were positive accounting for about 91% of the stations except Korem station (Figure 3.4 and Figure 3.3a). Nevertheless, the significant positive trends in Belg precipitation were higher compared with those in the other seasonal series. Nine significant positive trends (82%) detected in the Belg time series (Figure 3.3b). This is due to the South-Easterly winds from the Indian Ocean, and the Gulf of Aden

produce the Belg rains to the East-central part of the Northwestern highlands of Ethiopia (Seleshi and Zanke, 2004). Hence these stations record rainfall during this rainy period. The magnitude of the significant increasing trend varies from 0.47mm/year at Northern part (Wukro station) to 2.41mm/year at Southern part (Debre Tabor station) of Tekeze basin. According to these results, the significant increasing trend in Belg precipitation series experiences increasing trend throughout Tekeze basin for the last 50 years. The result of this study in higher variability and increasing trend Belg precipitation in Tekeze basin experiences similar result done by Cheung et al.(2008).

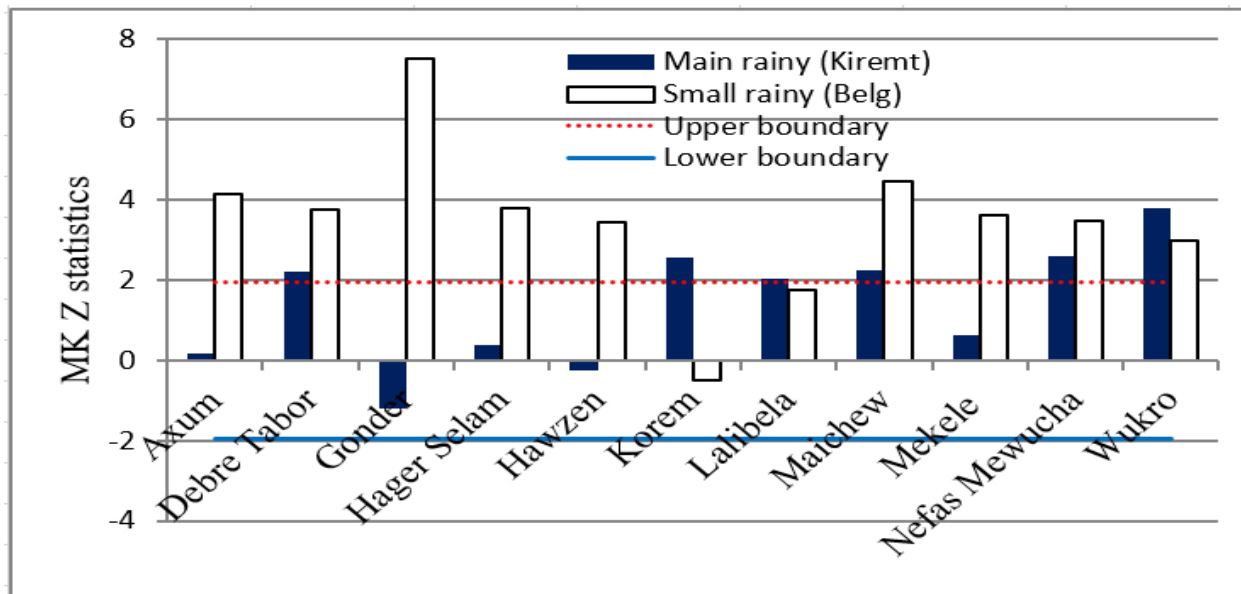


Figure 3.4 Mann Kendall Z values at different Tekeze basin stations

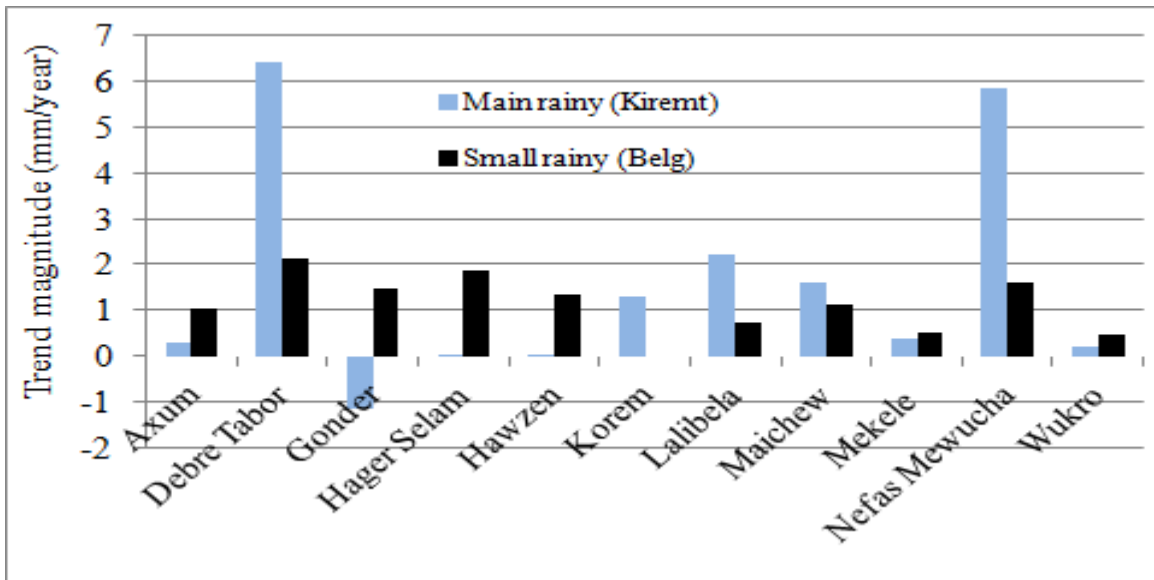


Figure 3.5 Results of seasonal precipitation trend magnitude at different weather stations

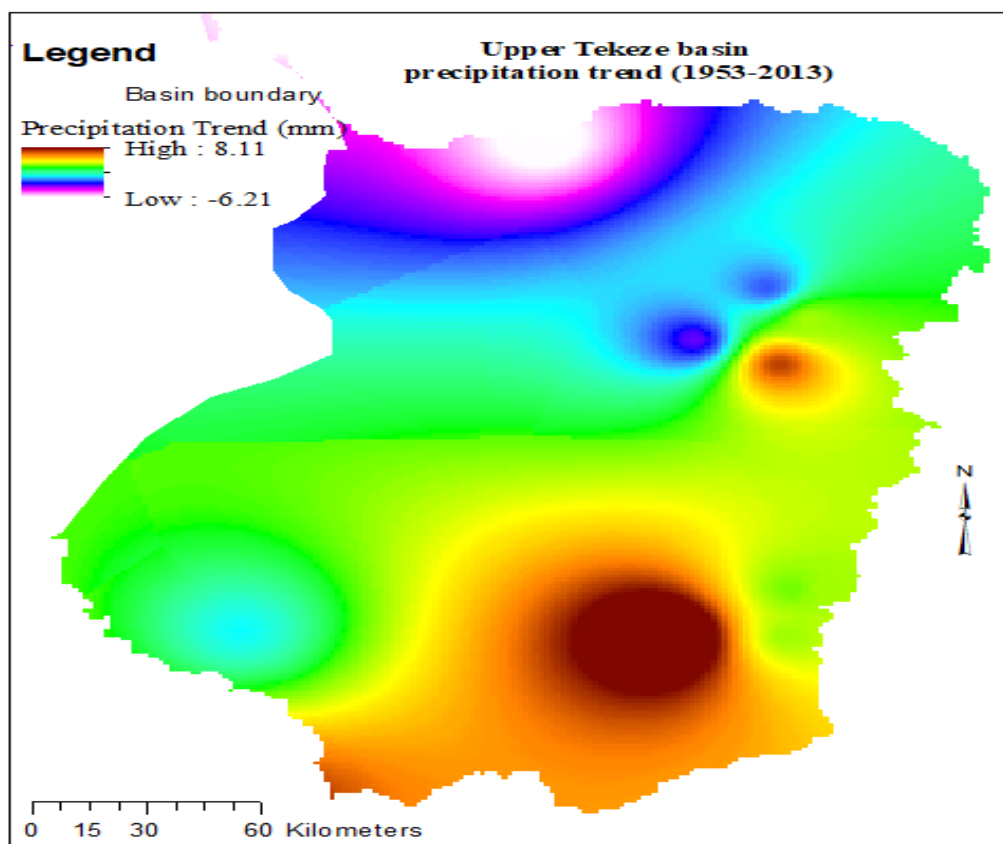


Figure 3.6 Annual precipitation increasing and decreasing trends in the Upper parts of Tekeze basin

### **3.3.2.3 Change Point Results**

Since the Mann-Kendall tests showed significant trend in seasonal precipitation at the significance level of 0.05, the Pettit test was further used to detect the change points of transitional years. For annual precipitation, there is no change point year could be detected at 95% confidence level as all stations annual precipitation shows non-significant trend. Most of the station's precipitation in both Kiremt (main rainy) and Belg (small rainy) seasons shift occurred around the 1970s or 1980s either positive or negative. This is mainly due to the drought period of Tekeze basin that lasted from 1978 to 1986. This result is confirmed the study of Conway (2000) and Seleshi and Zanke (2004), during the late 1970s to mid-1980s near-minimum precipitation, recorded confirming the unusually low rainfall received by Ethiopia during those years and the significant shift occurred.

### **3.3.3 Streamflow Trend and Variability**

Streamflow is a very useful indicator of long-term hydro-climatic changes. From a water resources management perspective, the identification of trend and variability in streamflow are critical for planning of water resources purposes. Trend analysis is useful for understanding dynamics and behaviors of hydrological and climatic variables over a long-term period. The non-parametric Mann–Kendall test was applied to the annual and seasonal streamflow data at Embamadre station over the period 1994 to 2008 with no substantial influence by water withdrawals for hydropower or other water use purposes.

The Z statistic of streamflow was 0.62 and showed a non-significant decreasing trend at the 5% confidence level. The annual streamflow was increased at a rate of  $1.867\text{m}^3/\text{year}$ . The observed increases in yearly streamflow come primarily from rainy season runoff.

To better analyze of the trend and variabilities on seasonal streamflow, according to the precipitation characteristics, one year divided into wet season (Kiremt: June-September), dry

season (Bega: October–January) and small rainy season (Belg: February–March). Kiremt (wet) and Belg seasons streamflow shows a significantly increasing trend with  $Z= 4.43$  and  $Z = 8.14$  respectively whereas Bega (dry) season showed a significant decreasing trend with  $Z$  value  $-10.35$ . The magnitude of the increasing trend in Kiremt varies up to  $4.69\text{m}^3/\text{year}$  and Belg season up to  $0.14\text{m}^3/\text{year}$ , the decline in Bega season up to  $0.59\text{m}^3/\text{year}$ .

This study of streamflow variability at Embamadre gauging station is significant as all streamflow's generated from the high altitude and mountainous regions usually reaches its maximum value at this station and hydrological regime of the Tekeze river mainstream is strongly affected by human activities like Tekeze hydropower reservoir and planned irrigation, hydropower and water conservation projects. Although annual precipitation exhibited an increasing trend for the past five decades, which in theory should result in more runoff, streamflow and water availability in the Tekeze mainstream at Embamadre has decreased and the environmental situation has been severely impaired because of limited water resources and may dried-up of the main stream during dry periods. Therefore, land degradation and landscape change with human activities, as well as the change and variability of climate all contributed to the trends of streamflow detected in this study. This result is in agreement with the study of Tesfaye et al., (2017) in the Tekeze basin and Tesemma et al., (2010) in the neighboring Upper Blue Nile basins who found main and small rainy season's significant increasing trends and decreasing trends in the dry seasons. Overall, this study provides an elaborate view of past precipitation and streamflow trends in the upper half part of Tekeze basin which should be use full for further research.

#### **3.3.4 Influence of Tekeze reservoir operation on the streamflow regime**

In the Tekeze River at Embamadre gauged stations all the 33 hydrologic parameters of medians, coefficient of dispersion (CD), and measure of HA were calculated with the IHA software. The

25<sup>th</sup> and 75<sup>th</sup> percentile values were calculated based on the available pre-impact streamflow records with considering low and high boundaries of the RVA target range. The RVA analysis showed that the natural flow regime in the middle Tekeze River at Embamadre station significantly changed after the operation of Tekeze hydropower reservoir (Table 3.4).

### 3.3.4.1 Magnitude of monthly streamflow

The result in Figure 3.7 indicated that the river flow become more smoothness in the post-impact period by two major changes, a decrease in high flow and an increase in low flow. Flow regime alterations were closely related to Tekeze hydropower reservoir operation that stores more water in rainy seasons (July through September) and release water downstream for low flow season power production. Tekeze hydropower reservoir operation altered the original hydrologic process, smoothend the peak swelling, and increase dry season discharge of Tekeze river.

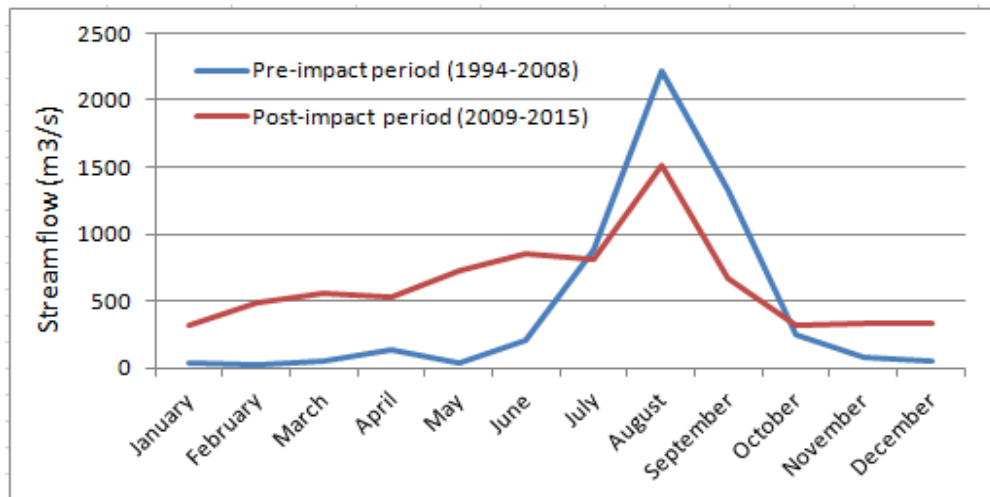


Figure 3.7 Comparison of median monthly streamflow before and after Tekeze hydropower reservoir dam construction

The magnitude of monthly flow from February to June, the normal low flow period, increased after 2009 when the reservoir behind the dam stored water for power production. Median discharge for all months after Tekeze hydropower dam construction differ significantly from values for these

months in the pre-dam construction period. Thus, during the low flow period of the year, operation of the dam increases median discharges while decreases high flow month's median flow. Figure 3.8 showed that an increase in November median flow and a decrease in August median flow.

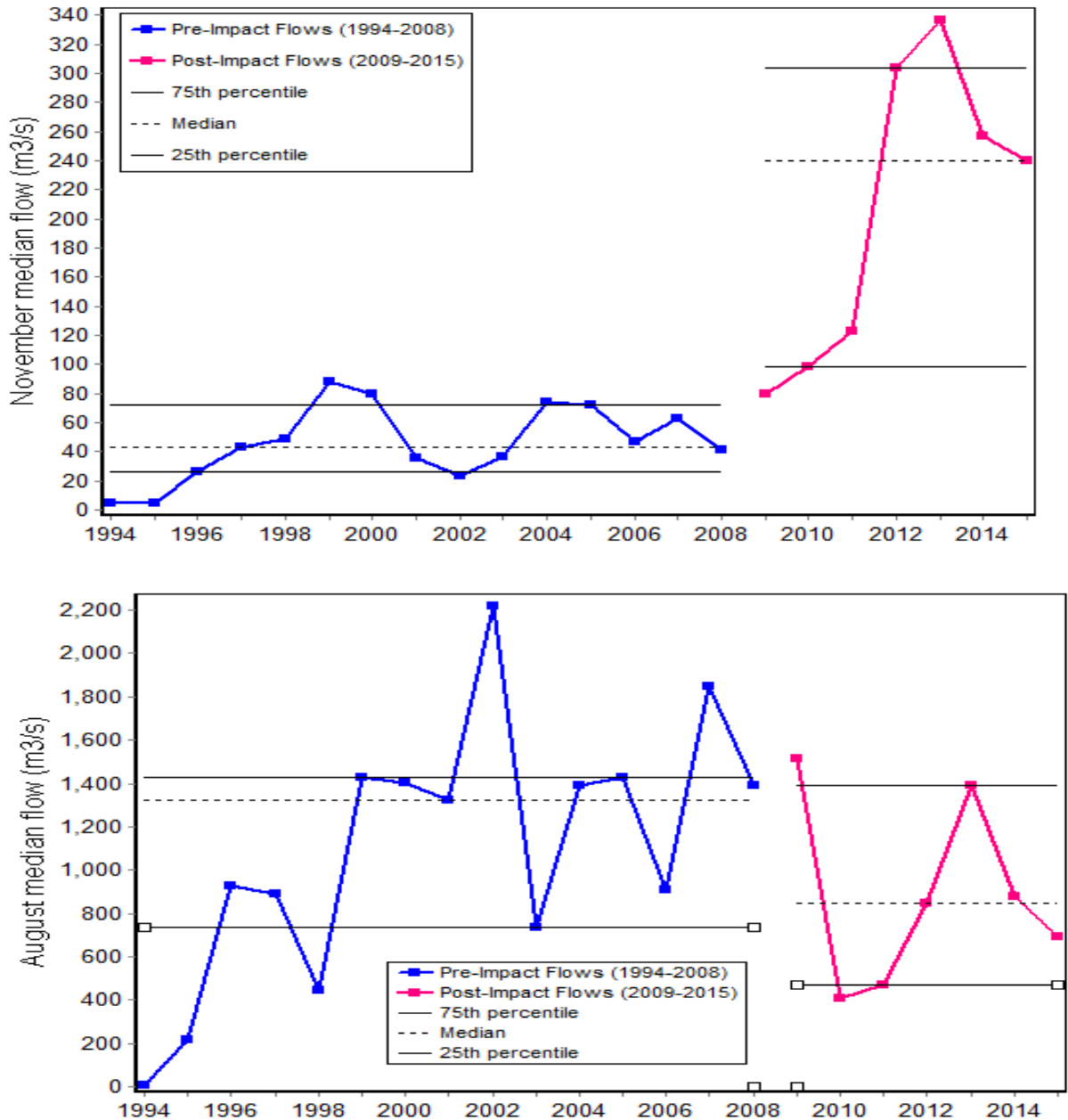


Figure 3.8 November and August monthly median flow change before and after Tekeze hydropower reservoir construction in Tekeze river

#### **3.3.4.2 Timing of annual extreme streamflow change**

The median Julian dates of each annual 1-day minimum move backward from the 130<sup>th</sup> day in pre-impact period to the 337<sup>th</sup> day in the post-impact period, with the low alteration of -14%. The median Julian dates of each annual 1-day maximum also move backward from the 224<sup>th</sup> day in pre-impact period to the 239<sup>th</sup> day in the post-impact period, with the low alteration of 29%.

#### **3.3.4.3 Rate and frequency of streamflow changes**

Table 3.4 showed that there were a change in the medians of rise rate, fall rate and number of reversals in the pre-impact and post-impact periods. The median of rise rate decreased from 39.3m<sup>3</sup>/s/day in the pre-impact period to 33.34m<sup>3</sup>/s/day in post-impact period, with high hydrological alteration of 114%. The median of fall rate also decreased by -3.4 m<sup>3</sup>/s/day in pre-impact period to -18.83 m<sup>3</sup>/s/day in post-impact periods with hydrological alteration of -100%. Together with these changes indicate that the dam significantly decreased the rate of rise of hydrographs, presumably owing to storage effects of the reservoir, and led to many more reversals between rising and falling stages of flow in the river. The medians of number of reversals also has been significantly altered and increased from 87 in pre-impact to 138 post impact, with high hydrological alteration of -100%.

Table 3.4 None parametric RVA scores at Embamadre station of Tekeze River

Hydrologic parameters	Pre-impact period (1994-2008)		Post-impact period (2009-2014)		RVA targets		
	Medians	CD	Medians	CD	Low	High	IHA (%)
Parameter Group #1							
July	477.70	0.64	488.60	0.84	296.30	526.20	29
August	1322.00	0.53	849.00	1.08	897.80	1400.00	-57
September	320.30	0.52	443.10	0.46	297.30	375.50	-57
October	110.80	0.79	264.90	0.65	86.87	139.40	-57
November	42.90	1.07	239.80	0.86	35.82	58.96	-100
December	32.50	0.84	211.30	0.67	25.77	37.46	-57
January	23.10	1.23	201.50	0.94	9.72	30.16	-100
February	21.30	1.02	304.10	0.48	9.10	24.90	-100
March	20.20	0.91	273.70	0.42	16.60	21.90	-100
April	16.10	1.50	293.20	0.76	7.95	29.15	-100
May	19.10	0.85	320.00	0.75	13.87	26.44	-100
June	58.55	1.13	312.00	0.69	31.40	74.95	-100
Parameter Group #2							
1-day minimum	3.70	1.92	64.70	2.17	2.15	8.06	-100
3-day minimum	9.00	1.42	154.90	0.97	2.27	9.37	-100
7-day minimum	9.81	1.33	184.40	0.82	2.47	13.28	-100
30-day minimum	14.21	1.01	201.50	0.80	4.71	17.22	-100
90-day minimum	17.12	1.13	201.50	0.88	9.97	22.70	-100
1-day maximum	3033.00	0.50	1719.00	0.65	2213.00	3130.00	-64
3-day maximum	2249.00	0.50	1451.00	0.43	1724.00	2470.00	-14
7-day maximum	1951.00	0.48	1240.00	0.46	1447.00	1995.00	-57
30-day maximum	1344.00	0.68	1015.00	0.50	1088.00	1553.00	-57
90-day maximum	748.40	0.91	723.50	0.22	665.50	958.00	71
Base flow index	0.03	2.08	0.44	0.93	0.02	0.07	-57
Parameter Group #3							
Date of minimum	130.00	0.21	337.00	0.46	108.10	154.20	-14
Date of maximum	224.00	0.05	239.00	0.05	220.60	233.90	29
Parameter Group #4							
Low pulse count	4.00	1.00	0.00	0.00	3.00	5.72	-64
Low pulse duration	4.50	3.11	3.50	1.43	3.00	12.16	-69
High pulse count	4.00	1.25	3.00	3.33	3.00	4.72	-64
High pulse duration	4.50	2.44	34.75	3.26	2.00	9.00	-20
Parameter Group #5							
Rise rate	39.30	1.20	33.34	0.35	23.48	45.74	114
Fall rate	-3.40	-0.82	-18.83	-0.52	-4.67	-2.20	-100
Number of reversals	87.00	0.30	138.00	0.25	80.84	96.16	-100

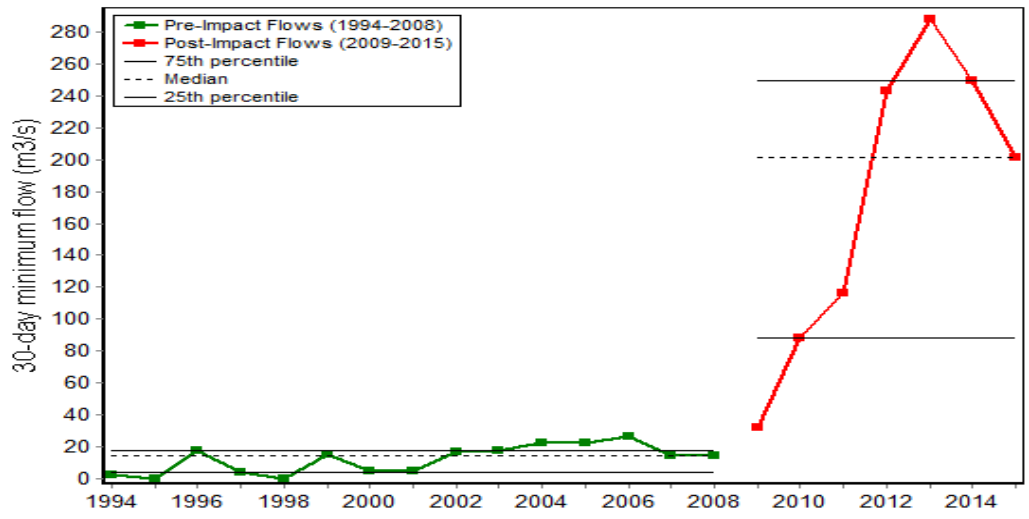
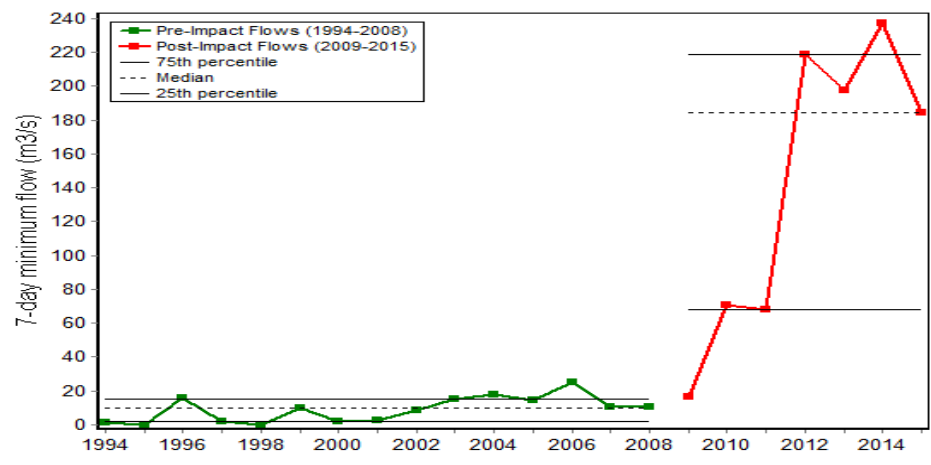
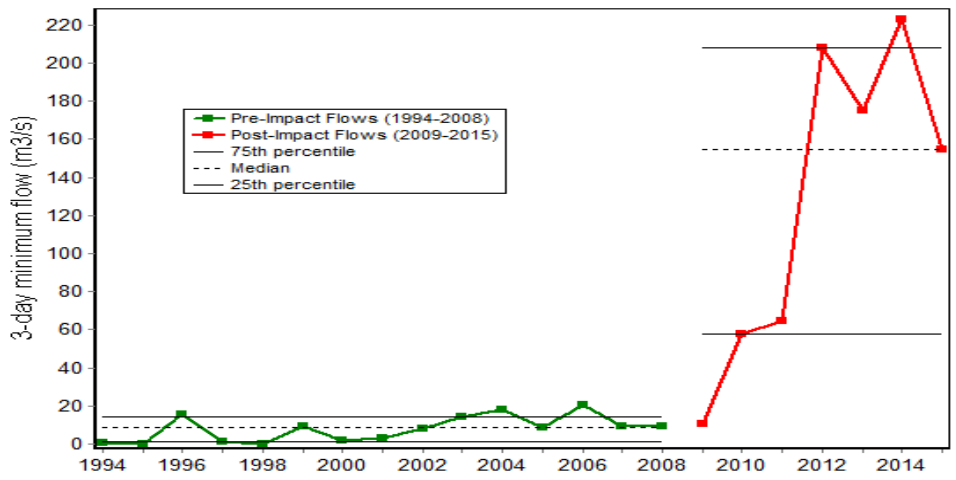
Note: the unit for monthly flow, 1-, 3-, 7-, 30-, and 90-day maximum and minimum flow is in m<sup>3</sup>/s, unit for duration of high and low pulse is days, and the rest of other IHA parameters are non-dimensional.

### 3.3.4.4 Magnitude and duration of annual extreme

Tekeze river time series of 1-day, 3-day, 7-day, 30-day, and 90-day maxima and minima medians flow in the pre-impact and post impact periods together with the median value (dashed line) and the boundaries of the middle category (i.e. from 25<sup>th</sup> and 75<sup>th</sup> percentile), which is computed with

reference to the pre-impact period are showed in Figure 3.9 and 3.10. In the RVA analysis, significance differences were observed in the annual maximum and minimum flows in the post impact periods. The medians of annual 1-day, 3-day, 7-day, 30-day and 90-day minimum flow for the post-impact period increased due to the reservoir attempt to capture high flood season flow for later dry season for hydropower production. By contrast, as the medians of annual 1-day, 3-day, 7-day, 30-day and 90-day maximum flow for the post-impact period decreased greatly due to the elimination of high magnitude flooding by storing water in the reservoir.

Except for low alteration in the 90-day annual maxima, the others were rather high. The hydrological alteration of annual 1-day, 3-day, 7-day, and 30-day parameter values fell within the RVA target value whereas the minima 1-day, 3-day, 7-day, 30-day and 90-day maxima medians reached -100%, which means most values of these five parameters fell out of the RVA target value (Table 3.4). The dispersion coefficients (CD) of annual minima and maxima flows in the post-impact period ranging from 0.22 to 0.97 are generally lower than those in the pre-impact period ranging from 0.48 to 1.92. The base flow index is larger in post-impact period because of low flow season water released from reservoir for hydropower production when natural flow is at its minimum. This is shown by a higher persistence of annual base flow index  $HA = 1.57$  for the upper category and accordingly lower persistence in lower and middle categories by negative HA index of -1.0 and -0.57, respectively. Therefore, the result showed that daily, weekly, monthly and annual maximal/minimal flow cycles were positively influenced by Tekeze hydropower reservoir operation.



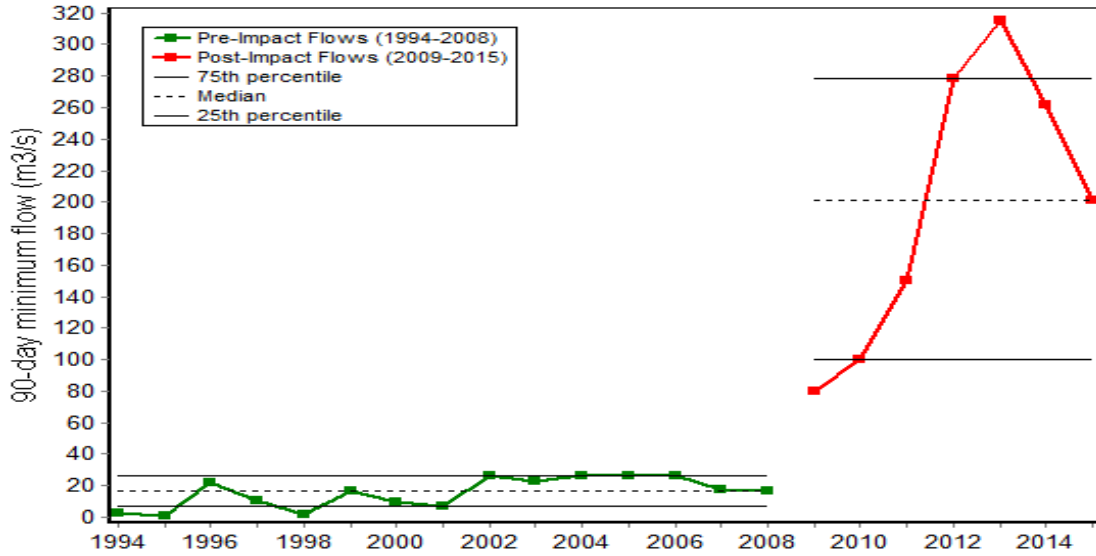
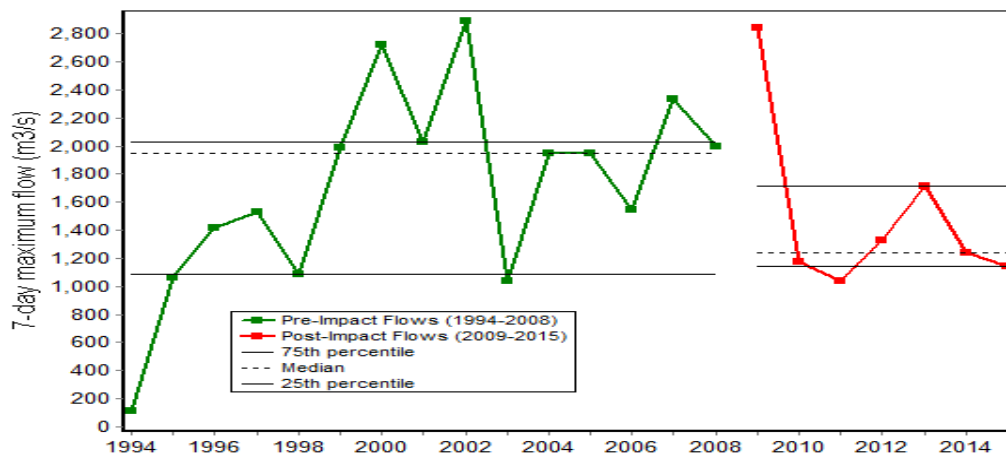
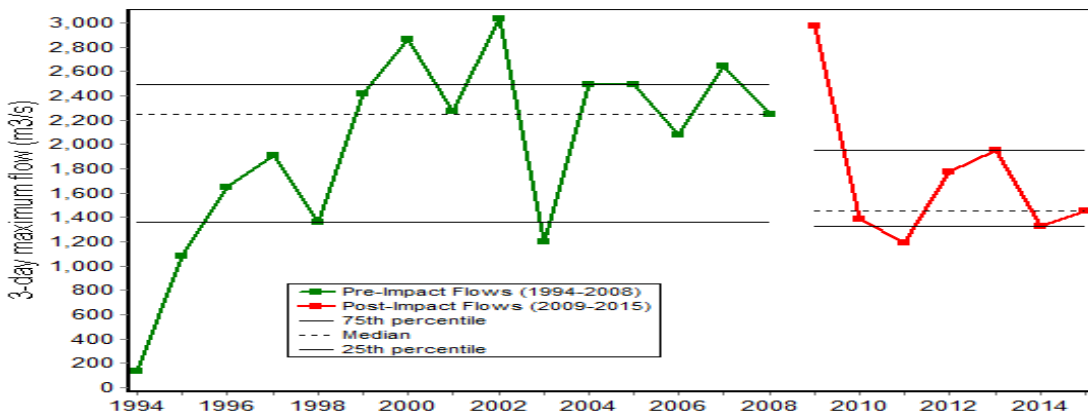


Figure 3.9 Hydrological alteration of 3-, 7-, 30-, and 90-day minimum flow before and after Tekeze hydropower reservoir construction in Tekeze river



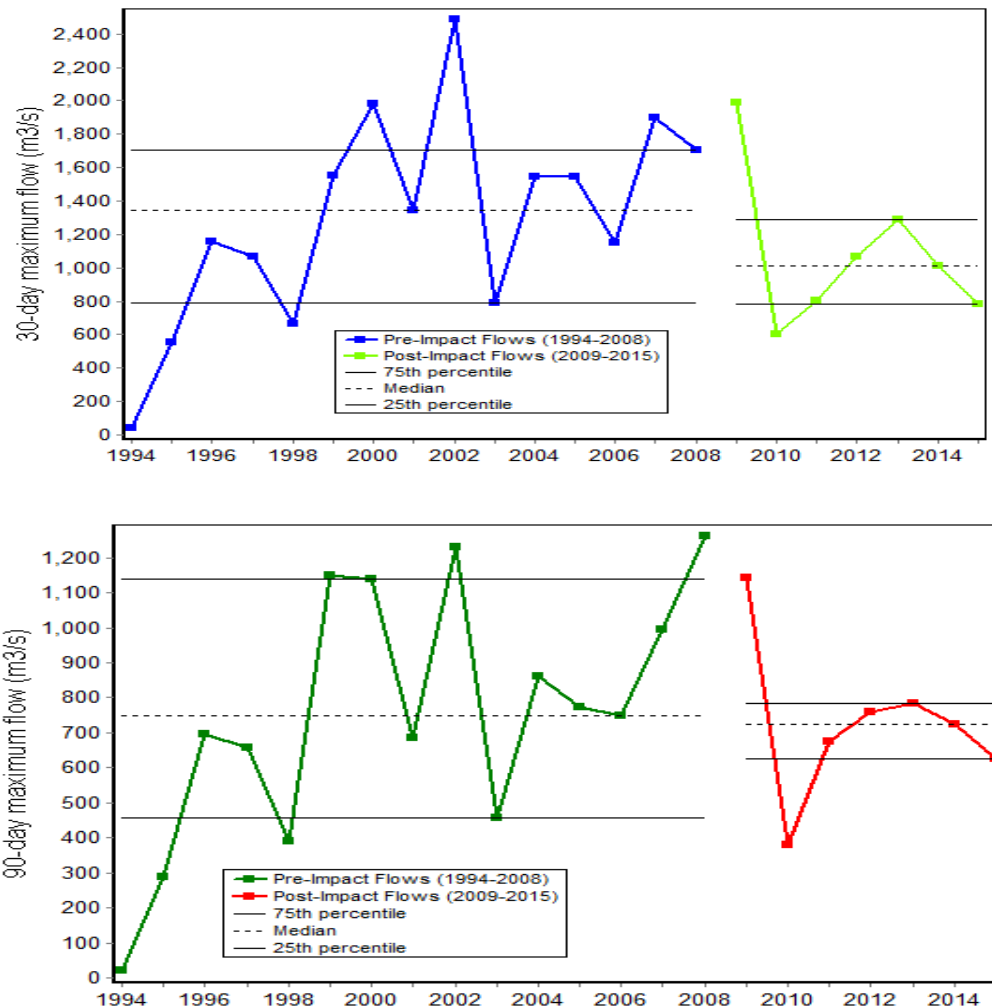


Figure 3.10 Hydrological alteration of 3- 7-, 30-, and 90-day maximum flow before and after Tekeze hydropower reservoir construction in Tekeze river

### 3.3.4.5 High and low pulses

Low pulse count, low pulse duration, high pulse count and high pulse duration have been changed, with hydrologic alteration of -64%, -69%, -64% and -20% respectively. Except high pulse duration the median of low pulse count, low pulse duration and high pulse count in the post-impact period were lower than those in the pre-impact period (Table 3.4). The coefficient of dispersion in the low pulse count and low pulse duration were higher in the pre-impact period, in contrast, the high pulse count and high pulse duration value were higher in the post-impact period. This indicates that the frequency and duration of low and high flow pulses in the Tekeze river had been influenced by Tekeze hydropower reservoir construction.

### 3.4 Conclusive Remarks

In this study, the non-parametric Mann–Kendall trend test and Pettit test were used to investigate the spatiotemporal trends and variability of precipitation data from different stations in Tekeze basin on the annual and seasonal timescales for the period 1953–2013 and streamflow at Embamadre for the period 1994–2014. The non-parametric Mann–Kendall test showed that annual precipitation has an increasing trend in southern part of Tekeze basin varies from 0.98mm/year to 8.12mm/year whereas the decreasing trend prevails in the northern part of the basin which ranges from -6.22mm/year to -2.35mm/year. There was no significant positive, or negative trends were detected by the trend tests in annual precipitation in this basin. The analysis of the seasonal precipitation time series showed a mix of positive and negative trends. In Belg and Kiremt season more than 80% of the precipitation stations showed positive trend whereas Bega showed a similar percentage but decreasing trend. All the three seasons show statically significant increasing and decreasing precipitation trends with abrupt change detected in the late 1970s and mid-1980s. In Belg and Kiremt seasons significant positive trends were found in 82% and 55% of the stations respectively, whereas in Bega 73% of the station show significant negative trends. The strongest positive trend of 2.14mm/year and 6.41mm/year was detected in Belg and Kiremt season at Debre Tabor station respectively and negative trend of -1.33mm/year detected in Bega season at Nefas Mewucha station.

Annual streamflow in Tekeze basin showed a non-significant increasing trend at a rate of 1.867m<sup>3</sup>/year. The seasonal streamflow showed similar projections like precipitation both increasing and decreasing trend. Streamflow trend increases in the Kiremt and Belg seasons whereas decreases in Bega (dry) periods. Statistical analysis performed using IHA at Embamadre streamflow station shows an increased in minimum flow duration and also decreased in maximum

flow duration, fall and rise rate. After the inauguration of Tekeze Dam, the hydrology altered as significant decline of high flows and increase of low flows, which were mainly attributed to stored water during rainy season and releasing it during dry season.

The findings of this research can provide some information to the government and community on the variability of rainfall and streamflow for current and future planned dams and irrigation projects. Such information also used for policy makers and managers within the context of water resource management, hydrology, agriculture, and ecosystem in Tekeze river basin.

#### **4. CLIMATE CHANGE IMPACT ON THE WATER RESOURCES OF TEKEZE BASIN<sup>2,3</sup>**

**Abstract:** Climate change impact on Tekeze Basin hydrology studied using bias corrected ensembles of CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios projections of precipitation and temperature. Soil and Water Assessment Tool (SWAT) used to simulate streamflow and distribution mapping bias correction improves precipitation and streamflow simulations. Tekeze basin showed an increase in mean temperature up to 1.07 °C for RCP4.5 and 2.21 °C for RCP8.5 climate scenarios in all time periods. Annual, long rain (*Kiremt*) and dry (*Bega*) seasons precipitation also showed an increasing trend up to 48% whereas short rain (*Belg*) season showed a decreasing trend up to 52% under both RCP climate scenarios for all future time periods. For this study, SWAT performs well with values of Nash-Sutcliffe efficiency ( $E_{NS}$ ) and  $R^2$  greater than 0.7 for simulating monthly streamflow with a reasonable accuracy. Projected streamflow in the basin will increase and its magnitude varies up to 58-66% in dry and 21-55% in rainy seasons for both RCP4.5 and RCP8.5 scenarios in 2020s, 2050s and 2080s projected time periods. Results from this study indicated that climate changes will alter quantity and timing of water that affect the basin hydrology and water resources. This increasing streamflow for future time horizon is advantageous for planning and operation of large water resources infrastructures in Tekeze basin in particular, and in the downstream Nile Basin countries; Ethiopia, Sudan and Egypt in general.

**Keywords:** Tekeze River Basin; Water Resources; SWAT; CORDEX-Africa; RCP Scenario; Climate Change

## 4.1 Introduction

Water resources issues faced around the world are complex, costly and challenging. Together with activities of humans like land cover and land use change, deforestation, land degradation, soil erosion, urbanization, population increase, changing social value and others (Liu et al., 2009), climate change impacts water resources planning and management. Climate change may alter quantity, quality, distribution and timing of water due to resulting changes in the hydrological cycle. These changes affect different water resources operations and managements like hydropower generation, irrigation practices, flood risk reduction, water quality, navigation, ecosystem and a combination of these future water resources planning and managements. In order to solve these water resources operation and management problems it is necessary to study the impact of climate change on the hydrology of the watershed (Adem et al., 2014; Dessu and Melesse, 2013; Grey et al., 2014; Melesse et al., 2011, 2009, Setegn et al., 2014, 2011).

It has been predicted that climate change and the resulting changes in precipitation and temperature regimes will affect the availability of water resources in different regions of the world (Piao et al., 2010; Setegn et al., 2011). African river basins are highly vulnerable to these changes. Many studies conducted to assess climate change impacts on water resources of Africa (Beyene et al., 2010; Gbobaniyi et al., 2014; Gizaw et al., 2017; Kim et al., 2014) especially in the Nile River basin which have competent applications in ten riparian countries (Taye et al., 2011). From a total flow of Nile River, about 86% of the flow contributes from Eastern Nile basin covering a total area of 60% which originates from Ethiopian highlands (Arsano and Tamrat, 2005; Mengistu and Sorteberg, 2012; Swain, 1997). This is the reason why several studies focus on Eastern Nile basin. Many studies done in the Eastern Nile basin especially Upper Blue Nile basin (Beyene et al., 2010; Enyew et al., 2014; Melesse et al., 2009; Mengistu and Sorteberg, 2012; Taye et al., 2011) to assess

the impact of climate change on water availability but only very little studies done on Tekeze river basin part of Eastern Nile in the Northwest of Ethiopia (Gizaw et al., 2017).

The primary tools for projecting climate are GCMs that are typically run at a horizontal resolution of 100km-250km due to their massive computational and data storage requirements. Since typical impact assessment models require inputs at much finer spatial resolutions, GCMs data are often downscaled using RCMs. RCMs are a widely used tool for producing regional climate data that use boundary conditions from forcing coarse scale global data sets such as a GCMs or reanalysis to simulate the climate of a region. To systematically explore uncertainties associated with downscaling, coordinated RCM simulations are necessary. Now a day's such coordinated efforts are available in different regions of the world. The CORDEX is a new initiative by World Climate Research programme (WCRP) (Giorgi et al., 2009) aims to foster international collaboration to generate an ensemble of high resolution historical and future climate projections at regional scale, by downscaling the GCMs participating in the CMIP5 (Taylor et al., 2011). Africa is a prime focus of this initiative due to its heightened vulnerability to climate change, and poorly developed adaptation structure. More recently, analyses in relation to CORDEX simulations over Africa can be found in the work of different researchers (Hernández-Díaz et al., 2013; Jacob et al., 2012; Nikulin et al., 2012). Nikulin *et al.* (2012) evaluate the ability of ten RCMs over Africa and conclude that all RCMs simulate the seasonal mean and annual cycle quite accurately. Likewise, it is verified that the mean of multi model outputs do better than individual simulation. Hernández-Díaz *et al.* (2013) strengthen the achievement of Nikulin *et al.* (2012). They successfully reproduce the overall features of geographical and seasonal distribution over most Africa. In their report, CORDEX simulations succeed in reproducing the average distribution of precipitation and its large geographical differences. Jacob *et al.* (2012) have integrated Regional Model (REMO) over six

CORDEX continents and found that REMO is well suited to examine projected future changes in all these domains despite wet and dry biases appear over the mountainous regions and East Africa, respectively. On the other hand, the African Monsoon Multidisciplinary Analysis-Model Intercomparison Project (AMMA-MIP) provides contribution relevant to CORDEX and achieves good correlation between the accumulated rainfall over the Sahel and the latitude of the African Easterly (Ruti et al., 2011). Ensemble outputs from CORDEX experiment are not only a compulsory for climate studies, and a roadmap to adaptation and mitigation strategies but also good source of data for us to apply them to our region, Ethiopia, where climate change is already observed (Conway, 2005; Elshamy et al., 2009; Mengistu and Sorteberg, 2012).

Nowadays there is available most recent Representative Concentration Pathways (RCPs) scenarios (Meinshausen et al., 2011) of the fifth phase of CMIP5 developed for fifth IPCC assessment report (AR5) (Taylor et al., 2011). CMIP5 incorporated new paradigms for developing future emission scenarios, introduced experiments to explore carbon-climate interactions and have finer resolution process and well-integrated earth system components than the earlier phase of CMIP model an ongoing process without specific end date, example third phase of CMIP3. The CMIP5 scientific gaps like poor quantification and understanding of radiative forcing (more coordinated representation of the atmospheric aerosol and land surface processes) and model biases will be considered in the next new sixth phase of Coupled Model Intercomparison Project (CMIP6). CORDEX after applying on an ensemble RCMs for multiple GCMs produced high resolution downscaled historical and future climate data based on CMIP5 simulations used for impact and adaptation studies (Gbobaniyi et al., 2014; Kim et al., 2014; Nikulin et al., 2012; Panitz et al., 2014). However, these high resolutions downscaled RCM simulations may not be directly used in hydrological model for hydrological impact assessment in watershed scale due to biases

(Christensen et al., 2008; Graham et al., 2007; Kim et al., 2015; Teutschbein and Seibert, 2010). These biases should be corrected if realistic future hydrology requires (Rojas et al., 2011) using different bias correction methods (Teutschbein and Seibert, 2012). The climate projection framework within CORDEX is based on the set of GCM simulations in support of the IPCC fifth assessment data referred to as CMIP5 climate projections. CORDEX focus on the GCM experiments using new set of climates forcing scenarios known as RCPs which represents RCP4.5 (mid-level) and RCP8.5 (high-level) emission scenarios. The definition of the RCPs allows for a parallel development of new socioeconomic, technical and policy scenarios that provide insights into the impact of policy decisions on the future climate (Vuuren et al., 2011). The RCPs focus on the ‘concentrations’ of greenhouse gases that lead directly to a changed climate and include a ‘pathway’ the trajectory of greenhouse gas concentrations over time to reach a particular radiative forcing at 2100.

Hydrological models that allow for a description of the hydrology of the region play an important role in predicting river discharges from gauged and ungauged catchments and understanding the rainfall–runoff processes in the catchments to enhance hydrological and water resources analysis. As such, a number of models have been developed and applied to study the water balance, soil erosion, climate and environmental changes in the Blue Nile Basin (Conway, 1997; Johnson and Curtis, 1994; Kebede et al., 2006; Mekonnen et al., 2009; Tekleab et al., 2011; Tilahun et al., 2013). But some of these models have limitations which include inappropriate scale, inability to perform continuous-time simulations, inadequate maximum number of sub watersheds, and the inability to characterize the watershed in enough spatial detail. Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2005), a watershed scale physically-based simulation model, was developed to overcome these limitations. The SWAT model offers continuous-time

simulation, high level of spatial detail, unlimited number of watershed subdivisions, efficient computation, and capability to simulate changes in land-management. Besides its obvious advantage as a hydrological modeling tool that includes modularity, ability to predict long-term impacts as a continuous model, and ability to use readily available global datasets, availability of a reliable user and developer support has contributed to its acceptance as one of the most widely adopted and applied hydrological models worldwide (Gassman et al., 2014). SWAT has been tested for a wide range of regions, conditions, practices and time scales (Gassman et al., 2007). SWAT is increasingly used for climate change assessment applications all around the world (Gassman et al., 2007; Schuol et al., 2008) and in the Upper Blue Nile Basin (Mengistu and Sorteberg, 2012; Setegn et al., 2010b; van Griensven et al., 2012). These studies showed that the SWAT model could describe the study areas with a quality that makes it suitable for water resource planning and management use. Hence, SWAT is a suitable hydrologic model to assess impacts of climate change on the water resources of Tekeze River basin part of the Eastern Nile Basin.

For the Tekeze basin, we focus on water as the key resource for development and flood security as well as economic development and livelihood and especially for hydropower production. Moreover, the most up-to-date knowledge the model outputs from CMIP5 of CORDEX-Africa for the representative concentration pathways, RCPs, to investigate climate impacts in the basin water resources. In this study, a climate change impact assessment was carried out for the Tekeze basin, which contributes a significant flow to the main Nile. The Ethiopian government has planned to increase reservoir water storage in this basin to increase hydropower generation and irrigation to facilitate growth and stabilize the national economy. In this regional specific Tekeze basin study, CORDEX-Africa that focused on bias corrected ensembles of GCMs/RCMs experiments using mid (RCP4.5) and high (RCP8.5) level emission scenarios were used.

The objectives of this study are to (1) test SWAT hydrological model in the Tekeze Basin (2) investigate the changes and trends in future precipitation and temperature across Tekeze river basin, and (3) assess the climate change effect on the future stream flow magnitude (water availability) under bias corrected ensembles of CORDEX-Africa RCM outputs of mid-range (RCP4.5) and high-level (RCP8.5) climate scenarios in this basin.

## **4.2 Study Area and Datasets**

### **4.2.1 Study Area**

This study focuses on the Ethiopian portion of Tekeze basin (Figure4.1) with topographic location 11<sup>o</sup>40' to 14<sup>o</sup>32'N and 36<sup>o</sup>30' to 39<sup>o</sup>50'E with catchment area 43,000km<sup>2</sup> upstream of Embamadre gauged station. The river begins at the spring near Lalibela in the central Ethiopian highlands. The topography varies from 4455meter above sea level (masl) in the Semein Mountains to 589masl in the Metema lowland areas. This topographic variation has a high potential for hydropower production in the mountainous areas and irrigation lands in the lowlands.

Climate of Tekeze basin varies depending on altitude. Rainfall increases as altitude increases but temperature decreases as altitude increases. Minimum and maximum temperature varies from 3-21<sup>o</sup>C in the highlands of Semein Mountains and 19-43<sup>o</sup>C in the lowland areas. The rainfall varies from 600mm in the lowlands to 1300mm in the highland areas. During the months from July to August 70% rainfall falls in the area. There are three seasons controlling the climate in Tekeze basin. These are the dry (*Bega*) season runs from October to January, no rain and dry in all parts of the basin. Small rain (*Belg*) season runs from February to May and most part of the basin receive considerable amount of rainfall. Wet (*Kiremt*) season runs from June to September all parts of the basin receive rain.

The main soils of Tekeze basin as per FAO classification are Eutric Cambisols, Calcric Cambisols and Eutric Vertisols mainly found in the highland and lowland areas of the watershed and Eutric Leptosols in the central part of the basin. Most of the basin areas are covered with rainy season agriculture and cultivated land in the form of intensively cultivated, seasonally cultivated lands and cultivated land with scattered trees and shrubs. Generally, the basin land use and land cover includes more than 70% of cultivated land and the remaining are shrub land (Range grasses), mixed forests, pasture/ grazing lands and exposed rocks (Tesfaye et al., 2017) . Major crops grow in this basin are Teff, Wheat, Barley, Maize and other Cereals.

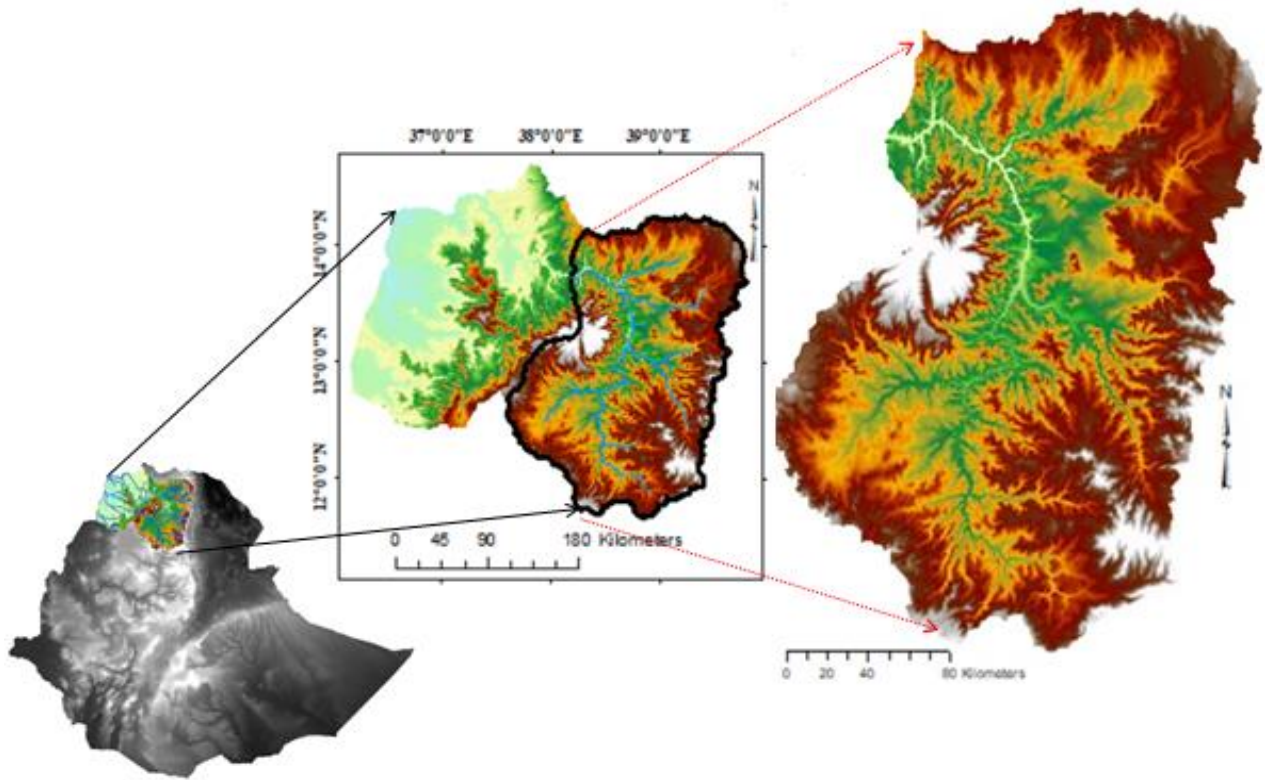


Figure 4.1 Location of upper Tekeze basin upstream of Embamadre gauging station

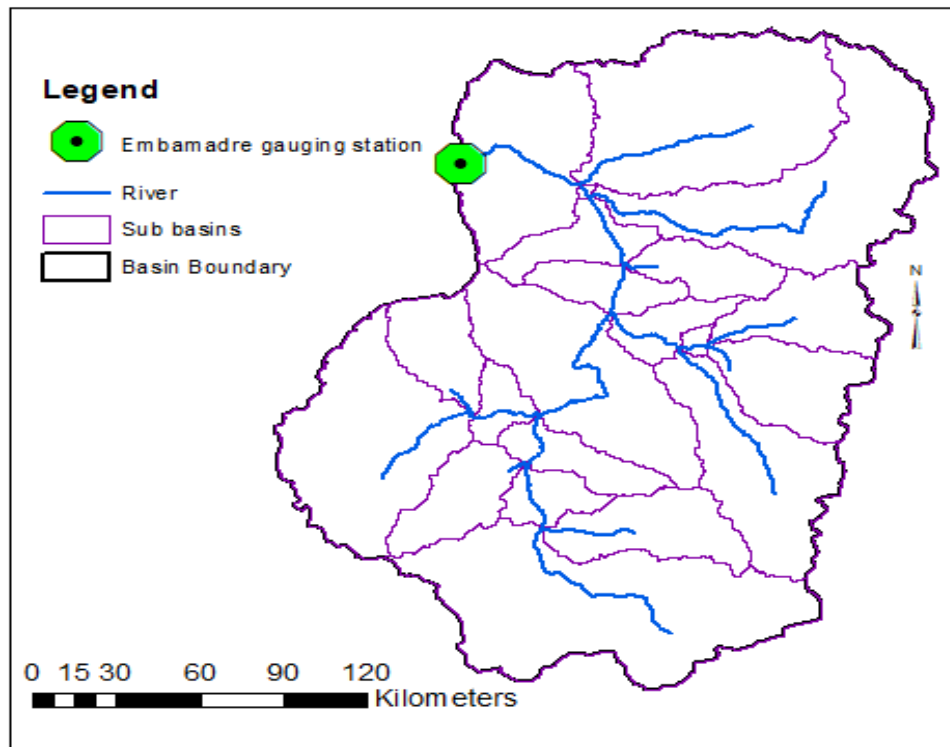


Figure 4.2 Sub-basins of Tekeze basin study area watershed delineated by SWAT

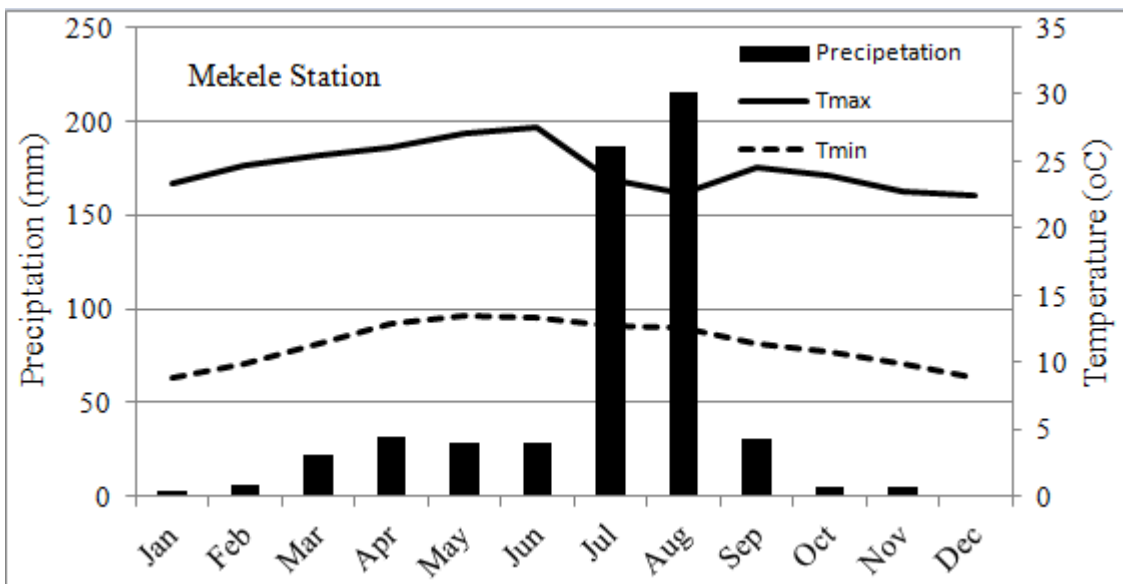
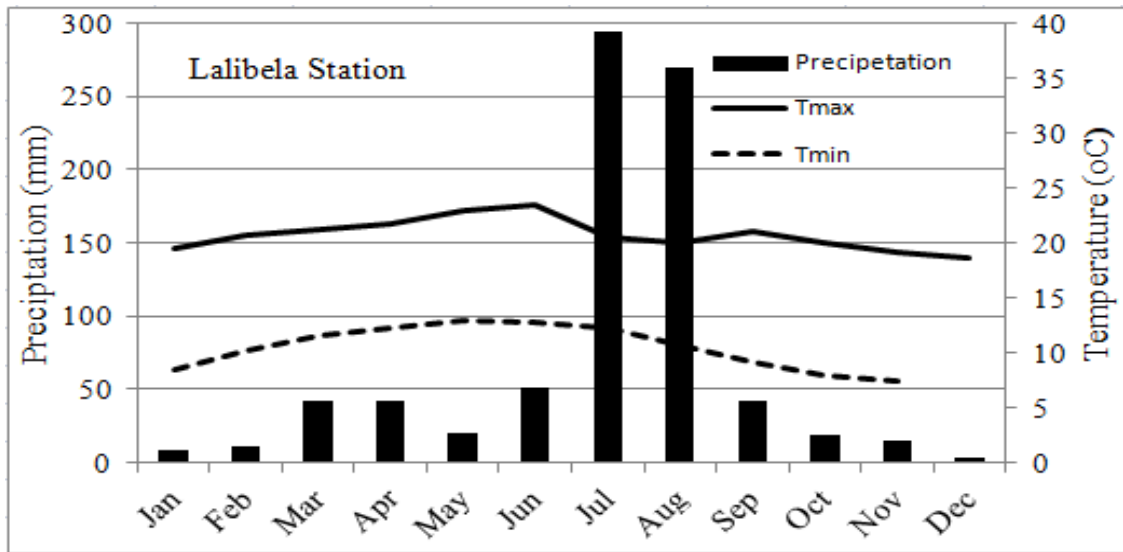


Figure 4.3 Mean monthly precipitation (mm) and maximum temperature ( $T_{max}$ ) & minimum temperature ( $T_{min}$ ) ( $^{\circ}C$ ) for selected stations of Tekeze basin

#### 4.2.2 Dataset Used

For climate change impact assessment studies using hydrological model different climatic and spatial data were used. These were digital elevation model, streamflow, temperature; precipitation and land use and land cover data.

#### **4.2.2.1 Digital Elevation Model (DEM)**

DEM used to delineate the watershed and the drainage patterns of the surface area analysis in the SWAT model. Sub-basin parameters such as slope gradient, slope length of the terrain, and the stream network characteristics such as channel slope, length, and width were derived from DEM. This study used a DEM that was a processed Shuttle Radar Topographic Mapping (SRTM) 30mx30m resolution topographic map obtained from Ethiopian Ministry of Water, Irrigation and Electricity, GIS and Remote Sensing department.

#### **4.2.2.2 Soil and Land use data**

Soil, land use/land cover data were used as an input into SWAT hydrological model to delineate sub-watersheds further into hydrologic response units (HRUs). The Soil data used includes the information to describe the physical and chemical properties of the soil like soil texture, hydraulic conductivity, bulk density, water content, organic carbon content and percentage of sand, silt, and clay content for each soil horizon. Land use/ land cover influences the hydrological properties of the watershed and used as an input for SWAT model. Tekeze basin land use/ land cover changes time to time due to several factors mainly changing agricultural practice, over increase in population density, urbanization, new hydropower and irrigation development. This basin is covered with agricultural lands, forests, grasses, bushes and shrubs. Soil, Land use/ land cover data of Tekeze basin were obtained from Ethiopian Ministry of Water, Irrigation and Electricity in shape file format. The land use and land cover of Tekeze basin after reclassification by SWAT includes 64% of agricultural land generic (AGRL), 14% of shrub land (range grasses, RNGE), 13% of mixed forests (FRST), and 9% of pasture/grazing lands (PAST).

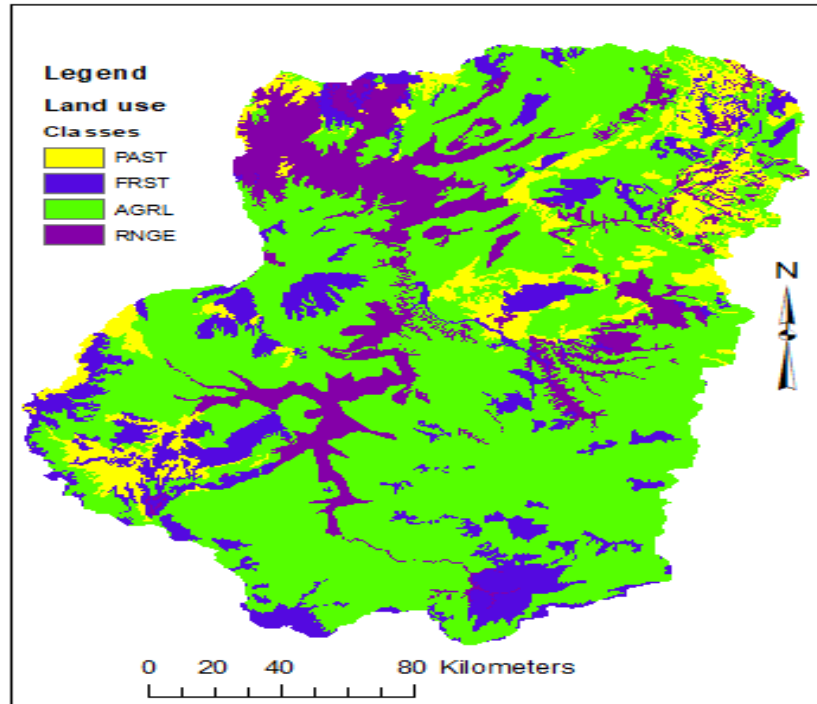


Figure 4.4 Major land use/land cover map of Tekeze Basin study area re-classified by SWAT

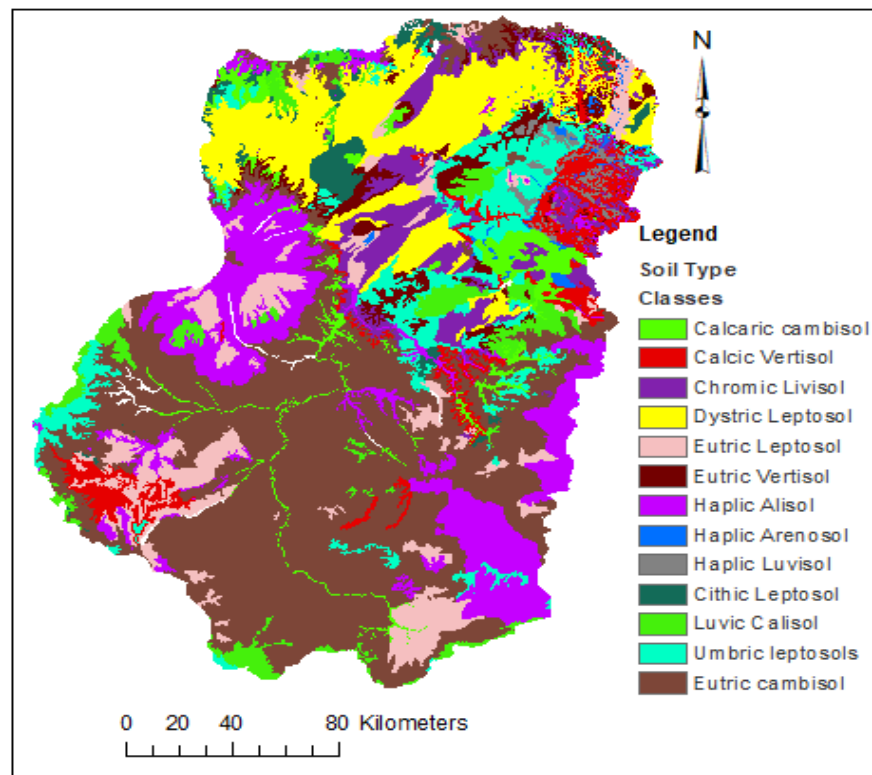


Figure 4.5 Major soil map of Tekeze Basin study area re-classified by SWAT

#### **4.2.2.3 Climate Data**

The SWAT model requires daily climate data of precipitation, maximum and minimum temperature to simulate the hydrologic response. There are numerous weather stations in Tekeze basin. For this study, stations recording precipitation and temperature data that have long period of records with small data gaps were used. The climate data for eleven stations (Figure 2.2) found within and near by the Tekeze basins from 1976-2013 collected from Ethiopian National Meteorological Service Agency. However, there are missing data on average less than 8% for both precipitation and temperature. The three steps visual inspection, comparison to the nearest station with in the same zone and regression relations between neighbouring stations and SWAT built in weather generator were taken to detect outliers and fill in the missing gaps in the data series. The SWAT built in weather generator used a first-order Markov chain model. For each sub basin input to the weather generator was observed precipitation data for the weather station that was nearest the centroid of the sub-basin and having a record length from 1994–2008. Given the observed wet and dry days' frequencies, the model determines stochastically if precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating values from a skewed normal daily precipitation distribution or a modified exponential distribution which is calculated based on the observed data.

#### **4.2.2.4 Streamflow/River Discharge Data**

The hydrological discharge (streamflow) daily data was required for performing sensitivity analysis, calibration and validation of the SWAT model. In the Tekeze River basin most of flow gauging stations located on upper part of the basin relatively small tributaries and/or near the head waters of the main river covering small catchment area with short periods of record, large data gaps, and high amount of missing data which was discussed in previous chapter, but Embamadre

station has relatively long record periods and cover almost half of the basin area. Daily stream flow data of the Tekeze basin at Embamadre gauged station (Figure 2.2) which has 15 years of record period continuous data from 1994-2008 was collected from Ethiopian Ministry of Water, Irrigation and Electricity.

#### **4.2.2.5 Climate Scenario Data**

In this research, climate change scenarios data from the newly available CMIP5 (Gbobaniyi et al., 2014; Kim et al., 2014; Nikulin et al., 2012; Vuuren et al., 2011) RCM ensemble output of CORDEX-Africa for African domain projections under Representative Concentration Pathways (RCP4.5 and RCP8.5) were used as input to hydrological model. Currently, CORDEX-Africa initiated by WCRP provides an opportunity for the generation of high resolution regional climate projections over Africa that is used to assess future impacts of climate change at regional and local scales. In this study, results of CORDEX-Africa ensemble RCMs simulations for the past (1951–2005) and future (2006–2100) climate projections downscaled from different GCMs under RCP4.5 and RCP8.5 with spatial resolution of 0.44° is used. CORDEX-Africa RCMs generate an ensemble of high resolution baseline (past) and future climate projections at regional scale by downscaling different GCMs forced by RCPs based on the CMIP5 (Nikulin et al., 2012; Vuuren et al., 2011). CORDEX-Africa climate projections use RCP4.5 and RCP8.5 climate scenarios.

RCPs are new climate change scenarios established by CMIP5 (Meinshausen et al., 2011; Taylor et al., 2011a), which can depict a wide variety of possible future climate scenarios. RCP scenarios have a better resolution that helps in performing regional and local comparative studies compared to previous climate scenarios, and RCP scenarios also represents an attractive potential approach for further research and assessment, including emissions mitigation and impact analysis. The fifth Assessment Report (AR5) scientific literature selects one mitigation scenario (RCP2.6), two

medium stabilization scenarios (RCP4.5 and RCP6.0) and one high emission scenario (RCP8.5). RCP2.6 scenario sees emissions peak early, then fall shown to be technically feasible. But one of RCP2.6 scenario key assumptions is the full participation of all developed and developing countries in the world in the short run to reduce all the main emitters, which is not possible in actual cases. Due to this, it is decided to choose one medium scenario (RCP4.5) and high scenario (RCP8.5) covering entire range of radiative forcing. RCPs represent pathways of radiative forcing, not linked with exclusive socio-economic assumption in contrary to Special Report on Emission Scenarios (SRES). Any single radiative forcing pathway can result from a diverse range of socio-economic and technological development scenarios. RCP4.5 is a mid-range scenario that stabilizes radiative forcing at  $4.5 \text{ W/m}^2$  (approximately 650 parts per million (ppm)  $\text{CO}_2$ -equivalent) in the year 2100 without exceeding this value, but this does not imply the climate system are stable (Thomson et al., 2011; Vuuren et al., 2011). Whereas RCP8.5 is upper bound of all RCP scenarios that stabilizes radiative forcing at  $8.5 \text{ W/m}^2$  (greater than 1370 ppm  $\text{CO}_2$ -equivalent) in the year 2100 (Riahi et al., 2011; Vuuren et al., 2011). The works of (Meinshausen et al., 2011; Riahi et al., 2011; Thomson et al., 2011; Vuuren et al., 2011) briefly describe each RCPs (RCP4.5 and RCP8.5) in detail and discussed the modeling system that have created each RCP, the main socio-economic assumptions, the underline trends in energy use and detail on emissions and land use.

Precipitation and temperature data from these scenarios are available from an ensemble of CORDEX-Africa regional climate model for the domain of Ethiopia at  $0.44^\circ$  resolution from 1951-2005 for baseline (past) used to calibrate and validate with observed data and 2006-2100 for future periods which is expected to capture a reasonable range in climatic and hydrological projections for Tekeze Basin.

### 4.3 Methodology

The most common approach for hydrological impact studies of climate changes is to run hydrological models with climate scenarios, usually provided by the outputs of precipitation and temperature from climate models bias corrected to the catchment of interest. In this study, ensemble of CORDEX-Africa RCMs under RCP4.5 and RCP8.5 climate scenarios with bias correction methods were used as an input for SWAT to assess future water resources of Tekeze Basin.

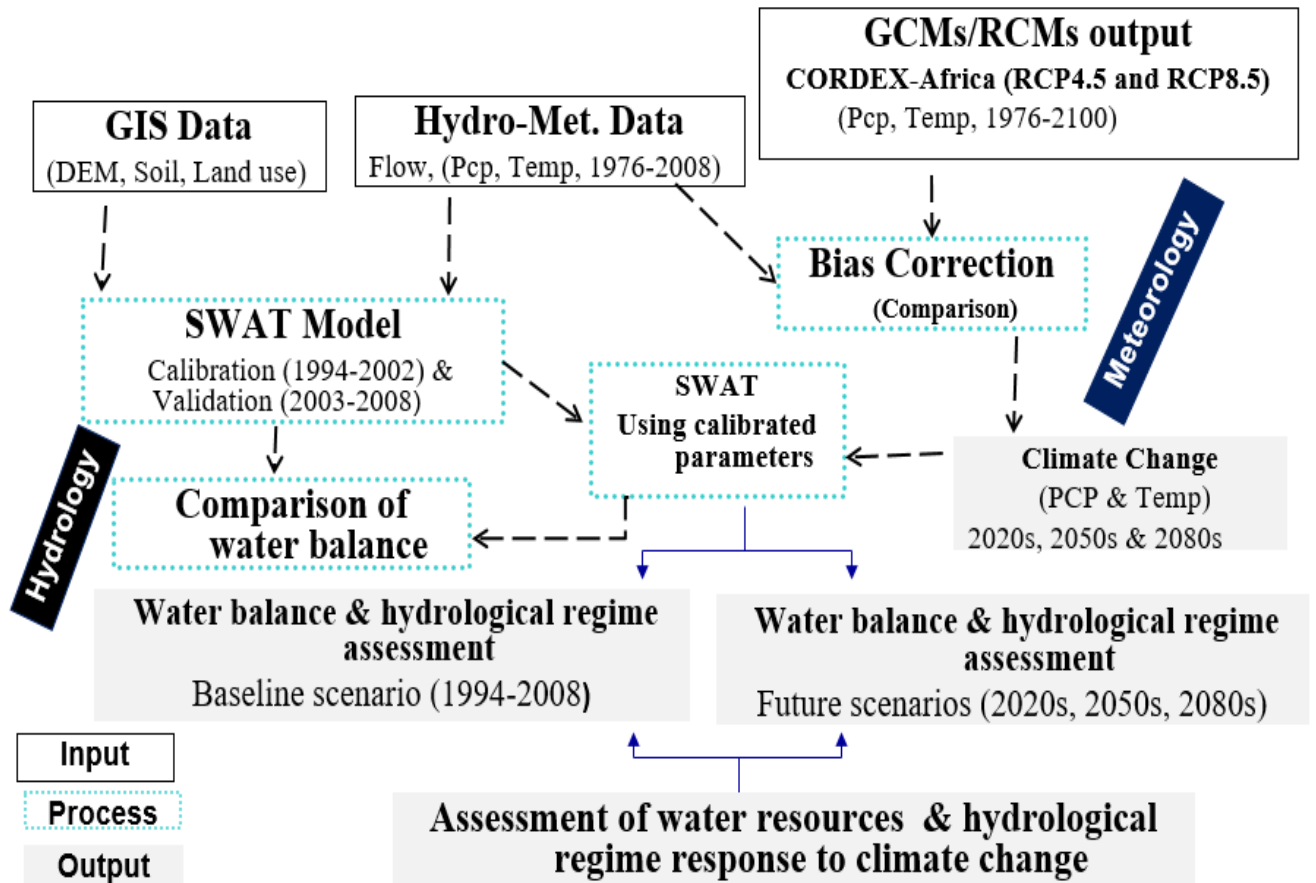


Figure 4.6 Conceptual diagram of the SWAT modeling process with climate change scenarios

### 4.3.1 Bias Correction Method

Numerous studies have assessed the impacts of climate change on water resources using climate variables from global climate models (GCMs) and water resources models. However, because of the relatively low spatial resolution (100–250 km) of GCMs, regional climate models (RCMs) are widely used for regional impact studies at catchment scales (25–50 km) climate variables. Although RCMs are able to simulate local climate at finer resolutions, outputs from RCMs cannot be used as direct input data for hydrological models due to systematic errors and require post-processing of the model outputs to remove biases (Christensen et al., 2008). Typical systematic model errors of RCMs include errors in estimation (over or under) of climate variables, incorrect estimates of seasonal variations of precipitation (Christensen et al., 2008), and simulations of more wet days of low intensity rainfall (drizzle effect) than they actually observed (Ines and Hansen, 2006). The physical characteristics of precipitation make it more difficult to correct and most studies tend to concentrate on precipitation correction. Methods of different complexity have been put forward, aimed at correcting various moments of the rainfall distribution.

Bias correction procedures employ a transformation algorithm for adjusting RCM output. The underlying idea is the identification of possible biases between observed and simulated variables, which is the bias for correcting both control and scenario RCM runs. A crucial assumption of bias correction is stationary of the bias, i.e., the correction algorithm and its parameterization for current climate conditions are also valid for future conditions (Christensen et al., 2008; Teutschbein and Seibert, 2012). Therefore, biases between the models are in general relatively stable, such that bias correction on average considerably improves future scenarios for many regions and all seasons. Bias adjustments methods usually do not account for the origins of biases in climate models and instead perform empirical adjustments. Bias correction methods of varying

complexity are applied to precipitation and temperature variables. This research limited to these two variables as they are the main atmospheric drivers for most impact and hydrological models, and due to the availability of high quality observational data records.

Various methodologies have been developed over the last decades to perform bias correction, from very simplistic methods, such as the so-called delta method only correcting the statistical mean of the simulations, to more sophisticated ones for example based on distribution functions (Piani et al., 2010; Teutschbein and Seibert, 2012). In this research, five methods, i) the delta change approach ii) Linear scaling, iii) local intensity scaling, iv) variance scaling, and v) distribution mapping were explored to adjust raw ensemble of CORDEX-Africa RCMs RCP scenarios output simulation data.

#### *i. Delta Change Method*

The delta change method consists of altering an observed (reference) climate series with change factors to obtain a new series representative of future changes. For the flux variables like precipitation relative change factors applied whereas for state variables like temperature absolute change is applied. Monthly change factors are derived and perturbed as follows for day and month (i, j), where i = 1, 2, 3, ..., 31 and j = 1, 2, ..., 12:

$$P_{obs} = P_{ref} \quad (4.1)$$

$$P_{(i,j)} = \Delta_{P(j)} * P_{obs(i,j)}; \Delta_{P(j)} = \frac{P_{fut(j)}^{avg}}{P_{ref(j)}^{avg}} \quad (4.2)$$

$$T_{obs} = T_{ref} \quad (4.3)$$

$$T_{(i,j)} = \Delta_{T(j)} + T_{obs(i,j)}; \Delta_{T(j)} = T_{fut(j)}^{avg} - T_{ref(j)}^{avg} \quad (4.4)$$

Where P (i, j) and T (i, j) are delta change perturbed daily climate change variables,  $P_{obs(i,j)}$  and  $T_{obs(i,j)}$  are observed precipitation and temperature climate variables in the reference period,  $\Delta_{P(j)}$

and  $\Delta T_{(j)}$  are the changes in climate as simulated by RCM-RCP scenarios and  $P^{\text{avg}}_{(j)}$  and  $T^{\text{avg}}_{(j)}$  are daily precipitation and climate means by month, the index ref indicates the reference (control) and fut indicates a future period.

The delta change method differs from other bias correction methods because it uses observations and only the RCM change signal but does not adjust the RCM simulations. Therefore, the delta change method cannot be evaluated for the control (baseline period) run as it gives perfect simulation by definition (equation 4.2 and 4.3 not valid in actual case). Due to this limitation the delta change method could not be assessed in this study.

### *ii. Linear scaling*

The linear scaling approach operates with monthly correction values based on the differences between observed and present day simulated precipitation and temperature raw data (raw simulated ensemble of CORDEX-Africa RCMs RCP scenarios data in this case). Linear scaling method aims to perfectly match the monthly mean of corrected RCM simulations with the observations. Precipitation is typically corrected with a multiplier and temperature with an additive term on a monthly scale. The applied correction factors and addends are assumed to remain unvaried even for future conditions.

Precipitation is corrected with a factor based on the ratio of long term monthly mean observed and control run data:

$$P^*_{concor,m(d)} = P_{raw,m(d)} \times \frac{\mu_{mpobs}}{\mu_{mpcon}} \quad (4.5)$$

$$P^*_{scencor,m(d)} = P_{scen,m(d)} \times \frac{\mu_{mpobs}}{\mu_{mpcon}} \quad (4.6)$$

Where  $P^*_{concor,m(d)}$  is corrected precipitation of control period on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $P_{raw,m(d)}$  is the present raw precipitation on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month from 1976-2005,  $P_{scen,m(d)}$  is the

future raw precipitation on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month from 2011-2100,  $P^*_{\text{scencor}, m(d)}$  is corrected precipitation of future scenario on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $\mu_{\text{mpobs}}$  the mean value of observed precipitation at a given month  $m$  and  $\mu_{\text{mpcon}}$  the mean value of control period raw simulated precipitation at a given month  $m$ .

Raw simulated temperature data is corrected with the help of an additive term based on the difference of long-term monthly mean observed and control run data:

$$T^*_{\text{concor}, m(d)} = T_{\text{raw}, m(d)} + \mu_{\text{mtobs}} - \mu_{\text{mtcon}} \quad (4.7)$$

$$T^*_{\text{scencor}, m(d)} = T_{\text{scen}, m(d)} + \mu_{\text{mtobs}} - \mu_{\text{mtcon}} \quad (4.8)$$

Where  $T^*_{\text{concor}, m(d)}$  is corrected temperature of control period on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $T_{\text{raw}, m(d)}$  is the present raw temperature on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month from 1976-2005,  $T_{\text{scen}, m(d)}$  is the future raw temperature on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month from 2011-2100,  $T^*_{\text{scencor}, m(d)}$  is corrected temperature of future scenario on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $\mu_{\text{mtobs}}$  the mean value of observed temperature at a given month  $m$ .

The temperature at a given month  $m$  and  $\mu_{\text{mtcon}}$  the mean value of control period raw simulated linear scaling approach adjusts monthly mean values and offers corrected data with a variability more consistent with the raw RCM-RCP scenarios data. Similar to delta change approach, the downside is that all events are adjusted with the same correction factor. It is furthermore not able to correct frequencies.

### **iii. Local intensity scaling of precipitation**

The local intensity method corrects the wet-day frequencies and intensities which can effectively improve the raw precipitation data which have too many drizzle days (days with little precipitation). It normally involves two separate steps:

1. The wet-day threshold for the  $m^{\text{th}}$  month  $P_{\text{thres}, m}$  is determined from the raw precipitation series to ensure that the threshold exceedance matches the wet-day frequency of observations. The number of precipitation events for both control (1976-2005) and scenario (2011-2100) run are corrected by applying the calibrated RCM precipitation threshold ( $P_{\text{thres}, \text{con}}$ ) so that all days with precipitation less than  $P_{\text{thres}, \text{con}}$  are redefined to dry days with 0mm precipitation:

$$P_{\text{con}(d)}^a = \begin{cases} 0, & \text{if } P_{\text{con}(d)} < P_{\text{thres}, \text{con}} \\ P_{\text{con}(d)}, & \text{otherwise} \end{cases} \quad (4.9)$$

$$P_{\text{scen}(d)}^a = \begin{cases} 0, & \text{if } P_{\text{scen}(d)} < P_{\text{thres}, \text{con}} \\ P_{\text{scen}(d)}, & \text{otherwise} \end{cases} \quad (4.10)$$

Where  $P_{\text{con}(d)}$  is the present raw precipitation on the  $d^{\text{th}}$  day from 1976-2005,  $P_{\text{thres}, \text{con}}$  is the present raw precipitation whose value greater than the threshold value,  $P_{\text{con}(d)}^a$  is the present adjusted dry and wet-day precipitation of control period on the  $d^{\text{th}}$  day,  $P_{\text{scen}(d)}$  is the future scenarios raw precipitation on the  $d^{\text{th}}$  day from 2011-2100 and  $P_{\text{scen}(d)}^a$  is the future adjusted dry and wet-day precipitation of future period on the  $d^{\text{th}}$  day. This procedure allows the scenario run to have a different wet-day frequency than the control and scenarios run.

2. A linear scaling factor ( $s$ ) is estimated based on the long term monthly mean wet-day intensities. This intensity factor is calculated by considering only wet-days (observed days with precipitation larger than 0mm) in to account and the RCM-RCP scenarios simulated days with precipitation larger than the adjusted precipitation threshold ( $P_{\text{thres}, \text{con}}$ ).

$$s = \frac{\mu_{\text{pobs}, m(d)}}{\mu_{\text{praw}, m(d)}} \quad (4.11)$$

Where  $s$  is linear scaling intensity factor,  $\mu_{\text{pobs}, m(d)}$  the mean value of observed wet-day precipitation ( $P_{\text{obs}(d)} > 0$ ) at a given  $d^{\text{th}}$  day and  $\mu_{\text{praw}, m(d)}$  the mean value of control period

raw simulated precipitation greater than the controlled threshold value ( $P_{\text{raw}, m(d)} > P_{\text{thres, con}}$ ) at a given  $d^{\text{th}}$  day.

This factor used to ensure that the mean of the corrected precipitation is equal to that of the observed precipitation. Finally, the RCM-RCP scenarios of present and future precipitation are corrected as:

$$P_{\text{con}(d)}^* = s * P_{\text{con}(d)}^a \quad (4.12)$$

$$P_{\text{scen}(d)}^* = s * P_{\text{scen}(d)}^a \quad (4.13)$$

Where  $P_{\text{con}(d)}^*$  is corrected precipitation of control period on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $P_{\text{scen}(d)}^*$  is corrected precipitation of future scenario on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month.

Local intensity scaling is an improvement of the linear scaling approach, because it combines the linear scaling advantages with a correction of the wet-day frequencies (precipitation threshold).

#### *iv. Variance scaling of temperature*

The variance scaling method was developed to correct both the mean and variance of normally distributed variables such as temperature (Teutschbein and Seibert, 2012). Temperature is normally corrected using variance scaling method with the following equation:

$$T_{\text{concor}, m(d)}^* = T_{\text{raw}, m(d)} - (\mu_{\text{Traw}, m} * \frac{\sigma_{\text{Tobs}, m}}{\sigma_{\text{Traw}, m}}) + \mu_{\text{Tobs}, m} \quad (4.14)$$

$$T_{\text{scen}, m(d)}^* = T_{\text{scen}, m(d)} - (\mu_{\text{scen}, m} * \frac{\sigma_{\text{Tobs}, m}}{\sigma_{\text{Traw}, m}}) + \mu_{\text{Tobs}, m} \quad (4.15)$$

Where  $T_{\text{concor}, m(d)}^*$  is corrected temperature of control period on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $T_{\text{raw}, m(d)}$  is the present raw temperature on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $T_{\text{scen}, m(d)}$  is the future raw temperature on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $T_{\text{scen}, m(d)}^*$  is corrected temperature of future scenario on the  $d^{\text{th}}$  day of  $m^{\text{th}}$  month,  $\mu_{\text{Tobs}, m}$  the mean value of observed temperature at a given month  $m$ ,

$\mu_{\text{Traw},m}$  the mean value of control period raw simulated temperature at a given month  $m$ ,  $\mu_{\text{scen},m}$  the mean value of future period raw simulated temperature at a given month  $m$ ,  $\sigma_{\text{Tobs},m}$  is the standard deviation of observed temperature at a given month  $m$ , and  $\sigma_{\text{Traw},m}$  is the standard deviation of control period raw simulated temperature at a given month  $m$ .

The variance scaling approach guarantees that the adjusted RCM control run has the same mean and standard deviation (i.e. variance) as the observed time series. Like the other bias corrected methods, the correction factors assumed to remain the same for future conditions, but allow for changes in response between control and future scenarios run. Variance scaling adjusts both the variance and the mean of raw RCM data. It performs much better than the linear scaling approach in terms of correcting several statistical characteristics and in terms of the variability range. It should be noted that variance scaling is not advisable as it is based on the invalid assumption that all local variability is related to larger-scale variability and, furthermore, tends to augment the mean square errors of uncorrected data.

**v. *Distribution Mapping***

Distribution Mapping (DM) bias correction method (Piani et al., 2010) which can better transfer the observed precipitation and temperature statistics to the raw ensemble GCM/RCM CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios were used. Distribution mapping was found to be the best correction method for both climate projections and hydrological impact qualifications; it performed especially well in terms of the simulation of hydrological extremes. To date, this is probably one of the most thorough studies in terms of inclusion of the most bias correction approaches for hydrological impact studies.

Precipitation is more challenging to correct its bias due to its physical characteristics, but it has more significant influence than temperature on streamflow simulation of Tekeze River basin.

Therefore, in this research, the precipitation bias corrected using DM gamma distribution function with maximum-likelihood parameter estimation method. The gamma distribution recommended function for distributions of precipitation with shape parameter  $\alpha$  and scale parameter  $\beta$ , and it has been proven to be effective (Fang et al., 2015; Piani et al., 2010). The gamma distribution-based correction method assumes that the probability distributions of both observed and simulated daily precipitation datasets can be approximated using a gamma distribution.

The probability density function for gamma distribution is given by:

$$f(x, \alpha, \beta) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (4.16)$$

Cumulative distribution function

$$F(x) = \int_0^x f(x) dx \quad (4.17)$$

Where  $f$  is the distribution function,  $e$  is Euler's number,  $x$  is an independent (random) variable and  $\Gamma(\alpha)$  indicates the gamma function evaluated at  $\alpha$ .  $\alpha$  is the shape parameter and  $\beta$  is the scale parameter of the gamma distribution, estimated by the maximum likelihood estimation method.

The gamma function is defined by

$$\Gamma(\alpha) = \int_0^\alpha x^{\alpha-1} e^{-x} dx \text{ For } \alpha > 0 \quad (4.18)$$

This method was used to adjust the raw RCP4.5 and RCP8.5 climate scenarios precipitation data mean, standard deviation, quantile and it preserves the extremes (Thiemeßl et al., 2012). Ensemble RCM of CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios in Tekeze basin simulate a low number of dry days which are compensated by too much drizzle. In this research for the local intensity scaling and DM methods small precipitation magnitude, less than 0.20mm

were excluded from this bias correction simulation to reduce much drizzle effects. This method corrects all ranges of the systematic errors (i.e., biases) concerning each meteorological station which is inherited in raw CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios of precipitation data.

For temperature time series, the Normal (Gaussian) distribution with location parameter  $\mu$  and scale parameter  $\sigma$  is usually assumed to fit best:

$$fN(X / \mu, \sigma^2) = x^{\alpha-1} \frac{1}{\sigma \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (4.19)$$

The scale parameter  $\sigma$  determines the standard deviation, i.e., how much the range of the Gaussian distribution is stretched or compressed. A smaller value for  $\sigma$  results in a more compressed distribution with lower probabilities of extreme values. By contrast, a larger value for  $\sigma$  indicates a stretched shape with higher probabilities of extreme values. The location parameter  $\mu$  directly controls the mean and, therefore, the location of the distribution.

### 4.3.2 Hydrological Modeling Using SWAT

In this study, Soil and Water Assessment Tool (SWAT) (Arnold et al., 2013), one of the extensively used hydrological model around the world (Gassman et al., 2007) and in Ethiopia (Dessie et al., 2014; Mengistu and Sorteberg, 2012; van Griensven et al., 2012) was applied for the simulation of stream flows in the Tekeze Basin.

SWAT is widely used to simulate hydrological processes under the scenario of changes in land use, land management as well as climate change. Various studies used SWAT for watershed scale hydrological modeling in the USA (Wang et al., 2008a, 2008b, 2006; Wang and Melesse, 2006), Italy (Fiseha et al., 2014, 2013), Kenya (Dessu et al., 2014; Dessu and Melesse, 2013, 2012), Ethiopia ( Mengistu and Sorteberg, 2012; Setegn et al., 2009, 2010b, 2010a, 2011; Tibebe and

Bewket, 2011; van Griensven et al., 2012; Yesuf et al., 2015) and Jamaica (Grey et al., 2014; Setegn et al., 2014).

SWAT model is a physically based, continuous time watershed model which simulates hydrological processes in the watershed. The details of SWAT were shown in Neitsch et al.(2005).The SWAT used together with ArcSWAT in ArcGIS Geographical Information System interface to process the datasets and construct the required input for the initial modeling setup. In SWAT model application, the study basin is first sub divided in to sub-basins based on digital elevation model and channel network, and further delineated into hydrological response units (HRUs) considering dominant soil/land use category in each sub-basin where each sub-basin was assumed to be constituted with a homogeneous soil, land use and climate. Routing of water is simulated from the HRUs to the sub-basin level, and then through the stream network to the basin outlet. The model predicts the hydrology ultimately streamflow (Neitsch et al., 2005) at each HRU using water balance equation, which contains precipitation, surface runoff, evapotranspiration, infiltration and subsurface inflow. The water balance equation of the hydrologic cycle is:

$$SW_t = SW_0 + \sum_{i=1}^t (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (4.20)$$

in which  $SW_t$  is the final soil water content (mm),  $SW_0$  is the initial soil water content on day  $i$  (mm),  $t$  is the time in days,  $R_{day}$  is the amount of precipitation on day  $i$  (mm),  $Q_{surf}$  is amount of surface runoff on day  $i$  (mm),  $E_a$  is amount of evapotranspiration on day  $i$  (mm),  $W_{seep}$  is amount of water entering to vadose zone from the soil profile on day  $i$  (mm), and  $Q_{gw}$  is amount of return flow on day  $i$  (mm).

When the rate of precipitation exceeds the rate of infiltration, surface runoff occurs. SWAT offer the methods of the Soil Conservation Service (SCS) curve number procedure (United States Soil

Conservation Service., 1972), and the Green &Ampt infiltration method (Green and Ampt, 1911) to estimate surface runoff. SCS curve number method was selected for this basin SWAT model simulation as the SCS curve number procedure uses daily precipitation and the Green &Ampt infiltration method requires precipitation input in sub-daily scale. In the SCS method retention parameter defined by Curve Number (CN) is significant, and it is a sensitive function of the land use, soil's permeability and antecedent soil water conditions. Surface runoff was estimated using Soil Conservation Service Curve Number (SCS-Curve number) method:

$$Q_{\text{surf}} = \frac{(R_{\text{day}} - I_a)^2}{(P_{\text{day}} - I_a - S)} \quad (4.21)$$

Where  $I_a$  is the initial abstraction which includes surface storage, interception and infiltration prior to runoff and  $S$  is the retention parameter (mm)

Retention parameter defined by

$$S = 25.4 \left( \frac{1000}{\text{CN}} - 10 \right) \quad (4.22)$$

CN is curve number for the day varies from 0 to 100 depending on soil permeability, land use and the antecedent soil water condition.

Initial parameter approximated as  $0.2S$ , Equation (4.21) becomes:

$$R_{\text{surf}} = \frac{(P_{\text{day}} - 0.2S)^2}{(P_{\text{day}} + 0.8S)} \quad (4.23)$$

Where  $R_{\text{surf}}$  is amount of surface runoff on day  $i$  (mm)

#### **4.3.2.1 SWAT Model setup**

The SWAT model utilizes the DEM to create stream network, sub-basin and delineate the watershed boundary of Tekeze River basin using the elevation or topographic data and also calculates the sub-basin parameters for example the longest path distance, the centroid and the slope of sub-basin. Tekeze stream network and sub-watersheds were delineated using ArcSWAT2012 integrated in ArcGIS version 10.2.2 suggested drainage area required to form the origin of the stream i.e. 23 sub-watersheds; and 277 HRUs of Tekeze river were delineated up to the point of outlet of a drainage area of 43,000 km<sup>2</sup> at Embamadre gauging station. Hydrological Response Unit (HRU) which is the smallest unit of the model to route streamflow was established after reclassification of land use and soil maps and then overlaid one upon each other. The threshold value was assigned to subdivide the watershed area into HRU which an area is having unique land use, soil and slope combinations. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This improves the accuracy of runoff predictions of the model and provides a much better physical description of the water balance. All model input data were projected to the same projection of Transverse Mercator projection.

#### **4.3.2.2 Sensitivity analysis, Calibration and Validation of SWAT**

It is necessary to identify most sensitive water flow parameters and the parameter precision for a given watershed or sub-watershed required for calibration and validation process of SWAT model. Generally local and global sensitivity analysis performed, and this analysis may yield different results. Local sensitivity analysis is performed by changing values at a time whereas global sensitivity analysis by allowing all parameter values to change at a time. Sensitivity of one parameter often depends on the value of other related parameters; hence, the problem with one-at-a-time analysis is that the correct values of other parameters that are fixed are never

known. The disadvantage of the global sensitivity analysis is that it needs many simulations. Both procedures, however, provide insight into the sensitivity of the parameters and are necessary steps in model calibration. After pre-processing of the Tekeze basin data and ArcSWAT2012 model set up, simulation was done. The built-in SWAT sensitivity analysis tool that uses the Latin Hypercube One-factor-AT-a- Time (LH-OAT) was used to identify sensitive flow parameters in Tekeze River Basin. Parameters identified from the sensitivity analysis were varied in sequence of their relative sensitivity within their ranges (Table 4.1) until the volume is adjusted to the required quantity. Out of 26 SWAT sensitive to water flow parameters the curve number (CN2), available water capacity (Sol-AWC), Surface runoff lag coefficient (Surlag), saturated hydraulic conductivity (SOL\_K), soil evaporation compensation factor (ESCO), Groundwater revap coefficient (GW\_REVAP), Ground water delay time (GW\_DELAY), threshold water depth in the shallow aquifer for flow (GWQMN), Manning coefficient for main channel (CH\_N2), the shallow aquifer for “revap” (RVPMN) and base flow alpha factor (ALPHA\_BF) were identified as being parameters to which the flow has medium, high or very high sensitivity. The ranking of the parameters is presented in Table 4.1. The curve number (CN2) was the main sensitivity parameter. This is so because the curve number depends on several factors including soil types, soil textures, soil permeability, land use properties etc. In addition, the relative sensitivity of the available water capacity (Sol-AWC), the soil evaporation compensation factor (ESCO) and the saturated hydraulic conductivity (Sol-K) were also highly sensitive.

Table 4.1 Order of sensitive parameters and their optimal value

S. No	Parameter	Description	Unit	Range	Parameter	
					Initial value	Optimal value
1	CN2	Curve Number, Condition AMCI	-	35-98	83	54
2	SOL_AWC	Soil available water capacity	mm/mm	0-1	0.1	0.63
3	ESCO	Soil evaporation compensation factor	-	0-1	0.95	0.02
4	SOL_K	Hydraulic conductivity of the saturated soil	mm/hr	0-2000	45	1.56
5	GW_REVAP	Ground water revap coefficient	-	0.02-0.2	0.02	0.18
6	GW_DELAY	Ground water delay time	Day	0-50	31	9.5
7	GWQMN	Threshold water level in shallow aquifer for base flow	-	0-5000	1000	1290
8	EPCO	Plant uptake compensation factor	-	0.01-1	0.4	0.11
9	ALPHA_BF	Base flow alpha factor	Days	0-1	0.048	0.54
10	Surlag	Surface run off lag coefficient	-	0-10	0.5	0.3
11	CH_N2	Manning coefficient for main channel	-	(-)0.01-0.3	0.14	0.1
12	RVPMN	Threshold water depth in the shallow aquifer for “revap”	-	0-500	450	45
13	CH_K2	Effective hydraulic conductivity of main channel	mm/hr	(-)0.01-500	0.01	75

Proper model calibration is important in hydrologic modeling studies to reduce uncertainty in model simulation. Model calibration is performed by carefully selecting values for model input parameters (within their respective uncertainty ranges) by comparing model predictions (output) for a given set of assumed conditions with observed data for the same conditions. The SWAT model was calibrated and validated for Tekeze river streamflow using the measured data at Embamadre gauge station. The available data divided into two-time periods, for calibration (1994-2002) and for validation (2003-2008) processes. During the calibration process, the model's input parameters guided by the sensitivity analysis adjusted to match the observed and simulated streamflow's. In general, SWAT accurately tracked the measured streamflow's of Embamadre for the time, even though some peak flow months were over predicted. In the validation process, the model was run with input parameters set during the calibration process without any change. After manual and automatic calibration monthly streamflow were compared

against the observed data. There are several ways in which SWAT can be calibrated and validated.

In this study, the Nash-Sutcliffe coefficient ( $E_{NS}$ ), coefficient of determination ( $R^2$ ) and Percent bias (PBIAS) were used to evaluate performance of SWAT model simulation in the calibration and validation process (Moriassi et al., 2007).

**Nash-Sutcliffe efficiency ( $E_{NS}$ ):**  $E_{NS}$  is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”) (Nash and Sutcliffe, 1970).  $E_{NS}$  indicates how well the plot of observed versus simulated data fits the 1:1 line. The optimal values to get best model performance is at  $E_{NS} = 1$ .  $E_{NS}$  is computed as shown in equation 4.8:

$$E_{NS} = 1 - \left[ \frac{\sum_{i=1}^n (Q_i^{Obs} - Q_i^{Sim})^2}{\sum_{i=1}^n (Q_i^{Obs} - Q_{Obs}^{mean})^2} \right] \quad (4.24)$$

Where  $Q_i^{Obs}$  is the  $i^{th}$  observed streamflow of day  $i$ ,  $Q_i^{Sim}$  is the  $i^{th}$  simulated streamflow of day  $i$ ,  $Q_{Obs}^{mean}$  the mean of observed streamflow,  $Q_{Sim}^{mean}$  the mean of simulated streamflow

**Coefficient of determination ( $R^2$ ):** describe the degree of co-linearity between simulated and measured data. The  $R^2$  describes the proportion of the variance in measured data explained by the model. The ranges of  $R^2$  varies from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable. Although  $R^2$  has been widely used for model evaluation, this statistic is over sensitive to high extreme values (outliers), and insensitive to additive and proportional differences between model predictions and measured data.

$$R^2 = \frac{[\sum_{i=1}^n (Q_i^{Obs} - Q_{Obs}^{mean})(Q_i^{Sim} - Q_{Sim}^{mean})]^2}{\sum_{i=1}^n (Q_i^{Obs} - Q_{Obs}^{mean})^2 \sum_{i=1}^n (Q_i^{Sim} - Q_{Sim}^{mean})^2} \quad (4.25)$$

Where  $Q_i^{Obs}$  is the  $i^{th}$  observed streamflow of day  $i$ ,  $Q_i^{Sim}$  is the  $i^{th}$  simulated streamflow of day  $i$ ,  $Q_{Obs}^{mean}$  the mean of observed streamflow,  $Q_{Sim}^{mean}$  the mean of simulated streamflow

**Percent bias (PBIAS):** PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. PBIAS is calculated by Equation 4.26:

$$PBIAS = \left[ \frac{\sum_{i=1}^n (Q_i^{Obs} - Q_i^{Sim}) * (100)}{\sum_{i=1}^n (Q_i^{Obs})} \right] \quad (4.26)$$

Where PBIAS is the deviation of data being evaluated, expressed as a percentage

Table 4.2 : SWAT model performance evaluation criteria(Moriasi et al., 2007)

Model Evaluation	$E_{NS}$	$R^2$	PBIAS
Excellent	$0.75 < E_{NS} \leq 1.00$	$0.70 < R^2 \leq 1.00$	$PBIAS \leq \pm 10$
Good	$0.65 < E_{NS} \leq 0.75$	$0.60 < R^2 \leq 0.70$	$\pm 10 < PBIAS \leq \pm 15$
Satisfactory	$0.50 < E_{NS} \leq 0.65$	$0.50 < R^2 \leq 0.60$	$\pm 15 < PBIAS \leq \pm 25$
Unsatisfactory	$0.00 < E_{NS} \leq 0.50$	$0.00 < R^2 \leq 0.50$	$PBIAS > \pm 25$

The final step is validation for the component of interest (streamflow). Model validation is the process of demonstrating that a given site-specific model can make sufficiently accurate simulations. Validation involves running a SWAT2012 model using parameters that were determined during the calibration process, and comparing the predictions to observed data not used in the calibration.

## **4.4 Results and Discussions**

### **4.4.1 Evaluation of bias correction methods**

The outputs of an ensemble of high resolution regional climate models (RCMs) from the Coordinated Regional-climate Downscaling Experiment for Africa (CORDEX-Africa) under RCP4.5 and RCP8.5 climate scenarios have been bias adjusted. The ensemble of CORDEX-Africa RCMs RCPs scenario simulations is divided into past (1951-2005) and future (2011-2100) periods, from which a reference period (1976-2005) to coincide with the observations.

All the four bias correction methods correct the biases in the raw RCM simulations and improve the raw RCM data to some extent, but there are considerable differences in the quality of adjusted RCM precipitation and temperature. Linear scaling a good estimation of the mean but does not well adjust the standard deviations, wet-day intensities and probability of wet days which over or under estimates depending on the stations, while the local intensity scaling and distribution mapping have a good estimation of all frequency based statistics. These results confirm the study by Teutschbein and Seibert (2012); i.e., the linear scaling method does not adjust the standard deviation and the percentiles while the distribution mapping method does.

The local intensity scaling method provides a good estimation in the mean, median, wet day probability and wet-day intensity, however there is a slight over estimation of the mean and under estimation in the standard deviation. The distribution mapping method of precipitation bias correction provides a good estimation in the mean, median, standard deviation, wet-day probability and wet-day intensity than Local intensity scaling methods in all the four selected stations of the basin. To analyze the performance of each precipitation bias correction methods, several statistical measures compared (Table 4.3).

*Table 4.3* Frequency based statistics of daily observed, raw RCM simulated (raw) and bias corrected precipitation at the selected weather stations of Tekeze basin

Bias correction method	Mean (mm)	Median (mm)	Standard Deviation (mm)	Probability of Wet-day (%)	Intensity of wet-day (mm)
Debre Tabor					
Observed	4.14	0	8.64	40	10.32
Raw	3.4	0	7.05	32	9.28
Linear scaling	4.13	0	8.71	33	12.74
Local intensity scaling	3.45	0	7.26	33	10.69
Distribution mapping	4.14	0	8.57	37	10.46
Gondar					
Observed	3.56	0	8.32	36	9.86
Raw	2.6	0	5.36	32	8.17
Linear scaling	3.56	0	7.35	33	11.12
Local intensity scaling	3.13	0	6.46	32	9.85
Distribution mapping	3.62	0	7.92	34	9.9
Lalibela					
Observed	2.32	0	6.15	30	7.81
Raw	6.6	0	11.75	45	15.78
Linear scaling	5.78	0	10.3	42	13.93
Local intensity scaling	3.24	0	5.77	40	7.94
Distribution mapping	2.53	0	6.53	34	7.85
Mekele					
Observed	1.58	0	5.23	21	7.38
Raw	1.43	0	3.72	32	5.11
Linear scaling	1.92	0	4.05	29	5.56
Local intensity scaling	1.54	0	4.98	27	6.73
Distribution mapping	1.6	0	5.17	23	6.89

These results in agreement with previous studies by different researchers stated that both parametric and non-parametric distribution based bias correction methods give the best performance in terms of reproducing the observed climate, whereas means based methods, in particular, linear scaling is almost always ranked as the least skilled bias correction method (Teutschbein and Seibert, 2012; Chen et al, 2013) next to delta change approach. In conclusion, all the above mentioned bias correction methods are significantly and consistently improved the

biases of RCM climate models outputs of precipitation and temperature. Among these different bias correction methods that have been suggested, distribution mapping have been found to provide particular good results. Therefore, in this study the distribution mapping (DM) bias correction method has been identified as the most efficient approach to bias correct climate model ensemble of CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios of precipitation and temperature, while reproducing its statistics at spatial and temporal resolutions suitable to run hydrologic models.

#### **4.4.1.1 Precipitation Bias Correction results using distribution mapping**

Distribution mapping bias correction method using gamma distribution function was used on ensemble results of CORDEX-Africa RCP4.5 and RCP8.5 climate scenarios simulated precipitation with observed meteorological stations: Lalibela, Gonder, Debre Tabor, Mekele, Nefas Mewucha, Korem, Maichew, Wukro, Hagere Selam, Hawzen and Axum found in Tekeze basin. The cumulative distribution function graphs (Figure 4.7) showed the effects of statistical correction (distribution mapping) methodology in the distribution of corrected RCP scenarios simulations at selected stations. These graphs can be used as a check how bias correction method simulates high precipitation events. This process removes the poor ability of CORDEX-Africa RCP scenarios in simulating the high precipitation spectrum. In CORDEX-Africa RCP scenarios, daily simulated Tekeze basin precipitation has many dry days in combination with too many drizzles which are the main sources of the bias in the mean and inability to reproduce extreme events. This method efficiently improves simulated precipitation data, which improves streamflow simulations which cannot be correct by calibration of SWAT hydrological model.

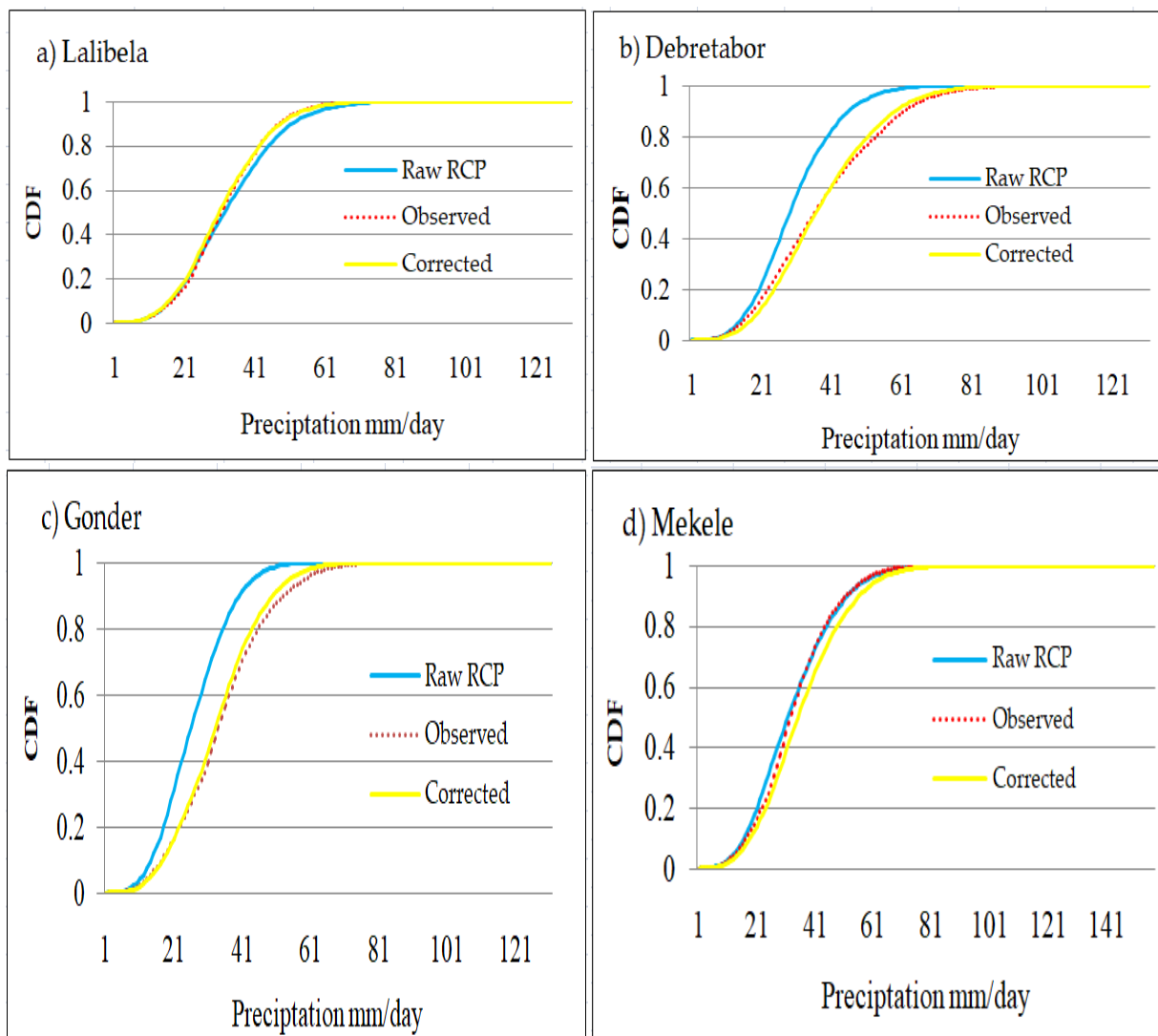


Figure 4.7 Comparison of climate scenario data before and after bias correction with respect to observed data at (a) Lalibela, (b) Debretabor, (c) Gonder, and (d) Mekele selected meteorological stations of Tekeze basin

The whole procedure applied separately for each month to correct for errors in the seasonal cycle. By correcting the full distribution, corrections on days with little rainfall will be different than for the days with extreme rainfall, thus accounting for the model's poorer ability to simulate extremes. This correction procedure corrects both the mean intensities and extremes. As a result, bias free precipitation values from CORDEX Africa RCPs scenario obtained by this procedure from all-weather observation stations for current and future climate condition.

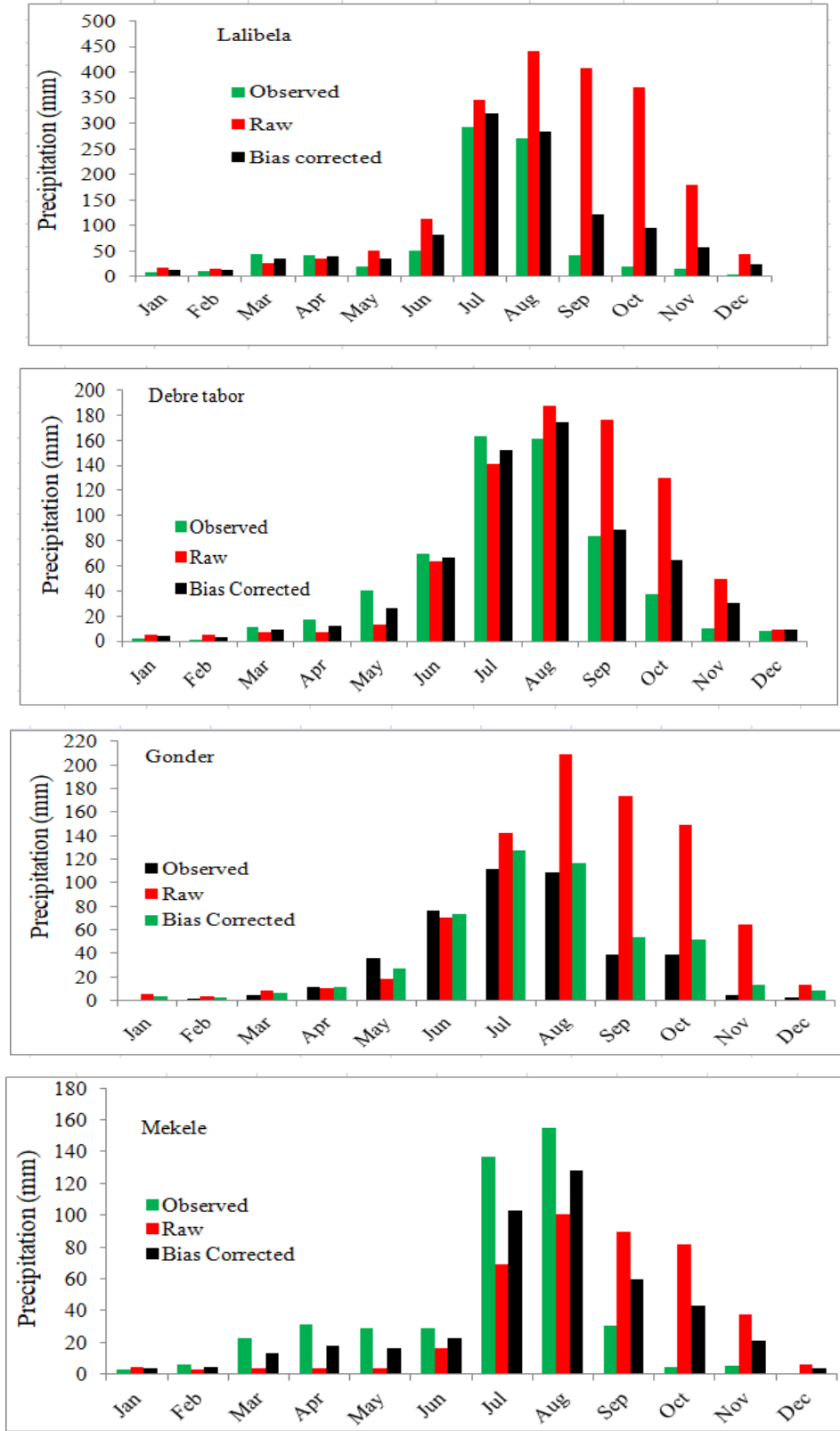


Figure 4.8 Observed, raw RCP simulated and bias corrected values of precipitation at the four selected stations of Tekeze basin

The monthly time series of observed precipitation for the base line period were in close agreement with those from the bias corrected base line RCP scenario values (Figure 4.8). These results indicated that the bias correction techniques significantly improved the quality of the CORDEX-Africa RCP scenarios data. Overall, the results showed that bias corrected data from distribution mapping bias correction methods could be reliably used for analyzing water availability in the future. The stationarity assumption, i.e., that the same correction algorithm applies to both current and future climate conditions is considered as the main drawbacks of distribution mapping method. In this study, climate scenarios of both RCP4.5 and RCP8.5 evaluated under three future periods of 2020s, 2050s and 2080s with reference to present day baseline period 1980s (1976-2005).

#### **4.4.2 Change of Projected Precipitation and Temperature**

##### **4.4.2.1 Projected Precipitation**

The result of the study after bias corrections of raw precipitation sample showed that the mean annual precipitation in the future increases over Tekeze basin (Figure 4.10). The change in mean annual precipitations varies from +32% to +40% for mid rang RCP4.5 and high-level RCP8.5 climate scenarios over all future time periods. In all future time periods, *Kiremt* (wet) season (June–September) precipitation showed an increasing trend and varied from +21% to +48%. While in *Belg* (minor rainy) season (February-May) precipitation amount decreased and changed from -15% to -52% under both RCP4.5 and RCP8.5 climate scenarios. The *Bega* (dry) season (October-January) showed a mixed trend where precipitation decreased up to -23% in the 2050s under RCP4.5 and -39.5% in 2020s for RCP8.5 climate scenarios. On the other hand, precipitation increases from +5.7% to +50% under both RCP4.5 and RCP8.5 climate scenarios. In the Tekeze basin, the projected seasonal precipitation has not shown any systematic decreasing or increasing trend (Figure 4.9) contrasting to a temperature which showed a rising trend under RCP4.5 and RCP8.5 climate scenarios of future time periods.

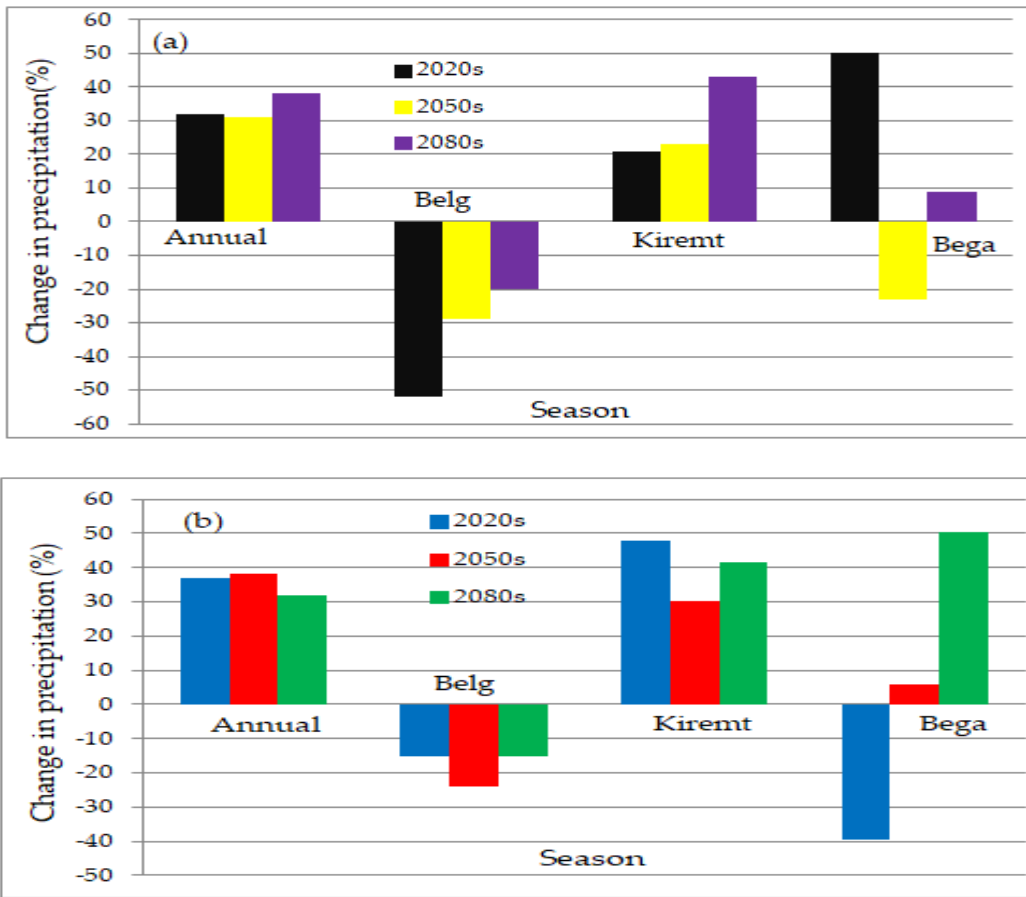


Figure 4.9 Mean annual and seasonal precipitation variation over Tekeze basin under (a) RCP4.5, and (b) RCP8.5 climate scenarios

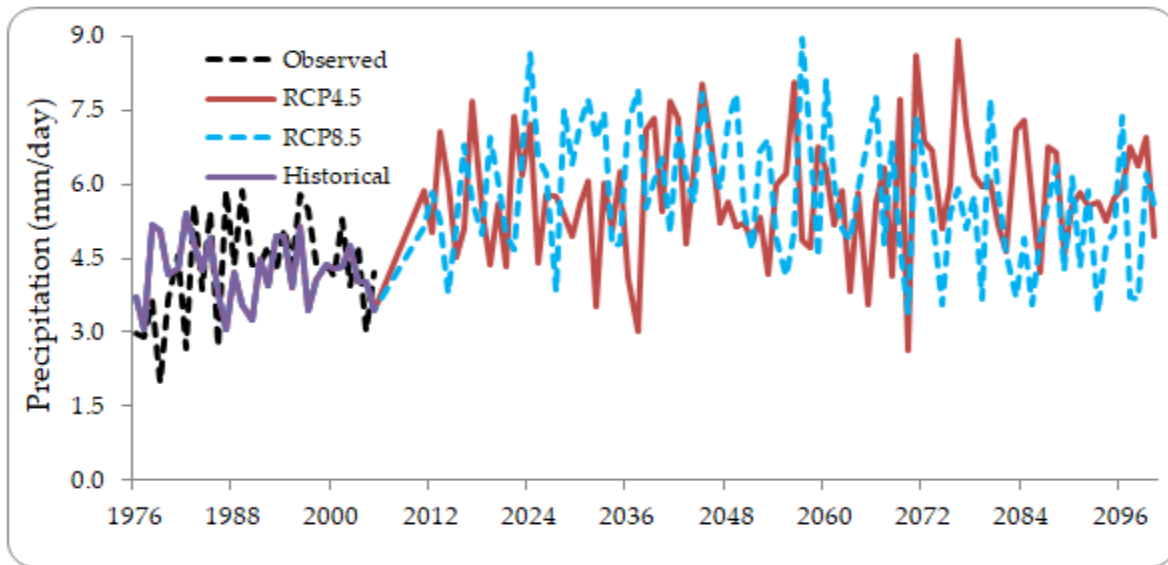


Figure 4.10 Long terms mean annual precipitation trend at Tekeze basin under RCP4.5 and RCP8.5 climate scenarios

Figure 4.11 shows future percentage changes of monthly precipitation amounts for different projected periods under RCP4.5 and RCP8.5 climate change scenarios. For RCP8.5 scenarios, the months of March, April and May would exhibit a decrease in precipitation amount compared to the baseline period whereas RCP4.5 scenario presented an increasing trend. The months of October through February would show an increase in precipitation compared to reference period for both scenarios and projected periods considered.

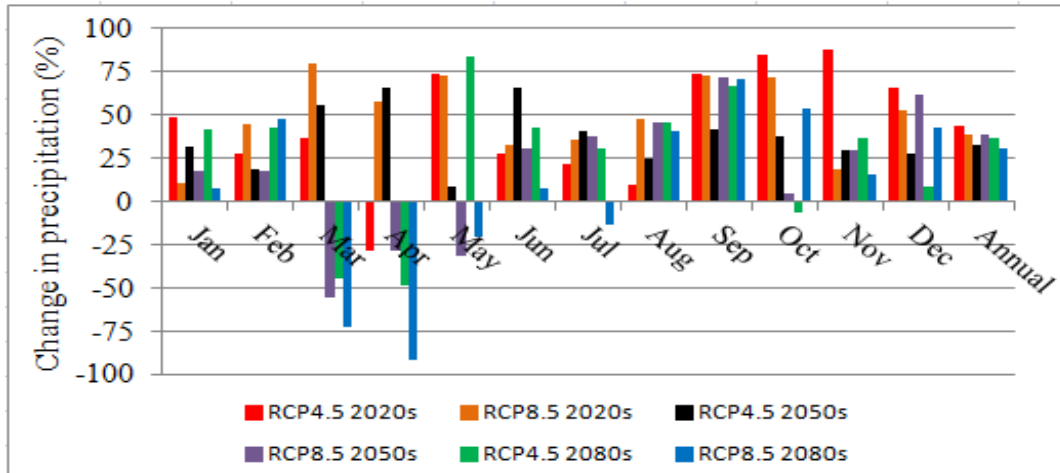


Figure 4.11 Change of monthly precipitation amount for the selected scenarios and projected periods.

#### 4.4.2.2 Projected Temperature

Tekeze basin exhibits an increase in projected minimum and maximum temperature under RCP4.5 and RCP8.5 climate scenarios (Figure 4.12). Mean annual minimum temperature varies from  $+0.61^{\circ}\text{C}$  to  $+1.87^{\circ}\text{C}$  under RCP4.5 and from  $+0.74^{\circ}\text{C}$  to  $+4.12^{\circ}\text{C}$  under RCP8.5 climate scenarios for the three-time periods. Similarly, mean maximum annual temperature showed increasing trend and varied from  $+0.80^{\circ}\text{C}$  to  $+1.00^{\circ}\text{C}$  under RCP4.5 and from  $+1.40^{\circ}\text{C}$  to  $+2.60^{\circ}\text{C}$  under RCP8.5 climate scenarios of future time periods. It also showed that the increase in daily minimum temperature higher than maximum temperature over the next 90 years under both climate scenarios but maximum temperature decreased up to  $-0.20^{\circ}\text{C}$  under RCP8.5 in the 2020s. Generally, the

mean annual temperature increases up to 1.07°C under RCP4.5 and 2.21°C under RCP8.5 climate scenarios for the next 90 years.

The projected seasonal maximum and minimum temperature in the Tekeze basin (Figure 4.12) indicated that a consistent increase in *Kiremt* (June-September), *Belg* (February-May) and *Bega* (October-January) in both scenarios for all time periods; except decrease in maximum temperature in Bega season in 2020s. Moreover, under CORDEX-Africa climate scenarios Tekeze basin temperature projection RCP8.5 predicted higher temperature increase than that of RCP4.5.

Projected mean annual minimum temperature may increase up to 1.1 °C and 3.38 °C under RCP4.5 and RCP8.5 scenarios, respectively in all future time periods. Similarly, mean annual precipitation may increase up to 45% under both scenarios for all future time periods. Figure 4.13 shows future change rates of monthly mean temperature in both scenarios for all future time periods. Mean monthly temperature will increase under both scenarios in all time periods except the months of January and February which showed a slightly decreasing trend in 2020s.

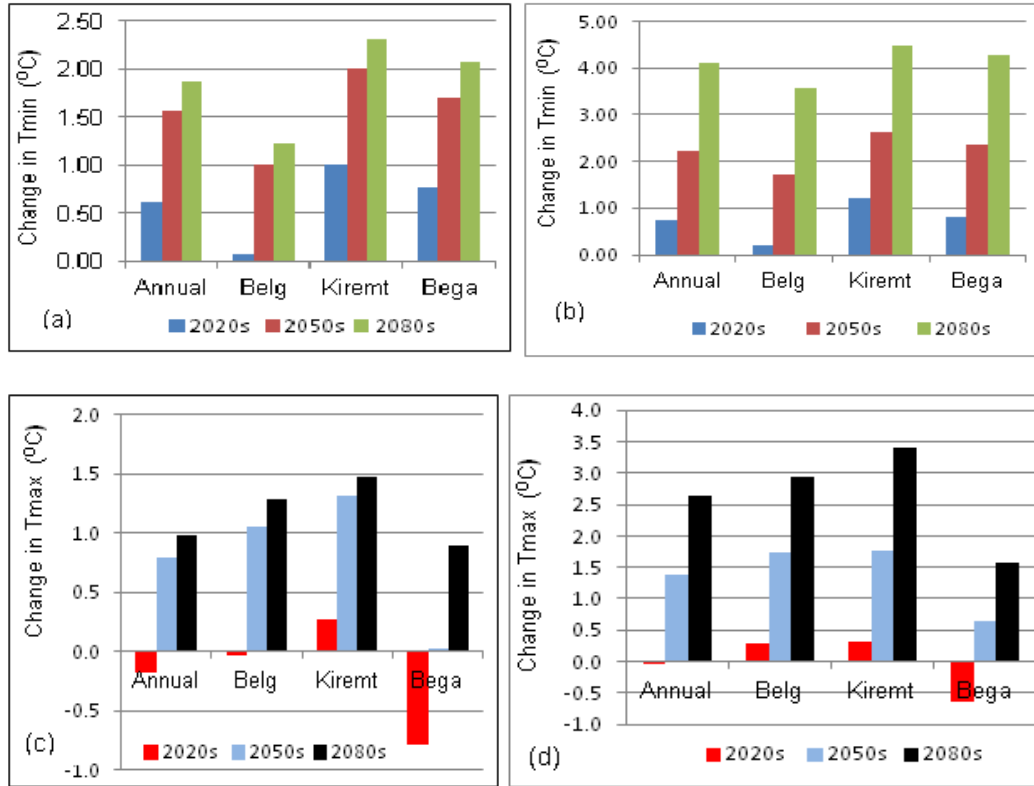


Figure 4.12 Mean annual and seasonal temperature projection in Tekeze basin under (a) minimum temperature change at RCP4.5 (b) minimum temperature change at RCP8.5 (c) maximum temperature change at RCP4.5 (d) maximum temperature change at RCP8.5 climate scenarios

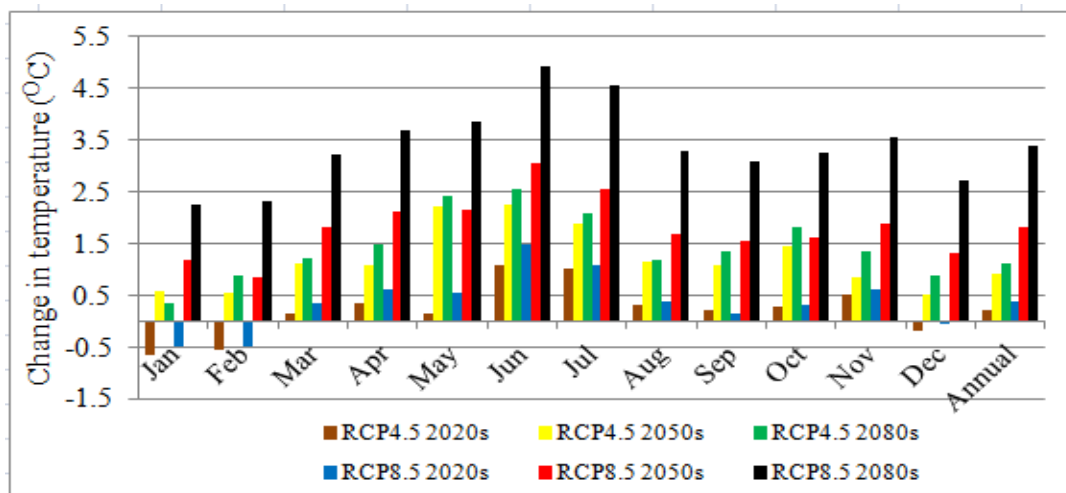


Figure 4.13 Rates of change of monthly mean temperature for the selected scenarios and projected periods

In general, bias corrected projected annual precipitation and temperature showed an increasing trend in 2020s, 2050s and 2080s over Tekeze basin under RCP4.5 and RCP8.5 climate scenarios. This study projected annual precipitation and temperature results confirmed the same trend with the study of Gizaw et al. (2017) conducted on Tekeze basin under both RCP4.5 and RCP8.5 climate scenarios using multiple CMIP5 GCMs not CORDEX data which showed increasing trend in 2050s and 2080s.

#### 4.4.3 SWAT Model Performance

In this study, SWAT hydrological model was calibrated and validated the streamflow of Tekeze River basin at Embamadre gauging station for a calibration period of 1994-2002, with the remaining 2003-2008 for validation. Figure 4.14 shows similar distribution of the observed and simulated streamflow hydrograph for both validation and calibration periods. The model performed well against the monthly streamflow. The calibration and validation results showed that SWAT model could simulate the monthly streamflow well with coefficient of determination ( $R^2$ ) and Nash-Sutcliffe efficiency ( $E_{NS}$ ) greater than 0.70. Also, Percent bias (PBIAS) is positive with reasonable underestimates with a value less than 10% (Table 4.4). SWAT well simulated the hydrology of Tekeze basin and forced to generate future streamflow under both bias corrected RCP climate scenarios.

Table 4.4 SWAT hydrological model monthly performance under validation and calibration periods in Tekeze Basin

Parameter	Calibration	Validation
Nash-Sutcliffe Efficiency ( $E_{NS}$ )	0.71	0.79
Coefficient of determination ( $R^2$ )	0.73	0.80
Percent bias (PBIAS)	0.53	0.45

In this research, SWAT model results of streamflow of Tekeze basin was considered for comparative analysis of observed streamflow with projection periods 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) under both climate scenarios.

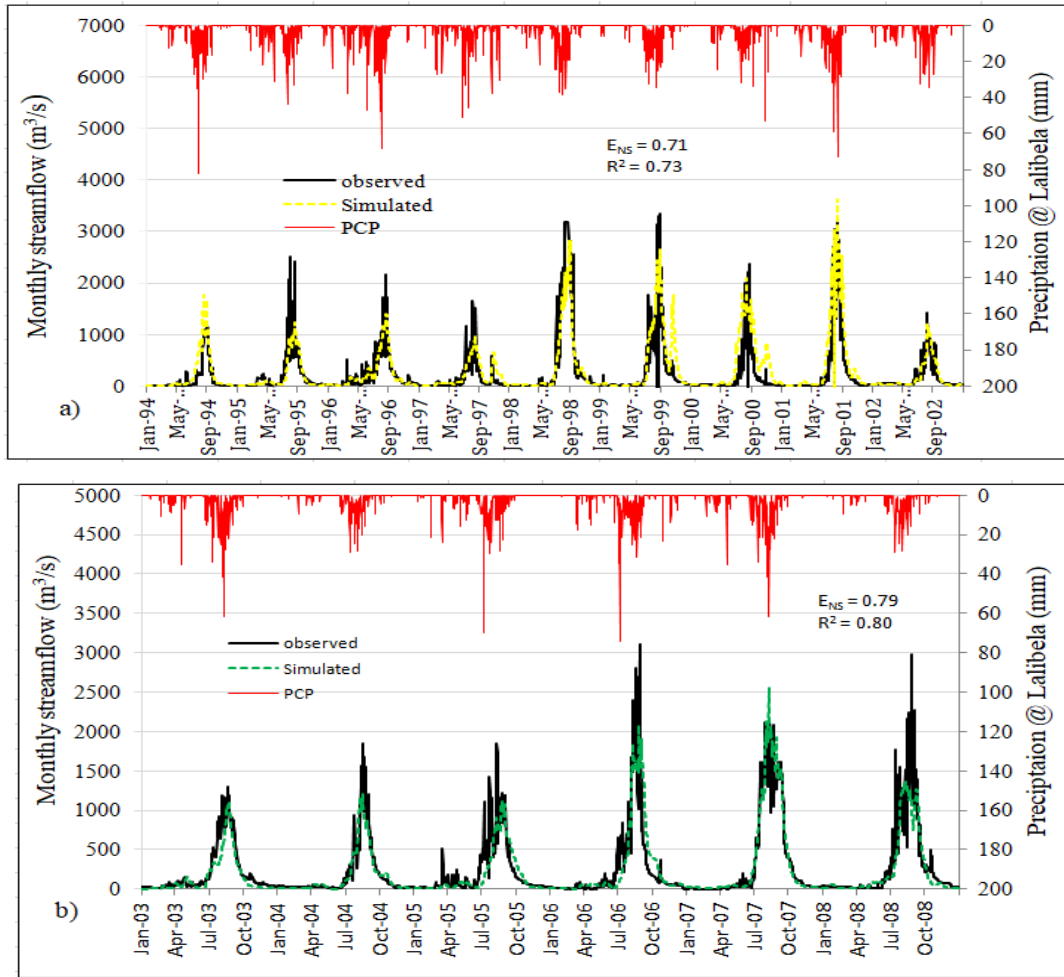


Figure 4.14 Observed and simulated monthly streamflow hydrographs during (a) Calibration and (b) validation periods.

#### 4.4.4 Streamflow Projection

Impact of climate change on the streamflow at Embamadre station downstream of the Tekeze hydropower reservoir was analyzed. Results in Figure 4.7 show that SWAT successfully simulated annual and monthly streamflow with a reasonable accuracy. Hence, the calibrated and validated

SWAT model forced to run for historical and future climate scenarios to generate future streamflow for both RCP4.5 and RCP8.5 climate scenarios. The effect of climate change on annual and monthly streamflow was also investigated as a percentage change with respect to the baseline period (1994–2008) under the two scenarios in three time periods 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100).

For all future time periods, both climate scenarios produced a moderate increase in mean annual streamflow which is due to projected increase in precipitation. However, RCP8.5 climate scenario in the 2080s showed a decrease in streamflow up to 23% due to higher increase in projected temperature that leads to rising in evapotranspiration than increased in precipitation. Figure 4.15 showed the percentage change of annual streamflow for both climate scenarios and the three-time periods. Under RCP4.5, the mean annual percentage change of streamflow will increase by 49%, 39% and 47% in the 2020s, 2050s and 2080s, respectively. Similarly, for RCP8.5, the mean annual percentage change of streamflow increases to 22%, 19% and 2% in the 2020s, 2050s and 2080s, respectively.

Seasonal projection streamflow showed a mixed increasing and decreasing trend (Table 4.5). In *Kiremt* (main rainy) season (June-September) and *Bega* (dry) season (October-January) streamflow will be increased under both RCP climate scenarios of future periods except *Kiremt* RCP8.5 in the 2080s which will decrease. In the *Belg* season (February-May), streamflow will be increased in RCP4.5 and will be reduced under RCP8.5 in all projected time periods.

Table 4.5 Mean annual and seasonal streamflow change (%) in Tekeze basin at Embamadre from the baseline period (1994-2008)

Period	<i>Belg</i>	<i>Kiremt</i>	<i>Bega</i>	Annual
Streamflow change (%) RCP4.5				
2020s	55.06	31.70	61.51	49.43
2050s	25.03	26.85	65.68	39.19
2080s	39.88	33.70	65.96	46.51
Streamflow change (%) RCP8.5				
2020s	-13.82	21.33	59.07	22.19
2050s	-47.36	21.14	58.81	10.68
2080s	-87.72	-39.12	58.49	-22.78

The monthly streamflow change shows a mix of positive and negative trends. Mean monthly streamflow showed an increasing trend in RCP4.5 and significant mixed trend under RCP8.5 climate scenarios (Figure 4.15). Under RCP4.5 climate scenario, change in average monthly streamflow ranges from 12 to 69% in 2020s and 13 to 67% in 2080s but in 2050s streamflow change shows mixed trend that decreases in March to May by up to 9% and increases on other months up to 39%. Mean monthly percentage change of streamflow under RCP8.5 climate scenario showed mixed trends in all time periods. Under RCP8.5, the mean monthly streamflow changes from -37 to 64%, -29 to 68% and -49 to 64% in 2020s, 2050s and 2080s, respectively. Individual month's trend showed that there was an increasing trend from August to February and a decreasing trend from March to July. Therefore, climate change will have a clear impact on the future streamflow an input of reservoir power production in Tekeze basin.

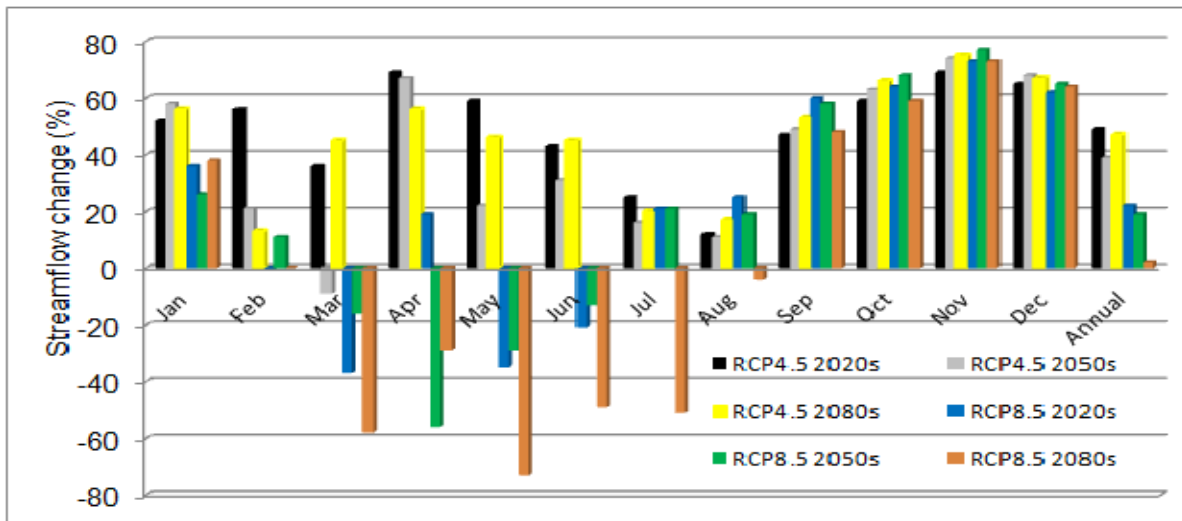


Figure 4.15 Mean monthly and annual streamflow changes under RCP4.5 and RCP8.5 climate scenarios.

The changes and variability of monthly (inter-annual) streamflow will be much greater than the annual streamflow changes in both scenarios in all time periods. This result showed that it is important for the hydropower reservoir planners and managers to consider, the monthly streamflow variability and changes for future planning and operation of reservoirs.

These mean annual projected results were in good agreement with the work of Gizaw et al. (2017) which showed that an increase in streamflow at Embamadre station in 2050s in both RCP4.5 and RCP8.5 but decreased in RCP4.5 2080s in the Tekeze basin and also the result were agreed with the works done in the neighboring basin using previous SRES scenarios by Adem et al. (2014) simulated a consistent increase in future stream flow at Gilgel Abay and Setegn et al. (2011) projected a declining in streamflow of Tana basin in 2080-2100.

#### **4.4.5 Climate Change Impact on Water Resources Planning**

Climate change calls into question the reliability of water resources and the quality of the available water, and challenges traditional water utility planning technique where water resource planning are based on recorded hydrology and weather information assumed to be stationary. This stationarity implies that hydrology and weather statistics and variability will not significantly deviate beyond the observed past conditions and are good representations of future conditions. However, Water resources planners, managers and policy makers are facing considerable uncertainties on future demand and variability of water. Climate change and its potential hydrological effects are increasingly contributing to this uncertainty. Streamflow is a critical hydrological parameter used for water resources planning and management in Tekeze basin. However, streamflow was affected by climate change. In this study, climate change scenarios of precipitation and temperature projected to transform the behavior of Tekeze basin affecting timing and volume of streamflow used for hydropower and irrigation production. The projected climate scenario after bias correction showed that an increase in temperature and change in annual and seasonal precipitation (Figure 4.10 and Figure 4.11) that affects water resources system of Tekeze basin. Projected streamflow showed a slight rise in streamflow in the basin (Figure 4.15) which will be used as an input for hydropower and irrigation projects reservoir planning and operation. Therefore, climate change will affect the planned and operational hydropower and irrigation reservoir projects in the Tekeze basin.

Annual, seasonal and monthly Tekeze reservoirs inflow changed due to climate change may alter frequency and duration of droughts that affect hydropower production of Tekeze reservoir. Tekeze reservoir watershed is projected to show an increase in precipitation and streamflow that may increase hydropower generation. Other implications based on this simulation includes,

- The rise of projected temperature in both RCP climate scenarios will increase evapotranspiration in the reservoir surface and upstream watershed that will reduce hydropower production.
- Kiremt (wet) season streamflow timing will be altered or delayed due to climate change may impact reservoir operations as well as release patterns of the downstream flow.
- The projected increase of extreme precipitation will lead to increased flooding events may be over top the spillway, and other structures will be affected dam safety and operation rule curves designed to prevent overtopping.
- Projected higher intensity precipitation will be eroded upstream farmland watersheds and increased sediment load to the reservoir that increases reservoir dead storage level which reduces reservoir capacity (lifespan).

As water utilities grapple with preparing for the large range of possible climate change impacts, many are searching for new planning techniques to help them better prepare for a different, more uncertain, future. The range of potential climate change impacts on rainfall and river flows should be included in feasibility assessment of new hydropower and irrigation reservoir planning and should be carried out within the context of basin-scale water resources management planning. Where a new hydropower or irrigation reservoir projects are assessed to be the best choice, policy-makers and planners should place more emphasis on investing in hydropower/irrigation schemes that maximize flexibility and that embrace adaptive management. Therefore, water resources planners and managers should incorporate climate change scenarios into the planning and design of Tekeze hydropower and irrigation projects in particular and in all Ethiopian river basin projects in general.

## 4.5 Conclusive Remarks

This research evaluated the effects of climate change on Tekeze basin hydrology resulting from bias corrected ensembles of CORDEX-Africa mid-range and high-level RCP climate scenarios (RCP4.5 and RCP8.5). Calibrated SWAT hydrological model was then used to transform these future climate scenarios to projected streamflow used as an input for reservoirs planning and management. Key findings of this chapter include:

1. Projected precipitation and temperature from ensemble CORDEX-Africa RCP scenarios have systematic errors (biases) which may lead to biased simulated streamflow which is not corrected by calibration of the hydrological model. However, distribution mapping method corrected the biases and improved precipitation and streamflow simulations.
2. Mid-range RCP4.5 and high-level RCP8.5 climate scenario showed that projected temperature consistently increases across Tekeze basin and precipitation projection may also increase annually and in the *Kiremt* and *Bega* except for *Belg* season which shows a mixed trend.
3. The SWAT model could reproduce the current hydrological condition of Tekeze basin at monthly time scale. The calibration statistical results were  $E_{NS} = 0.71$  and  $R^2 = 0.73$ , also the validation result was  $E_{NS} = 0.79$  and  $R^2 = 0.80$ . These results are indicative of the SWAT model's good performance in this basin.
4. Projected higher temperature and precipitation increase under RCP4.5 and RCP8.5 climate scenarios expected to increase projected streamflow of Tekeze basin. According to the latest inflow projections total inflow to Tekeze reservoirs slightly increase in all time periods.
5. This study result showed that climate change would affect the future planning of Tekeze basin hydropower reservoirs and irrigation projects. Therefore, the effects of projected precipitation and streamflow should be included in the feasibility assessment of Tekeze water resources planning and

management. Where a new hydropower reservoir assessed to be the best choice in the watershed, more emphasis needs to be placed on investing in hydropower schemes that maximize flexibility with climate change impact. Water resources planners and managers should incorporate climate change scenarios into the planning and design of Tekeze irrigation and hydropower Dams/reservoirs.

## 5. TEKEZE HYDROPOWER RESERVOIR OPERATION UNDER CLIMATE CHANGE<sup>4</sup>

**Abstract:** Optimal operation of reservoirs is very essential for water resource planning and management, but it is very challenging and complicated when dealing with climate change impacts. The objective of this chapter was to assess existing and future hydropower operation at the Tekeze reservoir in the face of climate change. In this study, a calibrated and validated Soil and Water Assessment Tool (SWAT) was used to model runoff inflow into the Tekeze hydropower reservoir under present and future climate scenarios. Inflow to the reservoir was simulated using hydro-climatic data from an ensemble of downscaled climate data based on the Coordinated Regional Climate Downscaling Experiment over African domain (CORDEX-Africa) with Coupled Model Intercomparison project Phase 5 (CMIP5) simulations under Representative Concentration Pathway (RCP)4.5 and RCP8.5 climate scenarios. Simulated and projected inflows to Tekeze hydropower reservoir were used as input to the US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM), a reservoir operation model, to optimize hydropower reservoir release, storage and pool level. Results indicated that climate change has a clear impact on reservoir inflow and showed increase in annual and monthly inflow into the reservoir except in dry months from May to June under RCP4.5 and RCP8.5 climate scenarios. HEC-ResPRM optimal operation results showed an increase in Tekeze reservoir power storage potential up to 25% and 30% under RCP4.5 and RCP8.5 climate scenarios, respectively. This implies that Tekeze hydropower production will be affected by climate change. This analysis can be used by water resources planners and managers to develop reservoir operation techniques considering climate change impact to increase power production.

**Keywords:** Reservoir Operation; Optimization; SWAT; HEC-ResPRM; Climate Change; CORDEX-Africa; Tekeze Hydropower Reservoir

## 5.1 Introduction

Water resources reservoirs are important tools for integrated water resources development and management (Yazdi and Moridi, 2017; Zhou et al., 2015), but nowadays their operation and management is challenging due to various factors (Birhanu et al., 2014; Rani and Moreira, 2010). The reservoir operates to supply water for municipal consumption, hydropower production, irrigation and industrial needs, flood control, recreation, navigation or ecological requirements. Currently, due to water crisis the global freshwater supply to meet the needs of the different sectors is falling short (David et al., 1999; Jury and Henry, 2007; Rijsberman, 2006). Factors that contribute to this include population growth, urbanization, climate change, land use change, land degradation and poor water resources management (Ghashghaie et al., 2014; Larson et al., 2013). Hence, to alleviate these problems and meet the freshwater and energy demand of communities, it will necessitate optimal operation of water resources reservoirs (Guo et al., 2011; Zhou et al., 2014).

Various researchers studied the reservoir operation throughout the world to get optimum level of release and optimal volumes of storage considering inflows and needs (Azizipour et al., 2016; Cheng et al., 2008; He et al., 2014; Lu et al., 2013). Most research conducted in the reservoir operations have specific objectives like hydropower (Azizipour et al., 2016; Cheng et al., 2008; Lu et al., 2013), flood control (He et al., 2014), irrigation (Birhanu et al., 2014) and environmental (Yin and Yang, 2011).

Water resources infrastructures have been designed and managed historically but these designs gave little attention to the effect of climate change and non-stationarity in hydrologic variables (Milly et al., 2008). Evidence suggests that these hydrologic variables used for water resources planning and management previously assumed stationarity in time have changed by anthropogenic activities (Stocker

et al., 2013). The increase in temperature, changes in precipitation and evapotranspiration rates due to climate change alters global hydrologic cycle (Huntington, 2010). The streamflow affected by intensity and frequency of precipitation leads to increase the intensity of floods and droughts. These changes affect water resources at local and regional levels (Vicuña et al., 2011). The hydrological processes and water availability affected by a change in the patterns of precipitation and temperature impacts agriculture, industry, communities, hydropower and aquatic life (Alazzy et al., 2014). Climate change impact on fresh water resources may change the mean annual streamflow, shift seasonal flows, increases floods and droughts and changes in sediment fluxes which affect reservoir operation (Lee et al., 2016; Lumbroso et al., 2015; C. Zhang et al., 2014).

Many researchers in different parts of the world have studied the impacts of climate variability and change on shifts in hydrological regimes and water resources (e.g., (Ehsani et al., 2017; Haile et al., 2017; Setegn et al., 2014; Zhu et al., 2018)). These studies assessed the current and future water resources availability and rainfall variability across the globe to support appropriate water resources planning and management. Different studies showed that Africa is highly vulnerable to climate change (Serdeczny et al., 2017). Climate change studies showed temperature increased and precipitation pattern changed throughout arid and semi-arid regions of Africa (Conway et al., 2009; Hales, 2007; Nikulin et al., 2012) and affected the hydrological processes that impacts reservoir operation. Most studies showed the impacts of climate change on African hydropower reservoirs (Beyene et al., 2010; Hamududu and Killingtveit, 2016; Kim and Kaluarachchi, 2009; Lumbroso et al., 2015; Yamba et al., 2011). Kim and Kaluarachchi (2009) and Beyene et al. (2010) projected that precipitation and temperature will be increased in the Nile River basin and have positive effect on hydropower production, but Yamba et al. (2011) and Hamududu and Killingtveit (2016) investigated that in the next 60 years hydropower production show a gradual reduction with large variability in the Zambezi River

basin. In the Nile River basin, the rapidly growing hydropower based energy need, population growth, food insecurity and finite water resources will lead to competitions for water in the riparian countries and this will be aggravated by the climate change. Several studies have been conducted on the variability of precipitation and streamflow in the Nile River basin (Abtew et al., 2009; Melesse et al., 2009; Mengistu et al., 2014; Setegn et al., 2011; Tarekegn and Tadege, 2006) that affects reservoir planning and management (Birhanu et al., 2014).

Most hydropower reservoir operators concern is existing hydrological variability without foreseeing climate change as a particular serious threat (Lumbroso et al., 2015). Hence reservoir operation need to incorporate plans to address hydrologic non-stationarity and uncertainty caused by climate change (Ehsani et al., 2017; Jamali Saeed et al., 2013; Vicuña et al., 2011; Vonk et al., 2014). Due to this, ensembles of Global Circulation Models (GCMs), scenarios and regional climate models (RCMs) used as input to hydrological model to generate future streamflow (Raje and Mujumdar, 2010; Wilby and Harris, 2006) that can be used as an input for reservoir operations.

Sedimentation may cause serious impacts on reservoir operation and functionality by reducing reservoir storage capacity and shortening reservoir useful life for human benefits. Studies showed that Northern part of the Tekeze basin watersheds are vulnerable to sedimentation and/or soil erosion problems for the sustainable use of small reservoirs developed for irrigated agriculture and Tekeze reservoir (Haregeweyn et al., 2008; Wolde, 2016). This reservoir sedimentation problem may lead serious reduction in reservoir storage capacity, causing future hydropower generation problems. However, rate of sedimentation of Tekeze reservoir remains unpredicted. More and wide knowledge is still needed to better understand and solve the sediment problem, and hence may improve future reservoir operation. But the focus of this research is to study potential climate change impact on hydropower reservoir operation and management by not varying sedimentation level.

Nowadays, reservoir operation techniques become increasingly important and researchers still searching the best technique. Many authors proposed and reviewed various reservoir operation models and methods (Labadie John W., 2004; Oliveira and Loucks, 1997; Rani and Moreira, 2010; Wurbs Ralph A., 1993; Yeh, 1985). Labadie (2004) extensively reviewed and evaluated various optimization methods and reported that no universally approved algorithm for all reservoir operations. Rani and Moreira (2010) investigated that optimization models usually require simulation models for verifying and testing planned operating policies. Dam managers use simulation models more relaxed than optimization models as simulation models are easier to interpret, apply and present to non-professionals (Labadie John W., 2004; Oliveira and Loucks, 1997). But Optimization models give reliable results. In recent years, to overcome these problems, a combination of simulation and optimization models applied in reservoir operation. In this research, US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Models (HEC-ResPRM), a combination of simulation and optimization model is used.

In this study, Tekeze hydropower reservoir was chosen due to: (1) Tekeze basin shows high rainfall variability (Abtew et al., 2009; Ayalew, 1999) which affects reservoir inflow; (2) Tekeze hydropower reservoir not designed by considering hydrological non-stationarity and climate change; (3) the reservoir has not been optimally operated and sometimes not fully functional during dry periods. Therefore, the objective of this chapter are to (1) assess impact of climate change on reservoir inflow using Soil and Water Assessment Tool (SWAT) and recent Coordinated Regional climate Downscaling Experiment over African domain (CORDEX-Africa) RCMs under Representative Concentration Pathway (RCP)4.5 and RCP8.5 climate scenarios, and (2) apply HEC-ResPRM optimization model to get optimal release, reservoir level and storage for optimal power production including in the face of climate change.

## 5.2 Material and Methods

### 5.2.1 Study Area

Tekeze hydropower reservoir is located in the tributary of Tekeze-Setit-Atbera river part of Eastern Nile upstream of Embamadre gauged stations approximately 80km west of the town of Mekele (Figure 5.1). The surface area of the Tekeze reservoir watershed is 29,404 km<sup>2</sup>. This watershed has high mountainous areas in its sources in the Northern Ethiopian highlands up to 4517 masl and low land areas as low as 800 masl with varying climate depending on altitude change. The rainfall increases with altitude from 600 mm to 1200 mm but it is a reverse for temperature which decreases from 26 °C to 10 °C. This watershed has a mean annual inflow of 4.4 Billion cubic meters at Embamadre gauging station and annual potential evapotranspiration of 1778 mm. This watershed also has a large elevation drop from its sources to low land areas near Ethio-Sudan border and offers significant hydropower potentials of 5960 GWh/year as discussed in chapter 2.

Tekeze single purpose hydropower reservoir located at 13°21' N and 38°45' E (Figure 2.2 and Figure 5.1) is the second tallest double concrete arch dam in Africa next to Katse arch dam in Lesotho. The purpose of this reservoir is for hydropower production with total installed capacity of 300 MW in four 75 MW Francis turbines at underground power house. The reservoir has a total storage capacity of 9293 million cubic meters (MCM) of which 5293 MCM live storage at 1140 m above sea level (masl) and 4000 MCM below dead storage level (1096 masl). The reservoir also has 147 km<sup>2</sup> surface areas at full supply level.

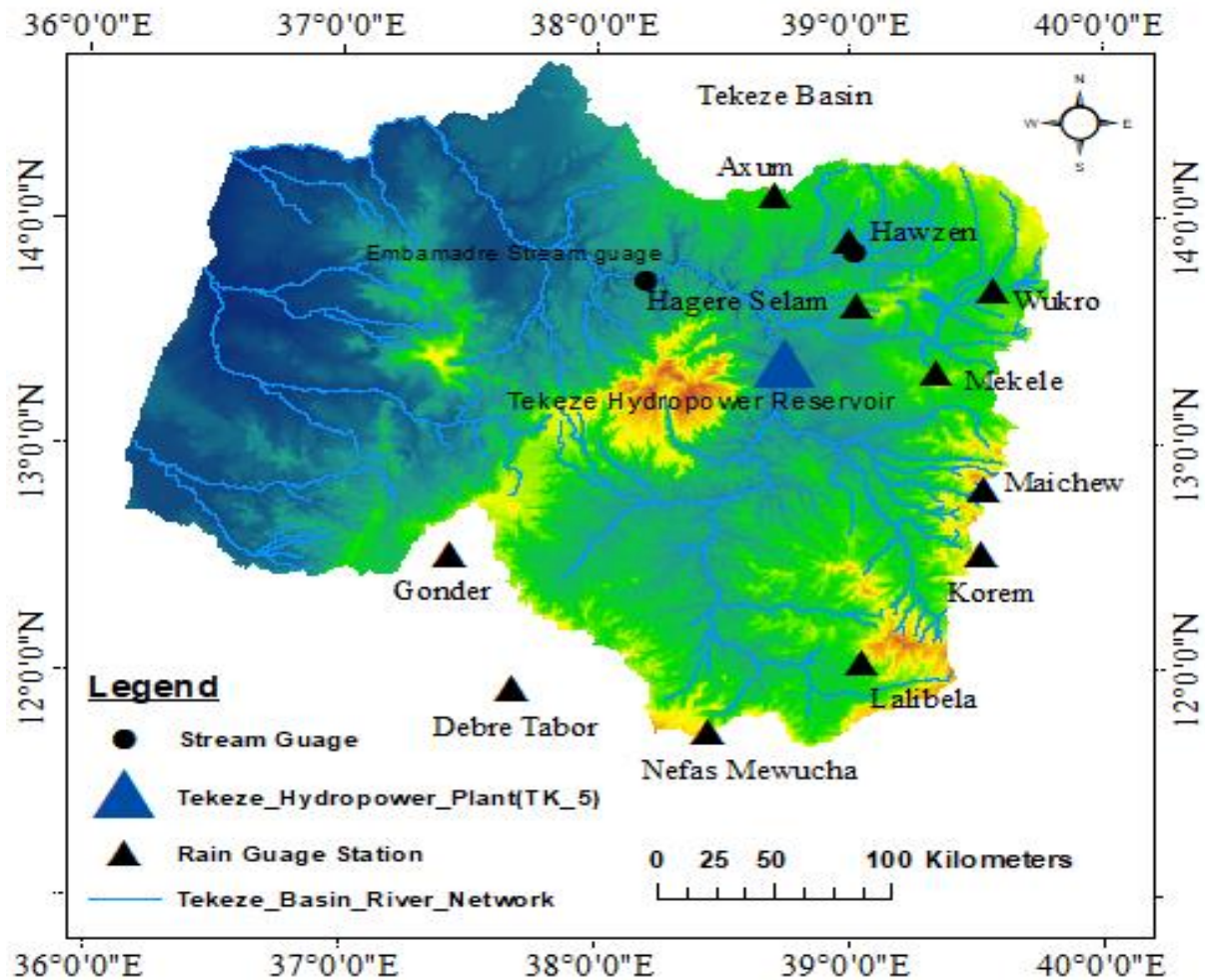


Figure 5.1 Location of Tekeze hydropower reservoir and weather stations

## 5.2.2 Datasets used

### 5.2.2.1 Historical and Future Hydrology

In this research, the four hydrological data periods analyzed at the outlet of Tekeze hydropower reservoir using the calibrated and validated SWAT model as discussed in chapter 4. These were the reservoir inflow data of: (1) observed and RCP scenarios historical records (1994–2008); (2) the near future period (2011–2040), middle future period (2041–2070) and the far future periods (2071–2100). SWAT simulates historical (past) and all future reservoir inflows using precipitation and temperature projections for eleven stations shown in Figure 5.1 from an ensemble outputs of CORDEX-Africa

RCMs downscaled from different GCMs from Coupled Model Intercomparison project Phase 5 (CMIP5) simulations available in 0.44° resolution for Ethiopian domain under two recent representative concentration pathways (RCP4.5 and RCP8.5) climate scenarios.

#### **5.2.2.2 Reservoir data**

HEC-ResPRM, a reservoir operation model, requires data like back ground map of the watershed, reservoir outlet capacities, elevation-area-storage curve, historical reservoir storage and water surface level, power production and flow time series to perform optimal operations. Water surface elevation values include the minimum operation level, the maximum operating level and historical maximum and minimum elevations needed for power production in each months of the year. These physical data were used to develop model constraints and allow the model to calculate penalties. All these data except power production were collected from Ethiopian Electric Power Corporation and Ministry of Water, Irrigation and Electricity. Tekeze hydropower reservoir characteristics, historical observed reservoir storage and pool level data are shown in appendix B.

### **5.3 Methods**

#### **5.3.1 HEC-ResPRM Optimization Model**

Several computer models have been developed to design reservoir storage capacity and establishing operational policies during preconstruction planning of new projects, to reassess the existing operation policies of reservoir systems and to support release decisions during real time operation. Operational models used for reservoir operation broadly classified as descriptive simulation, prescriptive optimization and hybrid models. Descriptive models simulates decisions of reservoir releases in pre-defined logical rules while the descriptive nature of simulation models allow for "what if" studies, their prescriptive capabilities are limited, prescriptive optimization models uses mathematical programming techniques to solve decision variables and the hybrid models are mainly describe simulation models

with piecewise optimization (McMahon and Farmer, 2009). Optimization models do not require explicit statements of operating rules, since operations are suggested (or prescribed) by the model. Instead, the objectives for reservoir operations must be explicitly stated in the form of *penalty functions*. In addition to the specification of quantitative operating objectives (penalty functions), optimization models of reservoir systems also require *mathematical constraints* to represent physical, engineering, or legal constraints to the system and a representation of hydrologic inputs to the system. Physical and engineering constraints on the system would include reservoir capacities and turbine or outlet capacities. In some cases, minimum in stream flows or other operational or legal constraints might be added, although it is usually preferable to represent such "soft" constraints with steep penalty functions. An optimization model, using often complex numerical solution algorithms, then prescribes desirable operating decisions which yield the minimum total penalty and satisfy all constraints defined for the system.

In this study, the US Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM) (Connell and Harou, 2011; USACE, 1992), a hybrid reservoir system operations optimizations software package developed to assist planners, operators and managers with reservoir operation plan and decision making, was used. HEC-ResPRM is a reservoir system operations optimization model developed to assist reservoir operators with decision making by demonstrating the optimal possibilities for reservoir management in the system. As an optimization model, HEC-ResPRM offers an idea of the best outcome that can be expected from the system or any operating strategy. The HEC-ResPRM is designed to further the efficiency and use of HEC-PRM (Perspective Reservoir Model) for a data intensive single or multi-objective reservoir system operation studies. HEC-PRM, a computational core of user friendly HEC-ResPRM software, is a generalized computer program that performs deterministic network-flow optimization of reservoir system operations. HEC-PRM

prescribes optimal value of flow and storage over time by minimizing penalty functions located throughout the water resources network. It also addresses a reservoir system operation problem of optimal long-term allocation of available water. HEC-ResPRM is a combination of simulation and optimization model when Perspective Reservoir Model (PRM) is integrated in to HEC-RES modeling platform. HEC-ResPRM can be used in conjunction with ResSim or alone to improve and analyze reservoir operation. HEC-ResPRM is an implementation of HEC-PRM shared with HEC-ResSim a sister reservoir system simulation tool in a graphical user interface for creating, running, sorting and analyzing optimization runs. The integration of PRM in to the HEC-Res modeling platform was made to facilitate the joint development and use of simulation and optimization models. The HEC-Res modeling system allows different network configurations and model runs to be managed and visualized within a single interface, thus forming a robust platform for complex data-intensive modeling studies. The Res implementation also allows users to produce graphical results directly from the Graphical User Interface (GUI). HEC-ResPRM uses HEC's data storage system (HEC-DSS) to store and retrieve of input and output time series data.

HEC-ResPRM is a monthly network flow programming model and gives optimal values of release and storage by minimizing penalty functions (Faber Beth A. and Harou Julien J., 2006; Ostadrahimi et al., 2012). Network flow programming is computationally efficient form of linear programming. A network solver finds optimal flow for the entire network simultaneously based on the unit cost associated with flow along each arc. In HEC-ResPRM, networks are constructed to represent a physical system, where nodes are junctions and reservoirs, and arcs are river reaches. To build a single model network that represents the whole network flow problem the network must encompass both space and time. The larger network is made up of the duplicate networks, connected by storage arcs, which represent Tekeze hydropower reservoir storage (flow in time) from one-time period to the next. Each arc is a possible path of flow, and a unit cost is associated with each arc. The slope of the penalty function is the unit cost. In this model the goal of optimization solver is to find minimum cost path for each unit of flow in the network over the time window. Finding the minimum cost path is accomplished through a network

flow linear programming technique called primal network simplex method. The solution to this problem is the set of minimum cost (optimal) releases and flows for every time step. These results provide insights about the system's operations and objectives under varying conditions and can be used to develop or improve operating rules.

Penalty functions associate a penalty or reward (negative penalty) with Tekeze hydropower reservoir levels of flow or storage (flow in time). It is the penalty functions that derive the solution to the optimization problem, which is why it is so essential to provide HEC-ResPRM with meaningful penalty functions. Therefore, a penalty function a representation of unit cost in terms of relationship between penalty and flow or storage. Hydropower generation is a nonlinear function of both net head and release (flow). In order to reasonably represent this relationship, HEC-ResPRM allows users to define multiple penalty functions, each based on a different storage level. It then uses an iterative process to select the release and corresponding storage levels of Tekeze Hydropower Reservoir for minimum penalty. This approach is, of course, an approximation of the actual complex conditions of power generation. All reservoir outlets of Tekeze hydropower reservoir in HEC-ResPRM are represented as one outlet because it cannot divide reservoir releases in to those that goes in through various gates. Therefore, at any time with added hydropower penalties, water being released from the reservoir which is assumed to be generating power. Multiple penalty curves can be used, each based on performance at a different reservoir storage. For Tekeze hydropower reservoir operation it is difficult to add hydropower penalties to generate optimum power due to lack of observed power production data and turbine efficiency curves as only one turbine is functional from a total of four turbines. Because in this reservoir all turbines are not functional and only one turbine was operational in the historical periods. Due to this reasons for this study, Tekeze hydropower reservoir operation under climate change were discussed based on the changes in reservoir storage, water level and release not in the power production.

Optimization problem represented by the network with cost associated with flow as follows:

$$\text{Minimize: } \sum_t^n C_t Q_t \text{ (For all nodes)} \quad (5.2)$$

$$\text{Subject to: } \sum Q_t - \sum a_t Q_t = 0 \text{ (For all nodes)} \quad (5.3)$$

$$L_t \leq Q_t \leq U_t \text{ (For all arcs)} \quad (5.4)$$

in which  $n$  is total number of network arcs;  $C_t$  is unit cost, weighting factor for flow along arc  $t$ ;  $Q_t$  is flow along arc  $t$ ;  $a_t$  is multiplier (gain) for arc  $t$ ;  $L_t$  is lower bound on flow along arc  $t$ ; and  $U_t$  is upper bound on flow along arc  $t$ . In this case, node represents a reservoir and river or channel junctions. Arcs represent inflow and outflow links in the reservoir system. Each arc has a minimum and maximum flow that it must carry in the reservoir system. The arcs (inflow and outflow links) may transfer water between two points in space (transferring water in channels) or in time (changing pool elevations in the reservoir). Also, flow is conserved in the reservoir (node). Equations (5.2) through (5.4) are special forms of linear programming problems solved using primal simplex method. An off the shelf solver (using a modified Simplex Algorithm) is used to determine the optimal allocation of water within the system. The results of the solver are processed to report and display reservoir release, storage volume, channel flow and other pertinent variables.

### 5.3.2 HEC-ResPRM Model Setup

HEC-ResPRM uses a map-based schematic to provide a meaningful representation of the optimization network as it relates to the physical river/reservoir system. The layout of the Tekeze river system is represented with a "stream alignment" which can be drawn by the user or imported from geo-referenced maps. It can also be imported from HEC-ResSim. HEC-ResPRM modeling system allows different network configurations and model runs to be managed and visualized within a single interface, thus forming a robust platform for complex, data intensive modeling studies. HEC's Data Storage System (HEC-DSS) is used for efficient storage and retrieval of input and output time series data.

In HEC-ResPRM, a watershed is a collection of data associated with a model of a particular water resources system, Tekeze hydropower reservoirs watershed in this case. Data for HEC-ResPRM includes the physical layout and properties of the system, time series input and output, and information associated with the optimization such as penalty functions, parameters and settings. Tekeze hydropower watershed data are viewed and edited in HEC-ResPRM through three separate modules: Watershed setup (Includes configuration of projects), Networks (including building run alternatives and Optimizations (where the model alternatives are run and results viewed). Each module provides access to specific types and directories of data within the watershed data tree as shown in Figure 5.2.

Each module requires the setup and entry of specific data. Changes to any module require updates to other module, so it is important recognize how each module interacts with the other. After performing an optimization one or more alternatives results can view and print in both tabular and graphical forms.

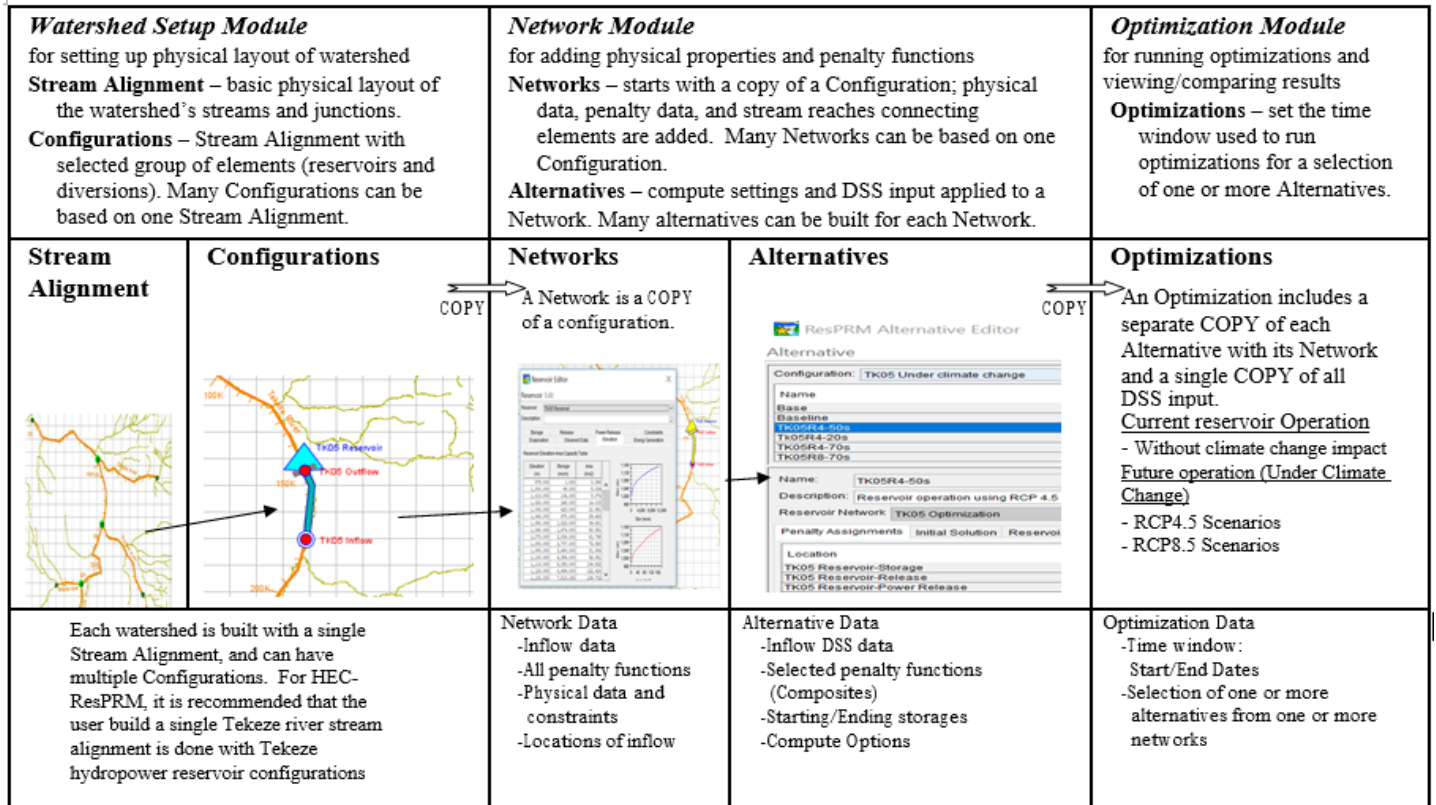


Figure 5.2 HEC-ResPRM schematization of Tekeze Hydropower reservoir operation

Watershed setup module used for laying out the physical extents of the model in which the basic shapes and branches of the Tekeze river system setting up one or more sets of projects (configurations) wish to model. The map region of the window contains a background map of Tekeze river, Tekeze hydropower reservoir, a stream alignment and the reservoir element. Back ground maps are optional but helpful when tracing the stream alignment. Project elements such as stream reaches, reservoir and diversion are added on to the stream alignment. The stream alignment forms the back bone onto which all the different elements will be added. All configurations of various project elements to be analyzed for this watershed share a common stream alignment. Stream alignment can be created in HEC-ResPRM or imported from various spatial data formats.

Network module used for imputing and editing element data, including penalty functions and placing additional elements on to the stream alignment. Network of reservoirs, stream reaches and diversions can be created. A network is created based on a selected configuration of projects on the stream

alignment and includes Tekeze river reaches that connects the project. An alternative in HEC-ResPRM is a group of data including climate change scenario effect that includes a network, a selection of composite penalties and settings, and a variety of compute settings. In HEC-ResPRM penalty functions are grouped in to penalty sets and composite penalties. Each penalty set is intended to represent one particular interest and consists of 12 individual penalty functions one for each month. The penalty functions may vary based on the season selected for each month. If a penalty applies consisting all year, a single “all year” season can be applied to every month. Monthly seasons can be automatically generated or created and applied to the months. A composite penalty also consists of 12 individual monthly penalty functions. The composites are the sum of the individual monthly penalty sets and are defined based on which penalty sets are selected. HEC-ResPRM is set up to accommodate the need to model and compare these types of variations in alternatives. An alternative in HEC-ResPRM is a group of data that includes a network, a selection of composite penalties and settings, and a variety of compute settings. Optimization runs are performed on these alternatives.

Optimization module designed to organize alternative runs, run optimization modules based on the alternatives settings and to visualize and analyze results. The optimization takes place through the HEC-PRM engine and solver. The time span (in this case the historical and projected periods) over which to perform the model run and the alternatives to be analyzed must specify for each optimization. Graphical results can be produced for one or more alternatives include in the optimization.

Sensitivity analysis in this study was done by adjusting the demands, changing the shape or magnitude of penalty curves and by changing initial and ending reservoir levels. After the HEC-ResPRM model fine-tuned, tests can be run on the performance under various inflow conditions for the historical periods from 1994-2008 and 2009-2011 after the reservoir constructed. A series of wet year streamflow constructed from historical data were run to see how the optimal results differ from average conditions. Calibration can be consisting of these repeated runs, which provide successive improvement of the model. Finally, the HEC-ResPRM model were run using the historical 2012-2017 reservoir inflow data and SWAT model simulated future reservoir inflow for the near (2020s), middle (2050s) and far (2080s) future RCP4.5 and RCP8.5 climate scenario data to get optimized Tekeze hydropower reservoir release, pool level and storage.

## 5.4 Results and Discussions

### 5.4.1 Impacts of climate change on reservoir inflow

The volumes of reservoir inflows over different time periods are unknown in real time operation and their volumes can be estimated using inflow forecasting models. The application of inflow forecasting models may be affected by large errors to forecast long period reservoir inflows. Due to this reason Climate projection models combine with hydrological models were used to get the projected Tekeze hydropower reservoir inflow volumes. Impact of climate change on the streamflow at Embamadre station downstream of the reservoir was analyzed. Observed streamflow data from a period 1994–2002 was used for model calibration and from 2003–2008 was used for validation. As shown in chapter 4 SWAT model successfully simulated annual and monthly streamflow with a reasonable accuracy. Hence, the calibrated and validated SWAT model forced to run for historical and future climate scenarios to generate future reservoir inflow for both RCP4.5 and RCP8.5 climate scenarios in all time periods. The total mean annual baseline (past) and future Tekeze hydropower reservoir inflow ( $\text{m}^3/\text{s}$ ) trends under RCP4.5 and RCP8.5 climate scenarios for all time periods are shown in Figure 5.3. Projected monthly reservoir inflow for 2050s time period under both RCP4.5 and RCP8.5 climate scenarios are shown in the appendix B.

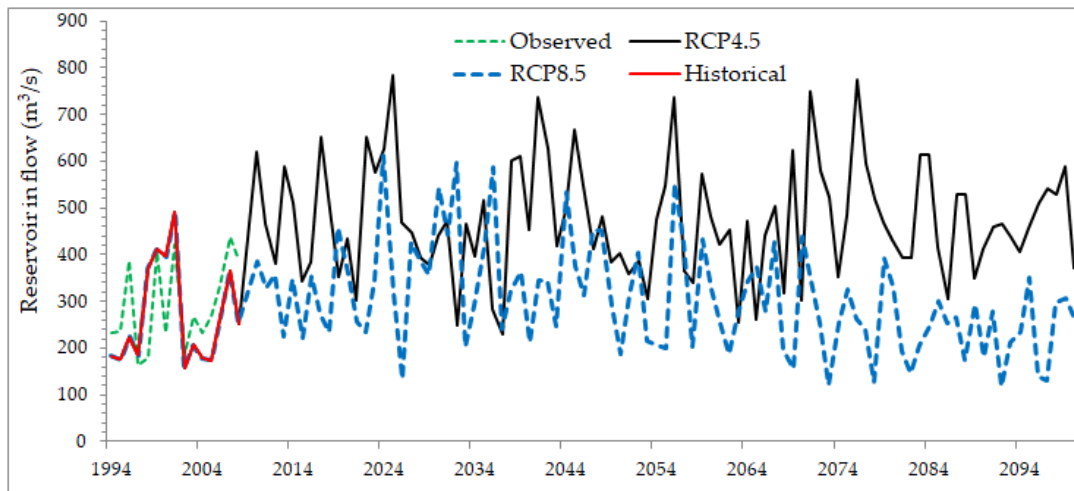


Figure 5.3 Annual Tekeze hydropower reservoir inflow trend for future time periods

### 5.4.2 Current Reservoir Operation

HEC-ResPRM optimization model run under current baseline condition (2009–2017). This model optimized the current Tekeze hydropower reservoir operation. The current optimized value (Table 5.1) of

HEC-ResPRM optimization model showed an increase in reservoir storage compared to current actual hydropower reservoir operation status. It is also indicated that the mean annual reservoir pool level increased up to 7.87 m (Table 5.2) that will store more water to produce power throughout the year. It contradicts the current actual Tekeze hydropower reservoir operation which produces insufficient power even very little or no power production during dry months. This implies that Tekeze hydropower reservoir was not optimally operated till now. The reservoir storage dropped to the minimum operating level and sometimes dries in the non-rainy months. Therefore, the current actual reservoir operation is not effective and should consider different well tested reservoir operation techniques under a changing climate. Due to lack of recorded power production data of Tekeze hydropower reservoir; this study uses reservoir release, storage and pool level for current and future reservoir operation under climate change for comparison.

### **5.4.3 Reservoir Operation under Climate Change**

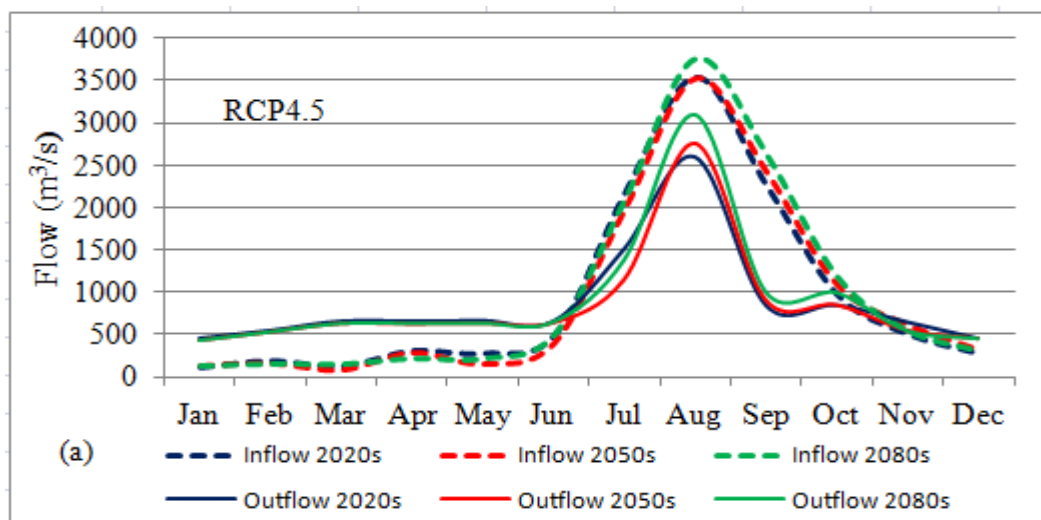
The future reservoir inflows generated by SWAT under RCP4.5 and RCP8.5 climate scenarios in three-time periods 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100) with other reservoir data were used to run optimization model to get projected optimal reservoir outflow (release), storage and pool level results.

#### **5.4.3.1 Projected Reservoir Inflow and Outflow**

Climate change impacted inflow and outflow (release) hydrograph of Tekeze hydropower reservoir considered in this study are shown in Figures 5.4a, b. According to the inflow projections based on ensembles of CORDEX-Africa RCM climate model simulations, total inflows to Tekeze hydropower reservoir expected to increase under RCP4.5 and RCP8.5 climate scenarios for all future time periods. Figures 5.4 a, b show that, total monthly inflow under RCP4.5 is greater than the total monthly inflow projected under RCP8.5 climate scenarios. However, under RCP4.5 climate scenario, the reservoir

inflow projections exhibit high fluctuations inter-annually as compared to RCP8.5 climate scenario and observed historical values. The highest inflow volumes under RCP4.5 were concentrated in the rainy months that spilled easily and affect the dry period reservoir storage level and or release.

There would be an increase in excess reservoir inflow during the rainy months of August through October under both RCP4.5 and RCP8.5 climate scenarios in all time periods. This increased spillage of available water inflow occurs because of the effect of climate change that increased the hydropower reservoir inflow under RCP4.5 and RCP8.5 future climate scenarios. According to the latest climate simulations, the overall inflow volume is predicted to be higher during rainy months and provided that the reservoir lacks sufficient storage capacity to accommodate these high flows. As a result, Tekeze hydropower reservoir forced to spill water without generating hydropower. This indicates that the increased in overall reservoir inflow volume does not necessarily be advantageous to produce more power. Therefore, decision need to be taken on the amount of water to be released and or stored now and retained for future considering the variations in inflow and demands.



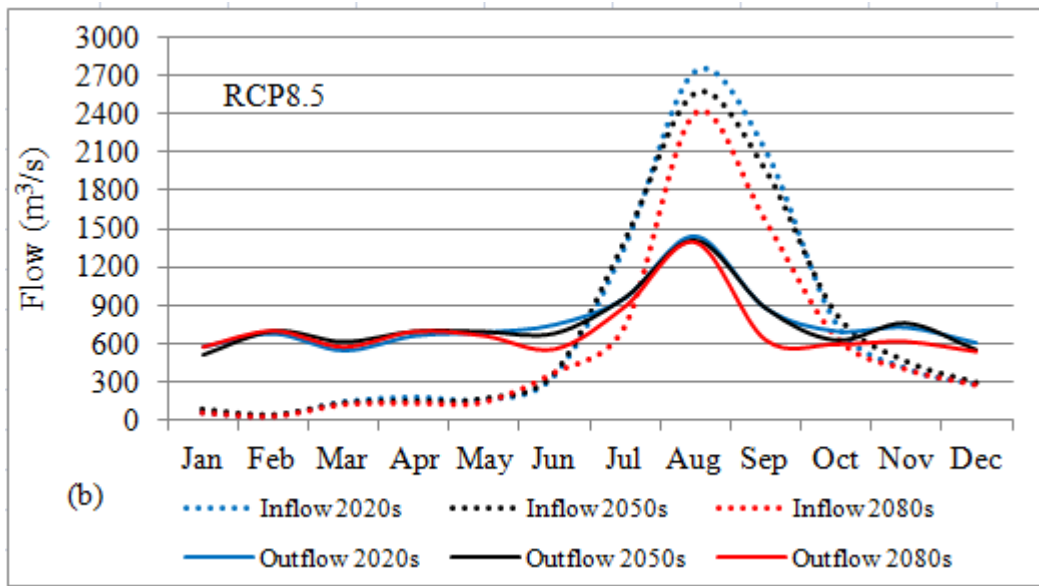


Figure 5.4 Mean monthly reservoir inflow and optimized outflow (release) for future time periods under: (a) RCP4.5 climate scenario; (b) RCP8.5 climate scenario.

In this study, the reservoir outflow (release) was obtained by HEC-ResPRM optimization model under RCP4.5 and RCP8.5 climate scenarios for 2020s, 2050s and 2080s-time periods. In all future time periods (Figures 5.4 a, b) under the two climate scenarios, the reservoir release will be increased to produce more power due to an increased future reservoir inflow and optimum water storage using optimization model. Under RCP4.5 climate scenario average monthly reservoir outflow varies from 353 to 2590 m<sup>3</sup>/s in 2020s, from 435 to 2757 m<sup>3</sup>/s in 2050s and from 442 to 3090 m<sup>3</sup>/s in 2080s. Similarly, average monthly reservoir outflow varies from 538 to 1445 m<sup>3</sup>/s in 2020s, from 514 to 1412 m<sup>3</sup>/s in 2050s and from 577 to 1396 m<sup>3</sup>/s in 2080s under RCP8.5 scenarios. In both scenarios, the minimum and maximum outflow value occurred during dry and wet periods, respectively. In all time periods, the optimum reservoir outflows (releases) under RCP8.5 climate scenario for the dry months of November through February were greater than the optimum releases under RCP4.5 climate scenario.

These changes show that under RCP8.5, the optimized reservoir stored more water in wet months for dry period release and projected higher storage level compared to RCP4.5 climate scenario.

#### 5.4.3.2 Optimum reservoir power storage under climate change

HEC-ResPRM optimized result showed an increase in projected mean annual Tekeze hydropower reservoirs storage under RCP4.5 and RCP8.5 climate scenarios. This increase was projected for three future time periods (Table 5.2) and the projected optimum stored water varies from 24 to 25% (RCP4.5) and 28.5 to 30% (RCP8.5).

Table 5.1 Mean annual optimized power storage under climate change scenarios.

Periods	Optimized Reservoir Storage (Mm <sup>3</sup> )		Change in Optimized Reservoir Storage (%)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Current optimized	6639		24.0	
2020s	6688	6880	25.0	28.5
2050s	6669	6903	24.6	29.0
2080s	6665	6958	24.5	30.0

HEC-ResPRM model result under both scenarios in current and all future time periods showed minimum and maximum reservoir storage periods (Figure 5.5 a, b, c). Tekeze reservoir reached at maximum storage (reservoir filled) in September and stayed somewhat constant optimum storage up to November. During August to September, main rainy months, the reservoir is filled, and optimization model keeps the maximum storage up to November. The reservoir storage tends to slightly be decreased starting from end of November until the beginning of February. After February, the reservoir storage decreased down to the optimization model capacity to store energy at a minimum flow and reached a minimum storage level in June to prepare and capture inflows in the wet main rainy months. In all

future months, there will be a stored water to produce power which is always greater than the current optimized value.

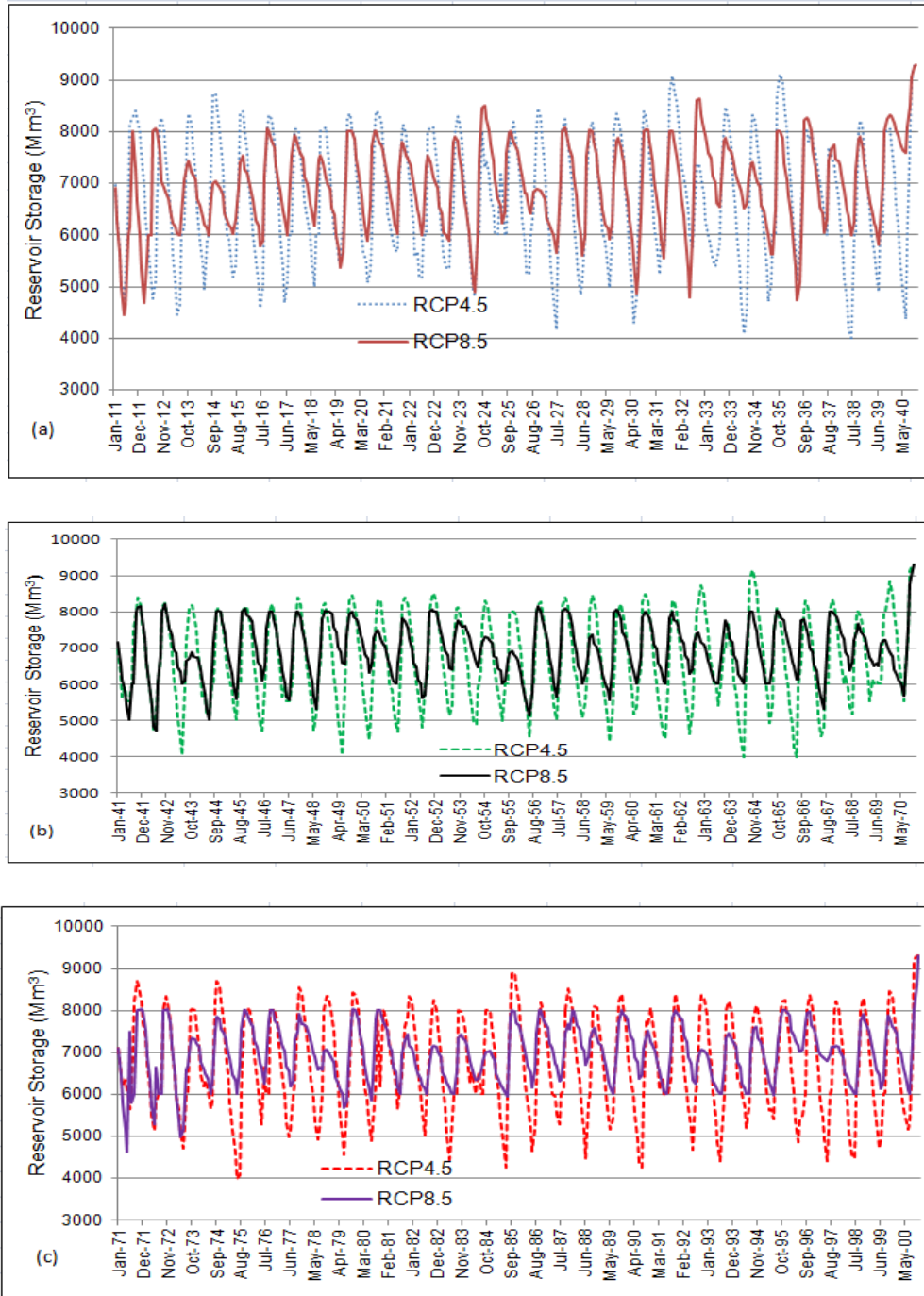


Figure 5.5 Monthly optimized reservoir storage variations under RCP4.5 and RCP8.5 climate scenarios for: (a) 2020s; (b) 2050s; (c) 2080s.

Figure 5.5 shows that more power is stored in both scenarios for the next 90 years as compared to current actual and current optimized value. The change in maximum optimum storage increased will be occurred in January and varies from 1693.4 to 1800.8 Mm<sup>3</sup> under RCP4.5 scenarios and from 1731.9 to 1851.1 Mm<sup>3</sup> under RCP8.5 scenarios in all time periods. The minimum optimal storage change increased will occur in July and varies from 392.2 to 424.7 Mm<sup>3</sup> under RCP4.5 scenarios and 803.6 to 956.6 Mm<sup>3</sup> under RCP8.5 scenarios in all time periods. This is due to climate change impact on the reservoir inflow and the capacity of the optimization model to operate the reservoir optimally. HEC-ResPRM optimization of future projections tends to make much greater seasonal use of reservoir storage than the current actual operations.

The monthly optimum stored water increases in all months for future time periods under both RCP scenarios as compared to the baseline period (base line varies from 4400 to 6500 Mm<sup>3</sup>). Optimized monthly reservoir storage variations are shown in Figure 5.4. The mean monthly optimum reservoir storage in the future time periods varies for RCP4.5 from 5100 to 8300 Mm<sup>3</sup> in 2020s, 4700 to 8050 Mm<sup>3</sup> in 2050s and 5000 to 8100 Mm<sup>3</sup> in 2080s. It also varies for RCP8.5 from 4900 to 8100 Mm<sup>3</sup> in 2020s, 4850 to 8020 Mm<sup>3</sup> in 2080s and 750 to 7900 Mm<sup>3</sup> in 2080s.

This storage versus monthly graphs shown in Figure 5.5 a, b, c can be used as a rule curve for a given period and climate scenario. These Operational guidelines (rule curves) can be inferred using the results of runs for different climate scenarios and time periods. Then these rules can be tested in ResSIM or HEC-ResPRM can test rules by making them constraints rather than penalty curves to encourage the desired behavior. These rules are particularly applicable to the refill season of the reservoir, where inflows are in excess of hydropower water supply demands. During the draw-down season, where reservoir inflows are less than demands, the system should be drawn down in order of the reservoir to

provide storage for the refill season. The storage versus mean monthly graphs (rule curve) of Tekeze hydropower reservoir for s specific time and climate scenarios was shown in Appendix F13.

#### 5.4.3.3 Optimum Reservoir Pool level (Elevation) under Climate Change

HEC-ResPRM optimization result indicates that Tekeze hydropower reservoir pool level will be increased under RCP4.5 and RCP8.5 scenarios in all projected time periods. This comparison made with the current mean annual reservoir operation pool level of 1112.61 masl from 2009–2017. In the three projected time periods, optimal pool level (Table 5.2) change varies from 8.26 to 8.45 m under RCP4.5 and 10.66–11.24 m under RCP8.5 climate scenarios. This is large elevation difference that will store more water in the rainy months for the dry season power production. The optimized pool levels under both scenarios in all time periods are larger than the current optimized pool level. This is due to the impact of climate change and hydrological non-stationarity on reservoir operation. The reservoir storage pool level change in RCP4.5 scenarios is lower than RCP8.5 scenarios due to increase in each year individual month’s fluctuations in RCP4.5 scenarios because of future inflow variability that reduced the mean annual reservoir water storage level.

Table 5.2 Mean annual optimized pool level variation under RCP4.5 and RCP8.5 climate scenarios in three future time periods.

Time Periods	Optimized Pool Level (masl)		Pool Level Change (m)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Current optimized	1120.48		7.87	
2020s	1121.06	1123.27	8.45	10.66
2050s	1120.87	1123.37	8.26	10.76
2080s	1120.89	1123.85	8.28	11.24

The Tekeze hydropower reservoir operational level is changing continually due to inflows occurred and releases are made to produce power. The start of dead storage level at 1096 masl (minimum live

storage level) has been assumed for power production. Figure 5.6 a, b, c shows the optimal reservoir pool level of Tekeze hydropower reservoir generated by HEC-ResPRM optimization model. These optimal pool level results have a similar pattern with the optimal reservoir storage variations and may be considered as rule curves for optimal operation of Tekeze hydropower reservoir under a given scenario and time period. The reservoir pool level stayed at high level every year from August to November when reservoirs filled during the rainy months of August through September. The drop of pool level in June caused due to optimization model constraint reservoir not emptied and a transition zone when the drawdown ends, and reservoir refill start.

The result in this study indicates the comparison of Tekeze hydropower reservoir optimal pool level and storage changes under climate change impacts. This will have a positive outcome in terms of showing the impacts of HEC-ResPRM optimization model and climate change impacts on the hydropower reservoir operation. However, it is sound to discuss the results in terms of how much hydropower produced in the future periods based on optimization models. This is difficult due to lack off observed historical power production data for comparison and turbine performance/ efficiency curves to prepare hydropower penalty functions as only one turbine is operational out four turbines.

In general, there is no doubt that the hydropower reservoir system of Tekeze basin will be affected by climate change. With over all predicted increases in precipitation and streamflow, inflow to the reservoir anticipated to increase. Therefore, even though both RCP4.5 and RCP8.5 climate scenarios exhibited higher water inflow volume to Tekeze hydropower reservoir, this did not necessarily result in significantly more hydropower generation. Optimal operation of the reservoir using HEC-ResPRM considerably increases the power production by storing the higher inflow volume to inflow deficiency periods even if hydropower production has a non-linear relationship with storage and water level (head).

Based on this research, the potential for hydropower production in the Tekeze hydropower reservoir is predicted to increase if appropriate reservoir operation techniques are used by operators and water managers to store and use the wet month's flow to the dry months. The optimal operation model developed in this study can be helpful to dam operators in building generation plans in the future. It also enables a flexible response when inflow occurs during actual operation that is different from the initial planning expectations, as it can generate new operational alternatives appropriate for the changing situation. Even if many optimization models and techniques have been developed in several fields of water resources system analysis such as hydropower reservoir operation around the world, the adaptation of such techniques and tools by water managers is slow. Researchers and scientists must accept the fact that the gap still exists between research studies and applications in practice. There need to be research on how to translate science to improve management operations of reservoirs for optimal results.

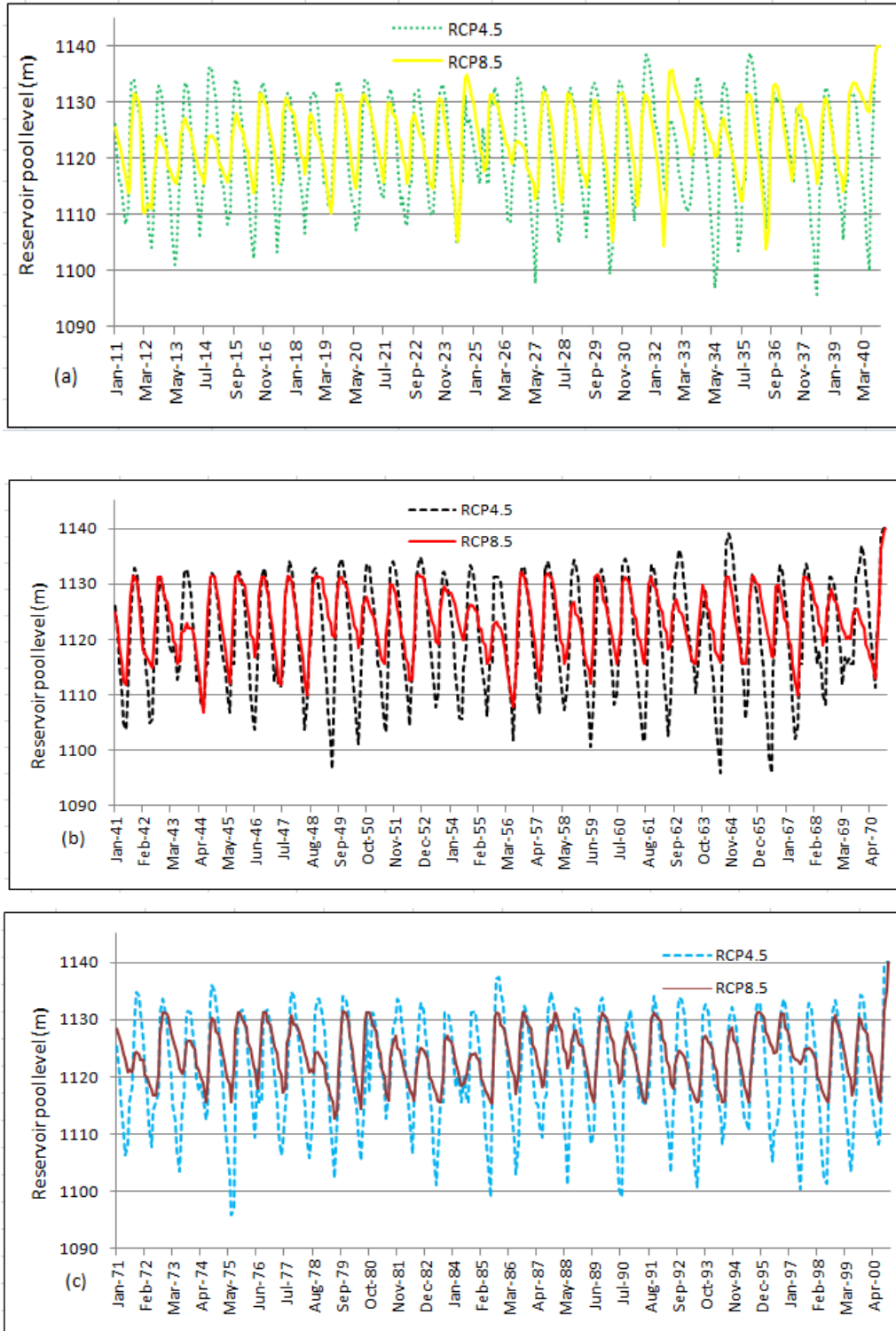


Figure 5.6 Monthly optimum pool level variations under RCP4.5 and RCP8.5 climate scenarios in three time periods: (a) 2020s; (b) 2050s; (c) 2080s

## 5.5 Conclusive Remarks

This study used a semi-distributed hydrological model (SWAT) and a reservoir optimization model (HEC-ResPRM) to evaluate the hydrological impacts of climate change on Tekeze hydropower reservoir operation in Tekeze basin part of Eastern Nile. In this research, it was evaluated climatic data (past and future periods) from the ensemble outputs of CORDEX-Africa RCMs under RCP4.5 and RCP8.5 climate scenarios for the periods of 2020s, 2050s, and 2080s. Calibrated SWAT model was used to generate climate change induced streamflow that was used as an input for optimal reservoir operation modeling. Analysis conducted on Tekeze hydropower reservoir inflows and outflow, reservoir storage volume and reservoir pool levels revealed the following:

1. This study found that the impact of climate change would increase in precipitation, temperature and streamflow in Tekeze basin under RCP4.5 and RCP8.5 climate scenarios over future periods which have an impact on current and future Tekeze hydropower reservoir operation.
2. Projected annual and inter-annual reservoir inflow showed increasing trend under both RCP4.5 and RCP8.5 climate scenarios.
3. HEC-ResPRM incorporates water storage, water surface elevation, release and power generation would provide better understanding of current and future conditions of Tekeze hydropower reservoir operation.
4. Current optimized power storage and pool level show more optimal results than the current actual operation, so it is recommended to change the current operating policy to produce more power throughout the year.
5. The projected increase of reservoir inflow under an ensemble of CORDEX-Africa RCP4.5 and RCP8.5 future climate scenarios lead to optimized reservoir power storage, pool level (head) and release that greatly exceed those historically observed, indicating a shift in current water system behavior.

6. The study showed that climate change clearly affects future reservoir planning and management in Tekeze basin. Therefore, water resources planners, managers and operators should consider climate change impacts in the design, planning and management of reservoir systems.
7. In practice, many reservoir system operators and water managers feel more comfortable to use pre-defined rule curves and simulation results which are easy to understand and operate as most optimal operating rules developed by scientists using sophisticated optimization models and algorithms are mathematically more complex. The use of a combination of simulation and optimization models may solve this problem.

## 6 CONCLUSIONS AND RECOMMENDATIONS

### 6.1 Conclusions

This study has been carried out in the Tekeze River basin to understand how changes in hydrological regime in the future caused by climate variability and climate change affects the performance of hydropower dam/ reservoir. The result of these studies can help to inform decision-makers about possible ways of planning and operation of reservoir/dam in the future to optimize power generation and to ensure that the demands of other users met.

The seasonal and annual trends of precipitation at eleven gauging stations of Tekeze basin and streamflow at Embamadre station which have good quality data sets with reliable data and adequate record length were analyzed by the non-parametric Mann-Kendall and Sen's method. The result demonstrated good agreement of performance in detection of the trends for precipitation at different parts of the basin. Based on the results of statistical methods, the stations found in the South and Eastern parts of the basin showed non-significant positive trends whereas non-significant negative trends observed at the Northern part of the basin at 5% significant level for the annual precipitation series. However, most of the precipitation stations showed significant increasing trends in *Kiremt* and *Belg* seasons. The trend and variability analysis of streamflow also showed that a non-significant increasing annual trend but *Kiremt* and *Belg* seasons streamflow trend showed a significant positive and *Bega* season with significant negative trends. The findings presented here on the spatio-temporal trends and variability's of Tekeze basin precipitation and streamflow can be implemented to improve the water resources strategies in the basin.

The hydrologic regimes before and after Tekeze hydropower reservoir operation were quantitatively analyzed using the range of variability approach based on the indicators of hydrologic alteration. The results for many of the parameters, the magnitude, duration and direction showed a significant alteration

like a significant increase in 1- through 90-day minimum streamflow, decrease in 1- through 90-day maximum streamflow, rise and fall rates decreased and increase in annual hydrograph reversals. Generally, the hydrologic regime of the lower Tekeze River changed significantly after the hydropower reservoir began operation. The result of this study will be beneficial to the future regional water resources management and effects of this alteration on river ecosystems with in the lower Tekeze basin. In this study a semi-distributed hydrological model (SWAT) and a reservoir operation optimization model (HEC-ResPRM) used to evaluate the hydrological impacts of climate change on hydropower reservoir operation in the Tekeze River basin, Ethiopia. Meteorological products assessed during the past periods (1976-2005) and the ensemble of CORDEX-Africa RCMs under RCP4.5 and RCP8.5 bias-corrected climate change scenarios during a future period (2011-2100) in concert with the proposed hydropower water infrastructure plans. Past simulations driver with ground-based forcing were calibrated and tested with stream gauging data at Embamadere. Analysis conducted on reservoir inflows, pool elevations and power storage volume for meteorological and infrastructure scenarios revealed the following:

1. Tekeze River basin has extreme hydrological variability and seasonality (Highly variable rainfall) that results in runoff highly variable and seasonal across the basin, and from year to year which has an impact on current operations and future planned hydropower reservoirs operation.
2. This study found that the impact of climate change will increase in precipitation, temperature, and streamflow in the Tekeze river basin in both biases corrected CORDEX-Africa RCMs under RCP4.5 and RCP8.5 climate scenarios over future periods.
3. According to the latest inflow projections based on RCP4.5 and RCP8.5, climate scenarios total inflows to Tekeze hydropower reservoirs slightly increases in all time horizons, stored water in the

reservoir increases which has many implications for future hydropower dams/reservoirs planning and operation.

4. The new reservoir optimization modeling approach HEC-ResPRM incorporates water storage, water surface elevation (i.e., head), and release would provide the better understanding of current and future conditions of optimum hydropower dams/reservoirs operation in the Tekeze basin.
5. The future period contained a significantly higher amount of precipitation relative to the historical simulation with the bias-corrected CORDEX-Africa RCP scenarios approach. This trend led to the projection of higher optimized reservoir inflow, pool elevation, and storage from the Tekeze hydropower reservoir. As a result, the future scenarios lead to optimized reservoir power storage and pool elevations in the operational reservoir that significantly exceeds those observed historically, indicating a shift in current water system behavior. Therefore, it is better first to improve existing hydropower reservoir (TK05) capacity rather than investing in new planned hydropower projects.
6. Incorporate climate change scenarios into dam design: The significant implication of climate change in Tekeze River basin for dams and reservoirs is that the future is uncertain, and can no longer be assumed to mirror the past. Hydropower reservoir/dam projects to design and operation should approach with extreme caution until reliable data series available in the basin. Climatic uncertainty should be incorporate into dam design, to avoid the hazards of over- or under-designed infrastructure and financial risk.

## 6.2 Recommendations

The modeling exercise was relatively successful in the planning and operation of Tekeze hydropower reservoir operation under hydrological variability and climate change. However, this study still has some limitations which could address in future research. Since it is the first study in Tekeze basin hydropower reservoir operation under climate change, further studies are recommended using multiple hydrologic models, climate models and hydropower reservoir simulation and optimization models which will provide more precise results. Therefore, to improve the outcome and the use of the entire model capabilities based on future insights of Tekeze hydropower projects, the following is proposed for future work:

- i. Statistical precipitation trend analysis of this study investigates only the magnitudes and changes of historical data without being able to quantify more precipitation characteristics like frequencies of high precipitations or low precipitations, increase or decrease in the number of rainy days, rainfall concentration index, standardized anomalies of annual rainfall and changes in dry-spell length. Therefore, further investigations are needed by considering all these characteristics and regionalize the results for the whole basin. Further investigation also needed for streamflow trend detection considering land degradation and landscape change with human activities.
- ii. Further climate change modeling at the Tekeze basin is needed to more clearly define the trends and ranges of climate change and extreme events that need to incorporate into hydropower development plans.
- iii. This study has not considered the changes in land use/land cover due to socio-economic development in the future. Land cover /land use properties were considered constant throughout the simulation period; such an assumption can affect the projections of streamflow in the basin. Land use changes including projected changes in associated with climate change impacts and effect

erosion and sediment yield which are necessary to evaluate predicted changes in runoff associated with future Tekeze River basin development. Hence, further studies are recommended to couple climate models and various bias correction methods with land use change to quantify the projected change in streamflow and sedimentation load in Tekeze hydropower reservoirs as well as its implication on future hydropower generation from Tekeze river basin.

- iv. Lack of sufficient observed data highlighted some of the challenges Tekeze basin face. The climate model analysis and hydrological modeling were affected by the absence of the data. Future work is required to collect more data through means that are sustainable. It is highly recommended to improve both climate and hydrological monitoring system in the whole Tekeze basin. Furthermore, existing monitoring network and data are insufficient to calibrate and verify hydrological models of Tekeze River basin. A long-term commitment to monitoring critical hydrological variables associated with climate change needed at the sub-basin level. That mainly includes maintaining and expanding monitoring networks for temperature, rainfall, river stage, and discharge. Specific focus should give to improving knowledge and confidence concerning the relationship between climate change and river discharge as discharge directly affects hydropower production.
- v. Further studies recommended using hydro-economic model that allowed for scenario calculation of how reservoir water levels, storage and power production changes with climate change scenarios and with a change in operating scheme of the reservoir (increase in turbine capacity). Also Further model development will enable the consideration of a variety of additional parameters, such as water withdrawal for planned irrigation, drinking water supply, or altered energy policies.

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## APPENDICES

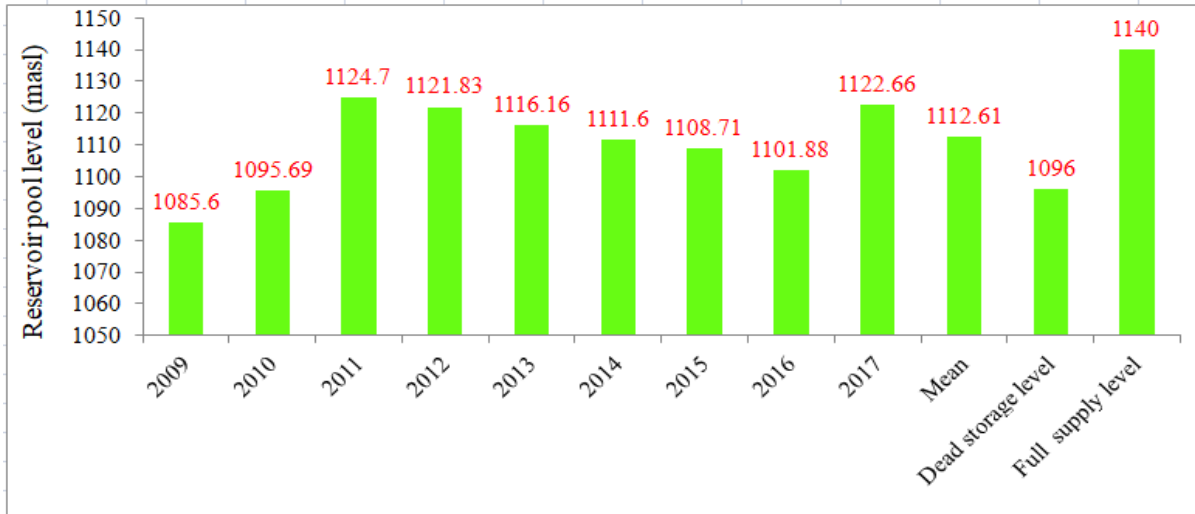
### Appendix A: Meteorological data of Tekeze River Basin

#### Appendix A1: Monthly rainfall data (mm) in some Tekeze Basin weather stations after missing data filled

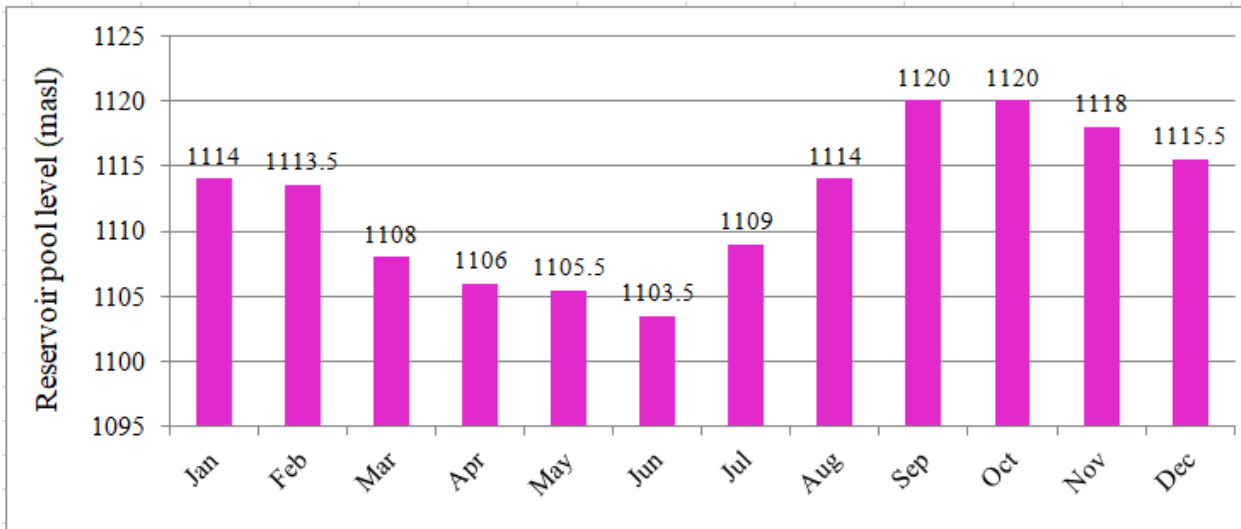
Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
<b>a) Lalibela Station</b>												
1994	0.00	3.10	8.40	46.50	3.40	41.60	446.00	311.00	65.00	3.70	1.80	0.90
1995	0.00	28.60	10.20	83.20	68.00	9.30	323.40	205.70	46.80	0.70	0.00	20.70
1996	31.90	1.80	118.70	47.00	56.20	161.60	296.50	288.40	20.50	0.70	35.00	0.80
1997	15.70	8.40	95.60	58.70	24.30	104.40	304.20	162.00	25.80	100.30	100.90	2.60
1998	5.90	7.70	37.40	10.80	44.00	17.60	340.80	258.60	58.10	21.50	0.00	0.00
1999	19.30	0.00	0.00	22.30	0.70	34.20	319.70	319.60	50.40	35.50	3.30	1.80
2000	0.00	0.00	25.90	79.90	13.50	16.20	213.10	206.30	71.10	80.70	36.60	9.30
2001	0.00	9.80	82.10	31.40	1.90	106.80	340.40	377.30	7.00	0.00	0.00	7.10
2002	34.40	19.40	45.60	34.70	6.80	51.80	214.30	245.10	55.70	1.50	12.80	0.00
2003	2.00	19.70	45.50	56.80	1.80	59.30	225.30	404.10	52.70	0.00	1.60	0.00
2004	2.80	11.60	12.00	20.30	0.00	45.50	242.40	188.60	19.00	10.20	0.80	0.00
2005	6.20	21.40	47.90	27.10	57.00	36.40	366.20	155.70	40.20	0.50	0.00	0.00
2006	0.00	1.00	54.40	43.80	20.30	23.90	301.90	324.30	43.60	25.60	23.60	15.30
2007	2.00	19.70	45.50	56.80	1.80	59.30	225.30	404.10	52.70	0.00	1.60	0.00
2008	2.80	11.60	12.00	20.30	0.00	1.52	242.40	188.60	19.00	10.20	0.80	0.00
<b>b) Gondar Station</b>												
1994	0.00	0.00	0.00	5.80	84.50	156.00	289.10	272.90	125.00	38.00	20.00	2.80
1995	0.00	0.00	34.50	36.70	86.50	107.80	284.50	308.60	86.90	12.40	0.40	19.80
1996	0.00	4.40	22.20	83.60	183.80	194.70	249.30	290.00	75.80	67.70	23.20	0.40
1997	0.00	1.80	28.20	42.80	124.20	184.80	239.70	230.40	33.10	200.30	40.20	13.70
1998	0.00	0.00	13.70	3.70	88.50	284.60	383.00	487.90	125.70	126.40	4.80	0.00
1999	35.50	0.00	0.00	42.00	127.10	158.70	432.80	424.40	187.40	337.80	11.30	52.60
2000	0.00	1.40	3.90	73.20	60.70	364.30	451.40	368.60	166.60	268.70	1.90	0.00
2001	0.00	0.90	3.30	29.40	88.90	415.40	568.90	491.30	118.20	144.80	16.00	0.00
2002	0.00	0.00	0.00	16.60	87.10	197.40	312.70	247.60	76.80	45.20	5.80	4.20
2003	0.00	23.50	9.70	0.60	37.30	258.40	311.70	291.60	116.10	21.30	0.00	5.70
2004	1.60	3.70	5.90	37.60	1.40	181.40	378.30	312.30	112.40	67.60	65.70	0.00
2005	0.00	11.20	60.80	12.10	24.20	137.50	289.00	276.20	169.30	42.80	17.40	0.00
2006	0.00	0.00	10.80	27.80	152.60	98.70	291.50	339.10	192.50	86.70	4.20	35.00
2007	22.90	0.50	22.20	87.80	65.60	285.60	422.80	457.80	172.50	8.10	5.00	0.00
2008	81.40	0.00	1.50	81.90	211.50	6.98	376.40	331.80	228.60	51.80	2.50	18.50
<b>c) Debretabor Station</b>												
1994	1.80	9.10	0.00	14.40	89.70	237.70	495.80	633.50	248.00	10.00	24.80	31.70
1995	0.00	0.00	27.60	31.40	98.70	75.70	411.50	405.90	168.10	20.70	7.70	25.30
1996	4.30	1.20	47.80	92.10	138.70	287.00	343.10	374.00	155.40	30.60	76.20	4.40
1997	3.40	0.00	73.70	43.10	197.30	225.10	449.70	359.00	197.00	314.00	12.30	137.60
1998	13.60	0.00	28.10	6.90	203.60	126.20	400.60	410.80	214.80	75.90	0.20	0.00
1999	34.50	0.00	0.00	16.70	44.60	200.10	453.70	345.70	245.00	250.40	11.20	19.50
2000	0.00	0.30	6.30	116.10	61.10	168.10	423.40	466.00	232.30	137.80	34.80	0.50
2001	0.00	1.30	17.20	24.00	95.40	197.50	496.70	410.00	184.80	60.10	4.50	7.20
2002	0.40	0.00	61.20	45.10	46.80	203.30	256.60	313.40	132.80	2.90	16.00	18.80
2003	0.00	13.90	33.70	19.20	9.80	97.00	438.40	404.30	200.70	16.70	33.30	14.80
2004	0.50	37.60	33.70	75.50	19.10	141.00	333.70	295.20	120.80	85.80	42.50	12.70
2005	1.30	0.00	34.10	10.30	56.30	224.40	473.60	436.00	216.20	5.00	29.70	0.00
2006	0.00	1.40	6.80	63.20	147.30	170.00	482.20	452.50	255.00	47.50	0.00	13.60
2007	22.90	0.50	22.20	87.80	65.60	295.80	422.80	449.60	172.50	8.10	5.00	0.00
2008	81.40	0.00	1.50	81.90	211.50	6.98	376.40	331.80	228.60	51.80	2.50	18.50
<b>d) Mekele Station</b>												
1994	0.00	5.30	0.40	43.80	0.80	67.60	147.90	317.80	70.10	0.00	1.80	2.00
1995	0.00	5.90	31.20	29.20	27.10	8.20	267.50	249.90	38.50	3.00	0.00	2.70
1996	1.40	0.00	59.50	12.50	92.20	47.90	109.20	224.00	7.10	0.00	31.40	1.10
1997	0.00	0.00	20.40	32.60	29.80	32.40	243.10	100.50	16.30	59.90	15.70	0.00
1998	10.00	1.20	10.60	10.60	22.00	48.00	289.00	318.80	31.70	22.00	0.00	0.00
1999	22.00	0.30	10.90	0.00	0.00	8.20	292.80	359.20	22.80	0.90	0.00	0.00
2000	0.00	0.00	0.00	10.40	24.60	5.40	201.40	182.00	15.80	2.20	10.30	3.50
2001	0.00	0.00	38.10	18.70	8.70	65.50	267.90	226.30	9.20	2.90	0.00	0.00
2002	12.90	0.00	35.50	4.20	23.00	60.80	95.50	208.60	28.00	0.00	0.00	0.30
2003	0.00	25.90	18.20	8.40	35.20	101.10	127.80	186.00	23.40	0.70	0.00	0.10
2004	10.90	0.20	35.20	20.50	7.10	25.40	64.30	221.10	1.40	3.10	0.80	0.00
2005	0.00	1.40	15.60	48.90	55.10	18.20	110.50	314.00	34.30	0.00	1.30	0.00
2006	0.00	0.00	31.30	117.60	46.30	38.10	187.10	298.90	23.60	12.00	0.00	0.30
2007	1.10	2.30	11.20	34.50	22.20	58.00	278.70	135.10	76.20	0.00	0.00	0.00
2008	7.50	0.00	0.00	23.90	5.90	0.43	94.10	103.30	27.40	7.70	4.10	0.00

Appendix B: Tekeze Hydropower Reservoir data

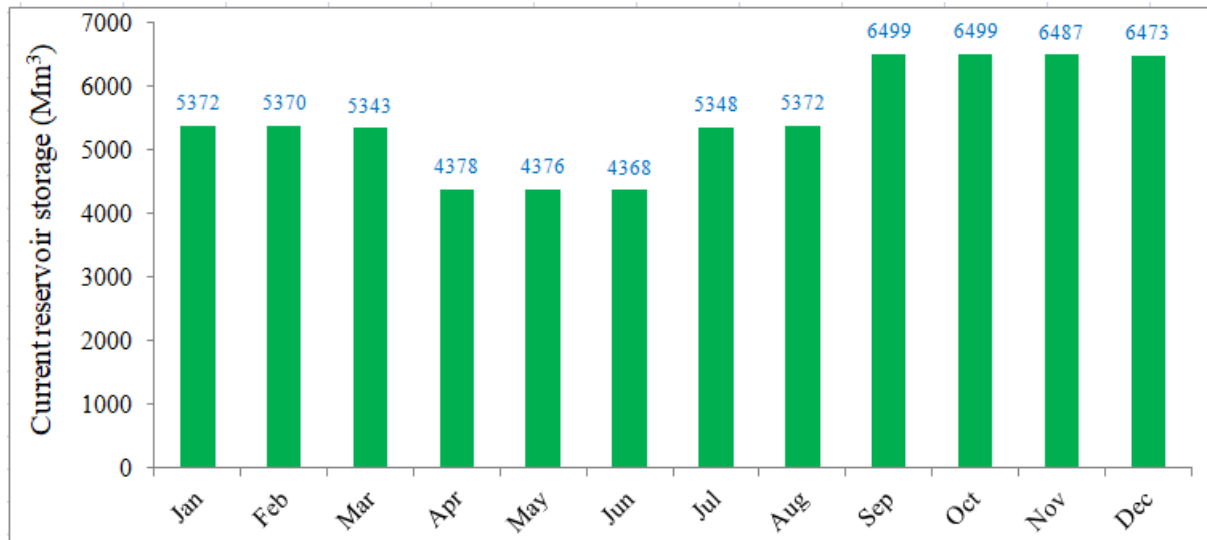
Appendix B1: Observed mean annual Tekeze hydropower reservoir pool level



Appendix B2: Observed mean monthly Tekeze hydropower reservoir pool level (2009-2017)



Appendix B3: Observed mean monthly Tekeze hydropower reservoir storage (2009-2017)



Appendix B4: Characteristics of Tekeze hydropower reservoir/Arch Dam (TK05)

Type	Characteristics	Unit	Value
Catchment	Catchment Area	Km <sup>2</sup>	29,692
	Annual inflow	10 <sup>9</sup> m <sup>3</sup>	3.75
	Annual precipitation	Mm	850
	Annual discharge at dam site	m <sup>3</sup> /s	120
	Sedimentation	10 <sup>6</sup> m <sup>3</sup> /year	30
Dam features	Dam crest level	Masl	1145
	Dam height	M	188
	Dam type	Type	Arch dam
	Commissioning year	Year	2009
	Dam crest length	M	420
Reservoir	Maximum retention level	Masl	1140
	Minimum operation level	Masl	1096
	Total storage	10 <sup>9</sup> m <sup>3</sup>	9.293
	Live storage	10 <sup>9</sup> m <sup>3</sup>	5.293
	Dead Storage	10 <sup>9</sup> m <sup>3</sup>	4
	Surface area at MRL	km <sup>2</sup>	147
Power plant	Powerhouse type		Under ground
	Turbine number and type	No	4-Francis
	Total Installed capacity	MW	300
	Maximum net head	M	162.8
	Minimum net head	M	120
	Maximum Discharge	m <sup>3</sup> /s	220

Appendix B4: Projected monthlyTekeze hydropower reservoir inflow under RCP4.5 scenario

Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2041	69	14	2	13	25	458	3557	4049	3083	875	505	233
2042	94	24	8	69	52	621	4126	3722	1743	970	398	209
2043	86	101	434	658	360	188	1098	2621	1675	638	397	163
2044	43	11	3	640	137	448	1683	3201	2182	679	448	290
2045	107	27	201	301	225	217	2684	3940	3234	1157	524	255
2046	92	26	7	32	92	467	3371	3763	1433	654	353	149
2047	39	12	5	807	207	555	1380	2817	961	889	361	165
2048	121	33	56	27	4	982	1865	3630	1724	657	330	150
2049	49	10	9	66	77	183	2380	2177	1462	687	397	200
2050	65	19	3	9	3	358	1744	2584	1760	834	497	197
2051	79	17	6	415	129	105	456	2589	2020	705	358	271
2052	82	15	7	363	81	209	1493	1789	1864	923	629	311
2053	169	117	81	37	10	293	791	2035	1337	589	319	362
2054	109	33	8	91	262	523	1389	3562	1625	1089	379	230
2055	133	34	21	374	190	234	1724	3424	2355	1258	544	429
2056	190	84	22	18	95	89	3020	4553	3543	1050	512	252
2057	101	31	138	118	180	214	1165	2345	1791	750	343	162
2058	77	17	287	239	102	408	924	1459	1744	931	472	210
2059	70	17	16	108	29	112	1234	3281	2899	1773	905	366
2060	173	54	9	46	89	737	1776	3355	2105	720	380	190
2061	64	19	15	240	75	104	540	3242	1478	1758	550	294
2062	126	30	7	102	79	123	1119	3399	1961	711	999	333
2063	171	68	18	217	66	182	131	1125	1324	521	1180	186
2064	91	15	197	72	37	172	2009	3462	1833	768	410	187
2065	75	17	5	2	1	29	967	2241	1065	444	226	103
2066	25	147	90	103	62	328	2150	2769	1749	815	368	191
2067	77	29	3	9	35	761	1668	3377	2532	948	438	209
2068	79	19	64	781	225	127	389	1915	1636	590	413	184
2069	77	16	12	1045	653	631	1185	2947	2831	1170	931	829
2070	263	145	43	8	8	17	1352	1238	2041	482	263	116

Appendix B5: Projected monthlyTekeze hydropower reservoir inflow under RCP8.5 scenario

Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2041	19	2	11	3	0	6	583	957	959	439	167	85
2042	35	7	39	36	70	21	688	933	661	188	108	42
2043	8	2	7	7	11	27	391	767	345	464	192	92
2044	91	18	4	3	3	65	1296	1000	783	353	187	79
2045	33	7	2	9	1	9	686	1235	658	301	123	57
2046	17	4	0	5	24	2	627	1042	560	212	98	49
2047	11	1	6	6	47	226	1215	982	581	206	141	66
2048	16	36	11	7	1	45	851	1043	861	607	202	97
2049	45	8	1	0	0	72	278	871	657	288	131	62
2050	22	12	3	2	9	1	353	646	454	146	118	43
2051	13	6	1	21	2	54	819	804	728	266	163	66
2052	19	4	1	38	9	16	392	1301	1003	305	191	82
2053	31	7	1	16	2	34	74	683	682	237	220	76
2054	130	118	48	20	3	110	35	515	464	237	295	53
2055	40	13	68	92	43	22	192	576	480	171	240	58
2056	23	3	17	1	70	179	1023	1156	1199	544	202	102
2057	48	9	10	1	29	31	685	1148	972	271	143	64
2058	18	4	1	3	4	23	303	539	667	171	96	39
2059	9	10	8	90	199	97	1015	1419	479	183	92	33
2060	6	12	30	3	2	36	364	704	939	321	141	70
2061	24	5	1	1	2	2	58	983	770	228	107	57
2062	16	2	9	50	5	3	199	718	514	146	99	69
2063	31	7	1	4	17	14	151	922	853	374	131	81
2064	27	5	0	0	12	208	795	1057	621	302	125	59
2065	25	5	2	49	114	312	774	1052	760	247	168	61
2066	18	13	1	0	9	29	295	1209	286	160	70	29
2067	9	1	0	1	14	87	934	1308	610	197	105	42
2068	8	2	3	12	1	11	291	595	513	282	111	50
2069	17	4	2	7	4	175	47	607	372	121	120	28
2070	4	1	0	0	0	21	772	1248	1022	309	145	71

## Appendix C: Climate and hydrological variability

### Appendix C1: Hydrological alteration analysis by RVA-Non parametric test of Tekeze river flow regime due to dam construction

Parameters	Pre-impact period: 1994-2008		Post-impact period: 2009-2015		RVA Boundaries		IHA	IHA (>67%)	IHA (<33%)
	Medians	Coeff. of Dispersion	Medians	Coeff. of Dispersion	Low	High	Middle category	High category	Low category
Parameter Group #1									
July	477.70	0.64	488.60	0.84	296.30	526.20	0.29	0.29	-0.57
August	1322.00	0.53	849.00	1.08	897.80	1400.00	-0.57	-0.57	1.14
September	320.30	0.52	443.10	0.46	297.30	375.50	-0.57	1.14	-0.57
October	110.80	0.79	264.90	0.65	86.87	139.40	-0.57	1.57	-1.00
November	42.90	1.07	239.80	0.86	35.82	58.96	-1.00	2.00	-1.00
December	32.50	0.84	211.30	0.67	25.77	37.46	-0.57	1.57	-1.00
January	23.10	1.23	201.50	0.94	9.72	30.16	-1.00	2.00	-1.00
February	21.30	1.02	304.10	0.48	9.10	24.90	-1.00	2.75	-1.00
March	20.20	0.91	273.70	0.42	16.60	21.90	-1.00	2.75	-1.00
April	16.10	1.50	293.20	0.76	7.95	29.15	-1.00	2.00	-1.00
May	19.10	0.85	320.00	0.75	13.87	26.44	-1.00	2.00	-1.00
June	58.55	1.13	312.00	0.69	31.40	74.95	-1.00	1.57	-0.57
Parameter Group #2									
1-day minimum	3.70	1.92	64.70	2.17	2.15	8.06	-1.00	2.00	-1.00
3-day minimum	9.00	1.42	154.90	0.97	2.27	9.37	-1.00	2.75	-1.00
7-day minimum	9.81	1.33	184.40	0.82	2.47	13.28	-1.00	2.00	-1.00
30-day minimum	14.21	1.01	201.50	0.80	4.71	17.22	-1.00	2.00	-1.00
90-day minimum	17.12	1.13	201.50	0.88	9.97	22.70	-1.00	2.00	-1.00
1-day maximum	3033.00	0.50	1719.00	0.65	2213.00	3130.00	-0.64	-0.46	1.14
3-day maximum	2249.00	0.50	1451.00	0.43	1724.00	2470.00	-0.14	-0.57	0.71
7-day maximum	1951.00	0.48	1240.00	0.46	1447.00	1995.00	-0.57	-0.57	1.14
30-day maximum	1344.00	0.68	1015.00	0.50	1088.00	1553.00	-0.57	-0.57	1.14
90-day maximum	748.40	0.91	723.50	0.22	665.50	958.00	0.71	-0.57	-0.14
Number of zero days	0.00	0.00	0.00	0.00	0.00	0.00	0.07	-1.00	
Base flow index	0.03	2.08	0.44	0.93	0.02	0.07	-0.57	1.57	-1.00
Parameter Group #3									
Date of minimum	130.00	0.21	337.00	0.46	108.10	154.20	-0.14	0.71	-0.57
Date of maximum	224.00	0.05	239.00	0.05	220.60	233.90	0.29	0.71	-1.00
Parameter Group #4									
Low pulse count	4.00	1.00	0.00	0.00	3.00	5.72	-0.64	-1.00	2.21
Low pulse duration	4.50	3.11	3.50	1.43	3.00	12.16	-0.69	-1.00	-0.29
High pulse count	4.00	1.25	3.00	3.33	3.00	4.72	-0.64	0.29	0.61
High pulse duration	4.50	2.44	34.75	3.26	2.00	9.00	-0.20	0.61	-1.00
Parameter Group #5									
Rise rate	39.30	1.20	33.34	0.35	23.48	45.74	-1.00	1.57	-0.57
Fall rate	-3.40	-0.82	-18.83	-0.52	-4.67	-2.20			
Number of reversals	87.00	0.30	138.00	0.25	80.84	96.16			

Appendix C2: Minimum and maximum 1-, 3-, 7-, 30- and 90- days flow at Embamadre using IHA

Year	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max
1994	0.3	0.6667	1.014	2.053	2.956	279.5	135.9	110.6	39.48	21.29
1995	0	0	0	0.1033	0.9878	1167	1085	1062	552.6	287.1
1996	8.2	15.8	15.97	17.96	21.57	2502	1650	1414	1157	695.7
1997	1.5	1.5	1.914	3.66	10.77	2153	1913	1533	1065	657.2
1998	0.2	0.2	0.2714	0.4	1.9	1662	1357	1088	662.3	389.6
1999	8.6	9.167	9.814	14.98	16.39	3173	2420	1986	1555	1151
2000	1.9	2.067	2.3	4.597	9.653	3346	2861	2717	1981	1140
2001	2.8	2.8	2.914	4.993	7.12	2369	2270	2029	1344	687.1
2002	7.7	7.9	8.729	16.58	26.52	3173	3033	2890	2488	1231
2003	13.8	14.27	14.97	17.48	23.14	1413	1201	1037	793.1	456
2004	17.6	17.77	18.1	22.2	26.49	3130	2490	1951	1548	859.5
2005	7.1	9	14.24	22.2	26.58	3130	2490	1951	1548	772.6
2006	14.3	20.67	25.19	26.71	26.71	3033	2082	1546	1148	748.4
2007	3.7	9.367	10.81	14.21	17.65	3390	2644	2331	1899	996.3
2008	3.7	9.367	10.81	14.21	17.12	3033	2249	1998	1702	1262
2009	10.3	10.66	16.78	32.19	79.87	3346	2973	2838	1992	1143
2010	28.2	57.72	70.7	88.09	100.2	1517	1387	1177	599.9	380.2
2011	64.7	64.7	67.82	116.5	150	1719	1189	1041	805.1	674.3
2012	196.7	208.4	218.7	243.3	278.3	2700	1774	1327	1070	760.7
2013	10.3	175.4	197.7	288	315.3	2108	1952	1716	1287	783.9
2014	80.97	223	237.3	249.3	261.3	1589	1328	1240	1015	723.5

## Appendix D: SWAT Hydrological Model parameters

### Appendix D1: Sensitive parameters for calibration of the SWAT model at Tekeze basin

Code	Parameter	Description	Unit	Range	Initial value	Optimal value
Parametres governing surface water response						
1	CN2	Curve Number, Condition AMCII	-	35-98	83	54
2	SOL_AWC	Soil available water capacity	mm/mm	0-1	0.1	0.63
3	ESCO	Soil evaporation compensation factor	-	0-1	0.95	0.02
4	EPCO	Plant uptake compensation factor		0.01-1	0.4	0.11
Parametres governing sub surface water response						
5	ALPHA_BF	Base flow alpha factor	days	0-1	0.048	0.54
6	GWQMN	Threshold water level in shallow aquifer for base flow		0-5000	1000	1290
7	GW_REVAP	Ground water revap coefficient		0.02-0.2	0.02	0.18
8	GW_DELAY	Ground water delay time	day	0-50	31	9.5
9	RVPMN	Threshold water depth in the shallow aquifer for “revap”		0-500	450	45
Parametres governing sub surface water response						
10	CH_N2	Manning coefficient for main channel	-	(-)0.01-0.3	0.14	0.1
11	SOL_K	Hydraulic conductivity of the saturated soil	mm/hr	0-2000	45	1.56
12	CH_K2	Effective hydraulic conductivity of main channel	mm/hr	(-)0.01-500	0.01	75
13	Surlag	Surface runoff lag coefficient	-	0-10	0.5	0.3

## Appendix D2: Land use and soil distribution of Tekeze basin re-classified by SWAT

Detailed LANDUSE/SOIL/ distribution SWAT model class Date: 9/22/2015 12:00:00 AM Time: 01:01:34

Watershed		Area [ha]	Area[acres]	
Number of Subbasins: 23		4441284.0000	10974634.8282	
<hr/>				
LANDUSE:		Area [ha]	Area[acres]	%Wat.Area
	Pasture --> PAST	382508.8230	945198.4272	8.61
	Forest-Mixed --> FRST	573567.2321	1417313.3089	12.91
	Agricultural Land-Generic --> AGRL	2842563.8418	7024117.3813	64.00
	Range-Grasses --> RNGE	642644.1031	1588005.7109	14.47
<hr/>				
SOILS:		Area [ha]	Area[acres]	%Wat.Area
	Calcic cambisol	524514.6136	1296101.8359	11.81
	Calcic Vertisol	138729.7492	342808.1469	3.12
	Chromic Livisol	206074.5984	509220.6363	4.64
	Cithic Leptosol	354636.4716	876324.4531	7.98
	Dystric Leptosol	467781.8982	1155912.4597	10.53
	Eutric Leptosol	332948.1981	822731.6450	7.50
	Eutric cambisol	1624352.4814	4013856.1992	36.57
	Eutric Leptosol	54768.6906	135336.1728	1.23
	Eutric Vertisol	408633.1524	1009752.9513	9.20
	Haplic Alisol	91637.1554	226439.9930	2.06
	Haplic Arenosol	26008.3279	64267.8788	0.59
	Haplic Luvisol	45364.5720	112098.1256	1.02
	Luvic Calisol	35632.4493	88049.5638	0.80
	Umbric leptosols	130201.6417	321734.7667	2.93

## Appendix E: Climate change in Tekeze basin

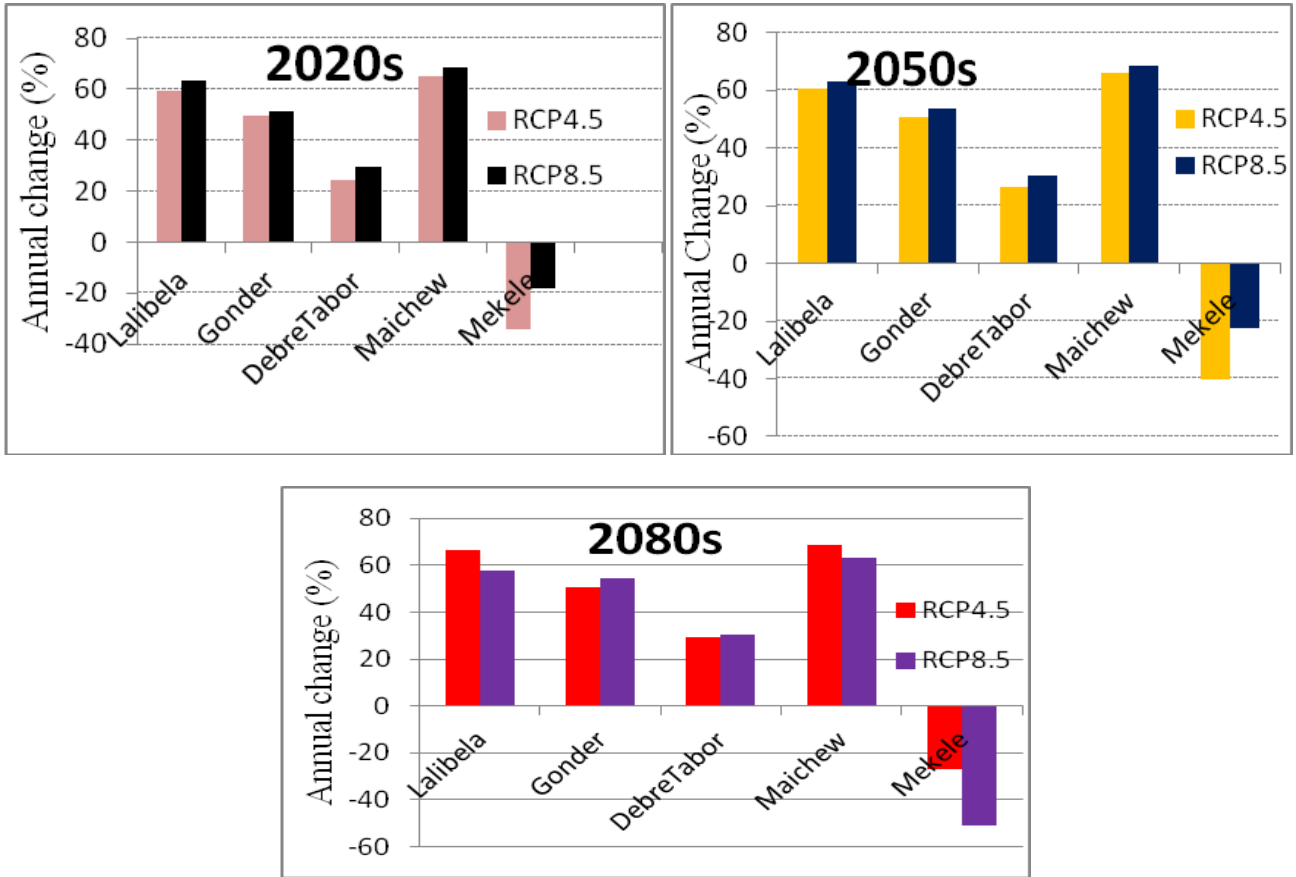
### Appendix E1: annual and seasonal changes of precipitation at different stations of Tekeze basin in different scenarios

Station	Season	Change in precipitation (mm)					
		RCP45			RCP85		
		2020s	2050s	2080s	2020s	2050s	2080s
Lalibela	Annual	1185.08	1250.80	1420.56	1408.78	1393.87	1119.64
	Belg	9.36	98.39	63.22	66.61	35.10	34.36
	Kiremt	612.26	1100.35	1240.98	1292.70	1242.75	978.91
	Bega	14.81	52.06	116.36	49.47	116.02	106.37
Gonder	Annual	430.37	449.71	451.69	456.88	501.68	524.63
	Belg	-13.87	41.86	-2.37	0.68	-1.59	37.10
	Kiremt	259.14	432.13	465.68	478.42	516.67	449.02
	Bega	46.47	-24.28	-11.61	-22.23	-13.40	38.51
Debre Tabor	Annual	192.07	214.30	250.06	255.13	265.76	261.55
	Belg	-37.07	7.17	-23.90	-26.24	-28.53	5.47
	Kiremt	91.87	235.33	300.71	318.27	321.60	233.39
	Bega	137.27	-28.20	-26.75	-36.90	-27.31	22.69
Maichew	Annual	1303.84	1369.56	1539.32	1527.54	1512.63	1198.40
	Belg	-72.83	16.20	-18.97	-15.58	-47.08	-87.82
	Kiremt	858.23	1346.32	1486.95	1538.68	1488.72	1224.89
	Bega	18.53	7.03	71.34	4.44	70.99	61.34
Mekele	Annual	-144.09	-162.18	-119.03	-85.41	-103.60	-189.87
	Belg	-74.19	-64.19	-73.04	-71.18	-73.35	-79.95
	Kiremt	-186.21	-103.14	-61.11	-17.02	-41.09	-120.26
	Bega	116.31	5.15	15.11	2.79	10.83	10.33

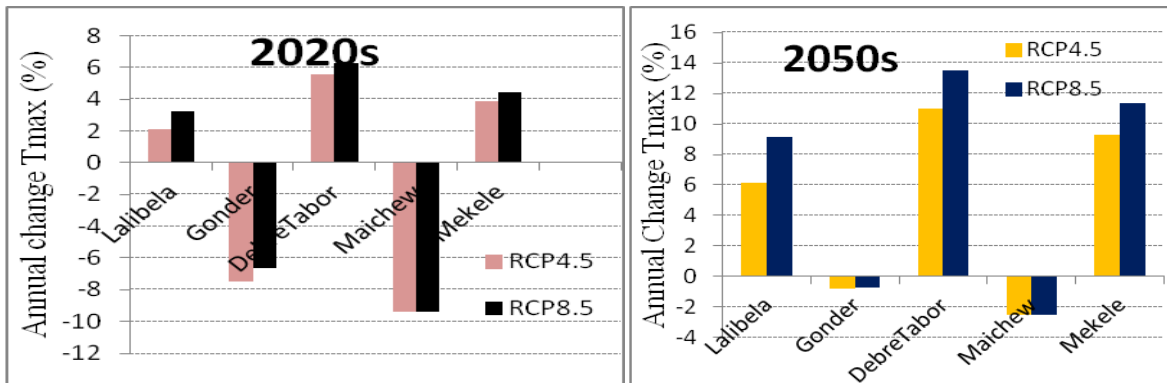
Appendix E2: annual and seasonal changes of temperature at different stations of Tekeze basin in different scenarios

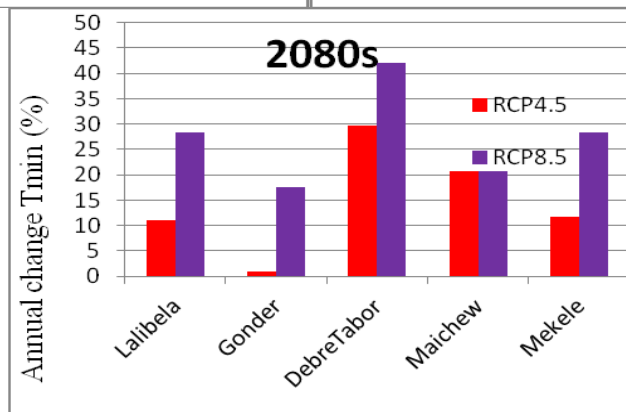
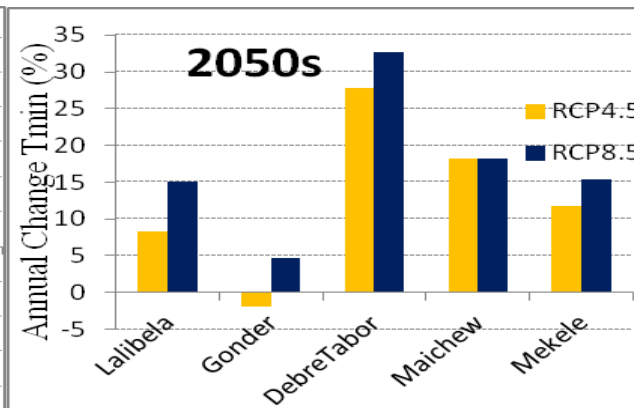
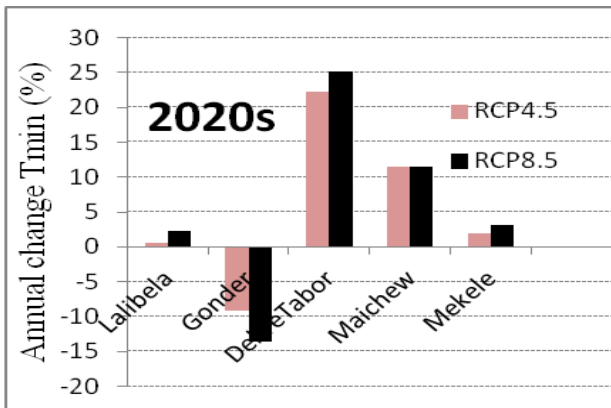
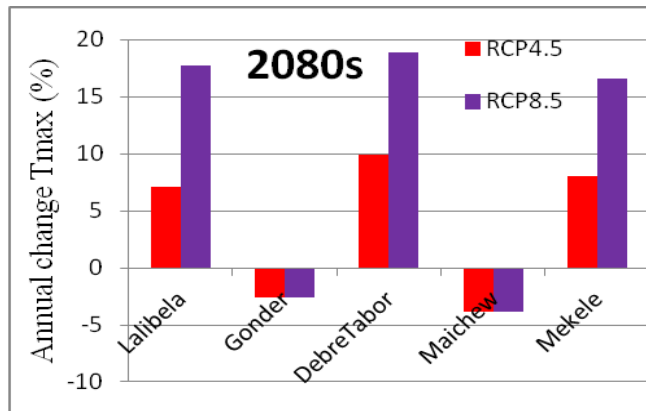
Station	Season	Change in Temperature (°C)											
		Change in Minimum Temperature						Change in Maximum Temperature					
		RCP45			RCP85			RCP45			RCP85		
		2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
Lalibela	Annual	0.04	0.90	1.26	0.23	1.78	3.97	0.49	1.42	1.64	0.75	2.14	4.43
	Belg	-0.51	0.28	0.60	-0.38	1.27	3.48	1.08	2.24	2.42	1.54	3.06	5.25
	Kiremt	0.24	1.11	1.51	0.49	1.97	4.10	0.17	1.20	1.37	0.29	1.83	4.59
	Bega	0.40	1.30	1.67	0.58	2.10	4.32	0.21	0.82	1.14	0.42	1.54	3.44
Gonder	Annual	-1.08	-0.18	0.22	-0.89	0.75	3.01	-1.84	-0.93	-0.65	-1.61	-0.18	-0.65
	Belg	-1.64	-0.66	-0.45	-1.39	0.24	2.47	-2.31	-1.22	-0.95	-1.87	-0.36	-0.95
	Kiremt	-0.32	0.59	1.03	-0.05	1.46	3.71	0.07	1.07	1.29	0.12	1.64	1.29
	Bega	-1.28	-0.47	0.08	-1.25	0.54	2.85	-3.28	-2.63	-2.29	-3.09	-1.81	-2.29
DebreTabor	Annual	2.74	3.65	4.00	2.86	4.58	6.85	1.34	2.24	2.49	1.54	3.00	5.27
	Belg	2.49	3.47	3.69	2.66	4.46	6.70	1.20	2.29	2.55	1.62	3.15	5.33
	Kiremt	3.17	4.11	4.41	3.38	4.93	7.10	2.11	3.12	3.22	2.12	3.70	6.45
	Bega	2.55	3.37	3.90	2.53	4.37	6.76	0.70	1.31	1.70	0.88	2.15	4.04
Maichew	Annual	1.06	1.92	2.28	1.06	1.92	2.28	-1.95	-0.74	-0.80	-1.95	-0.74	-0.80
	Belg	0.76	1.55	1.87	0.76	1.55	1.87	-1.21	-0.05	0.12	-1.21	-0.05	0.12
	Kiremt	0.53	1.40	1.80	0.53	1.40	1.80	-2.87	-1.84	-1.67	-2.87	-1.84	-1.67
	Bega	1.90	2.80	3.16	1.90	2.80	3.16	-1.78	-0.31	-0.85	-1.78	-0.31	-0.85
Mekele	Annual	0.30	1.58	1.58	0.44	2.11	4.47	1.05	2.00	2.21	1.21	2.66	4.98
	Belg	-0.74	0.41	0.41	-0.65	1.07	3.35	1.03	2.04	2.28	1.38	2.85	4.96
	Kiremt	1.41	2.79	2.79	1.65	3.35	5.71	1.91	3.01	3.15	1.91	3.50	6.41
	Bega	0.23	1.54	1.54	0.33	1.92	4.35	0.21	0.95	1.20	0.34	1.62	3.57

Appendix E3: Comparison of mean annual precipitation on selected stations of Tekeze basin under RCP 4.5 and RCP8.5 scenarios for 2020`s,2050`s and 2080`s as compared to the base period 1975-2005.



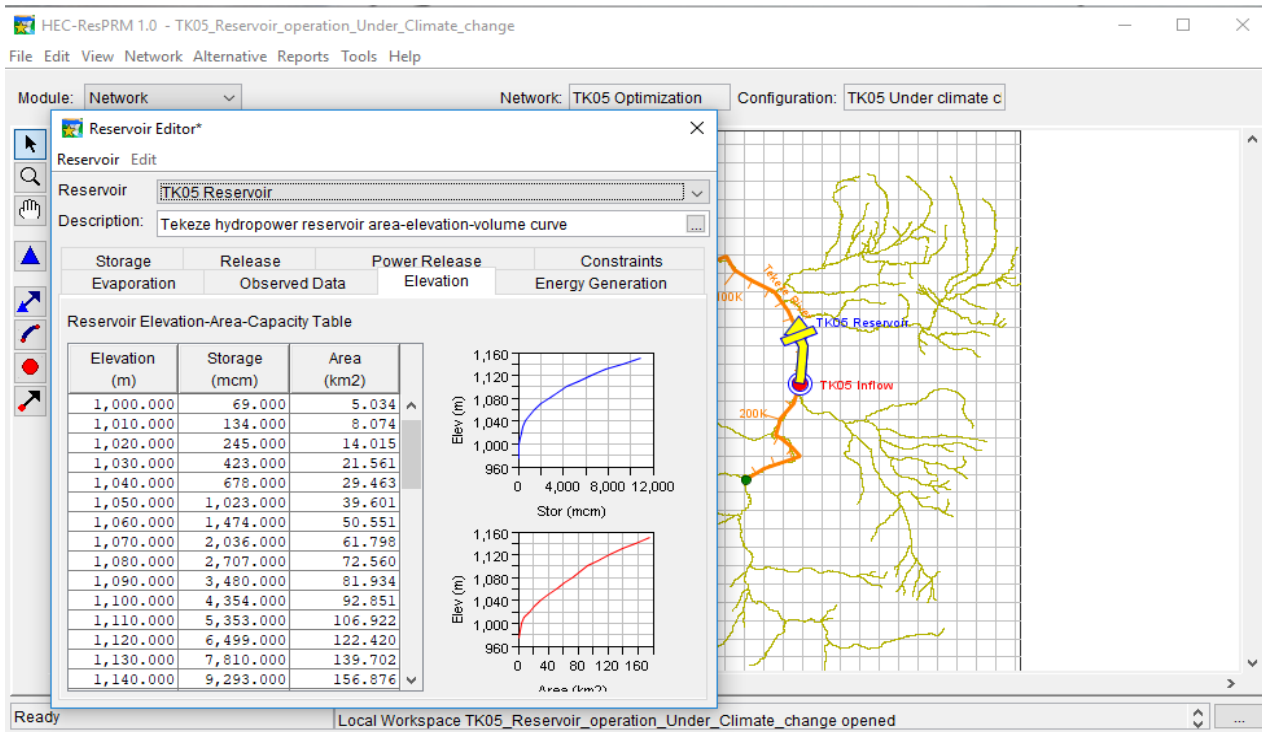
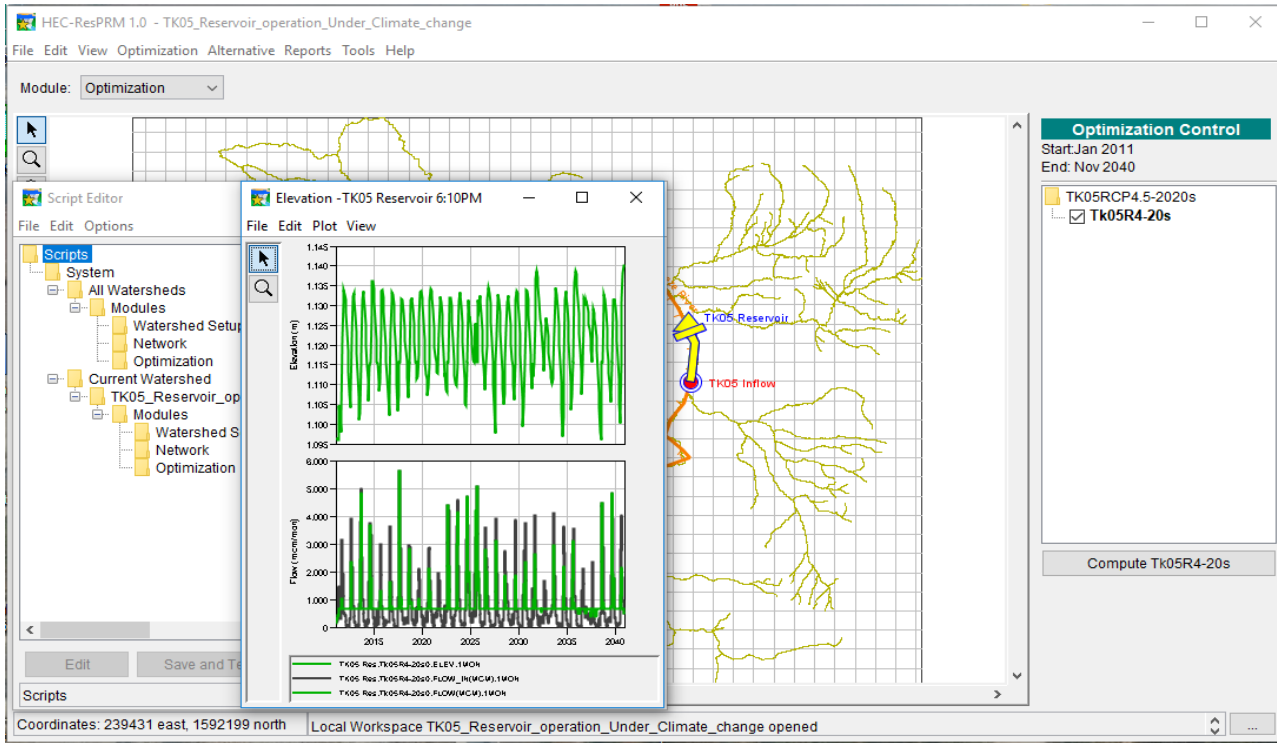
Appendix E4: Comparison of mean annual maximum and minimum temperature at selected stations of Tekeze basin under RCP 4.5 and RCP8.5 for 2020`s,2050`s and 2080`s as compared to the base period 1975-2005.



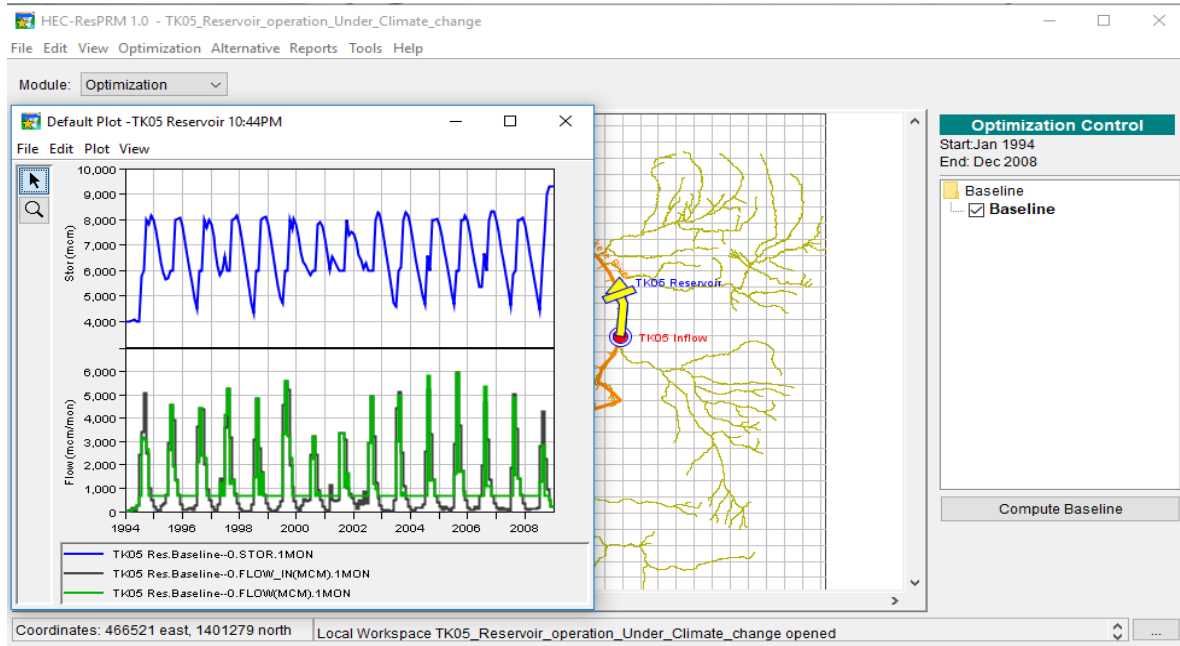


## Appendix F: HEC-ResPRM Analysis Results

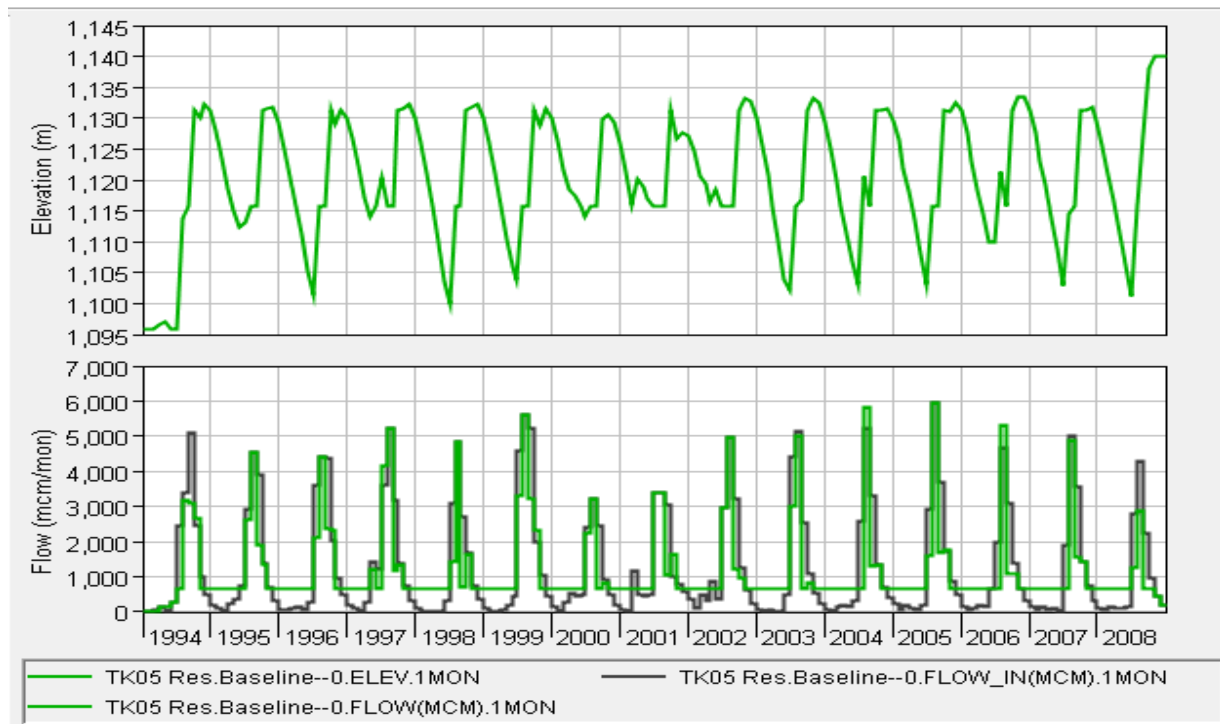
### Appendix F1: HEC-ResPRM configuration map at optimization and network modules



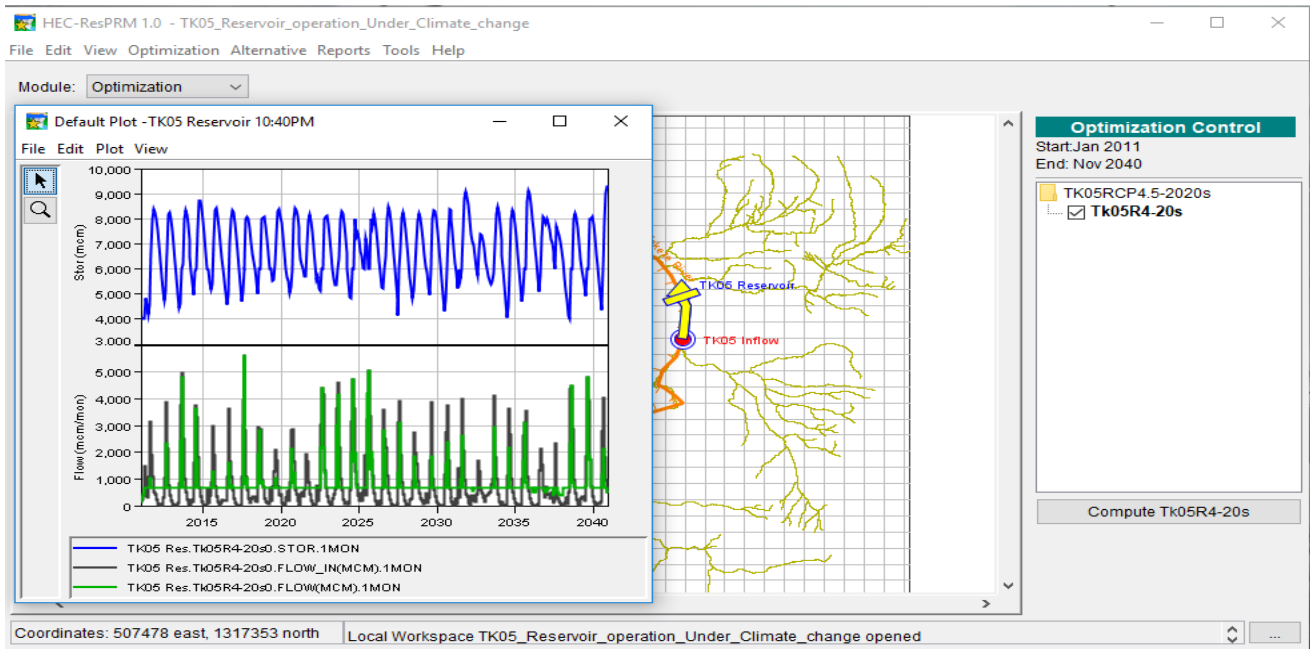
## Appendix F2: Monthly optimized storage and release at Tekeze hydropower reservoir at baseline period



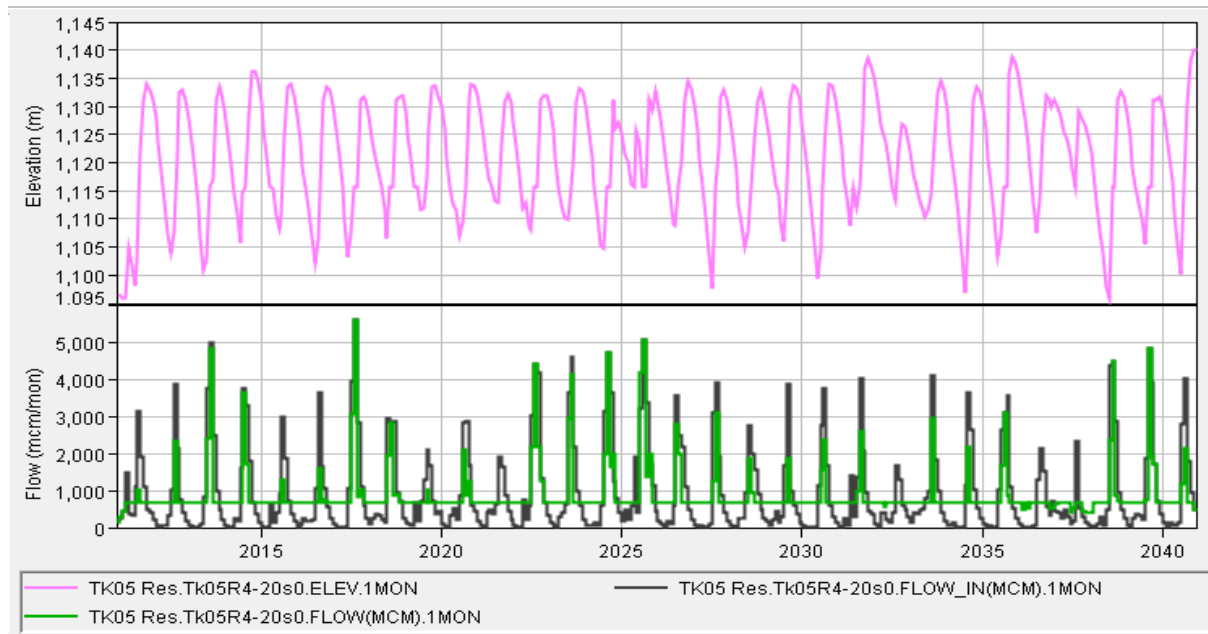
## Appendix F3: Reservoir pool level and release at Tekeze hydropower reservoir at baseline period



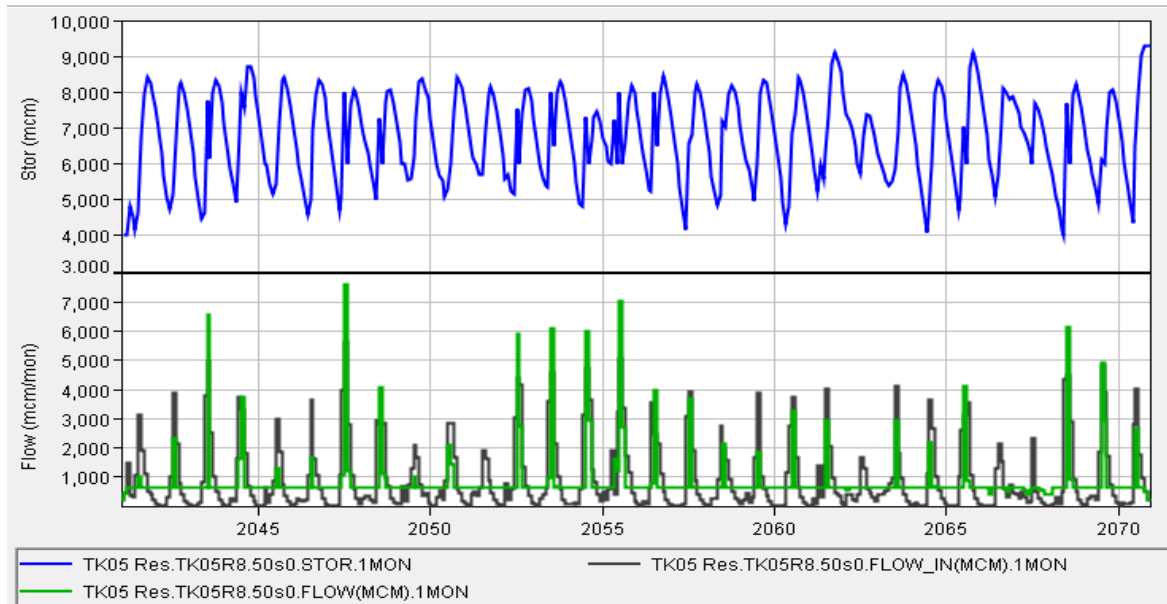
Appendix F4: Optimized storage versus release at Tekeze hydropower reservoir under RCP4.5 in 2020s



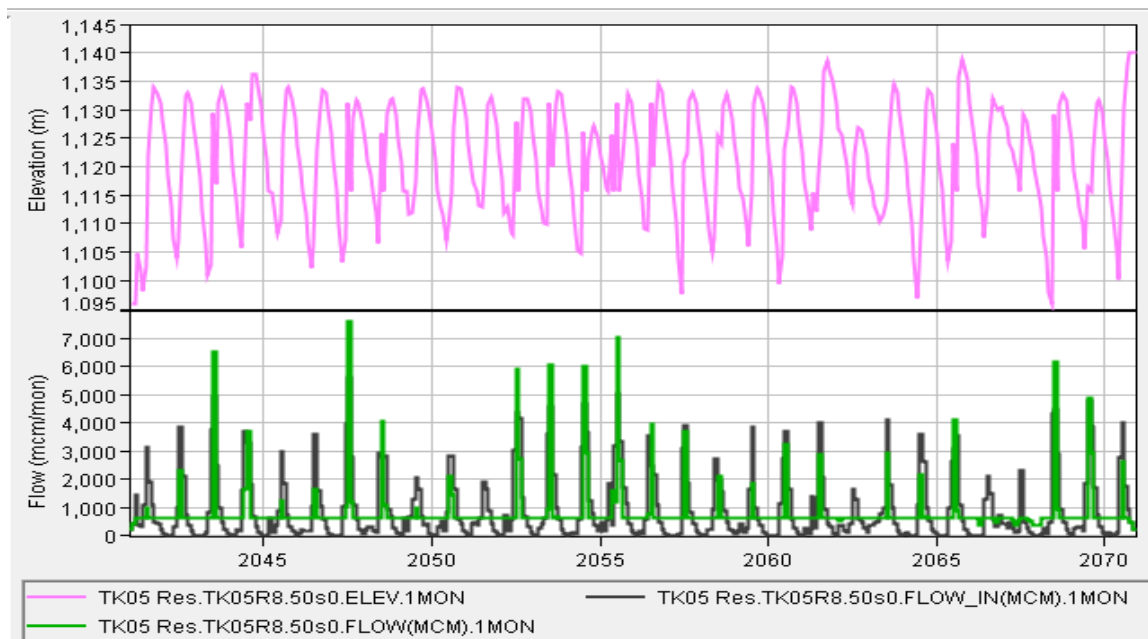
Appendix F5: Optimized pool level versus release at Tekeze hydropower reservoir under RCP4.5 in 2020s



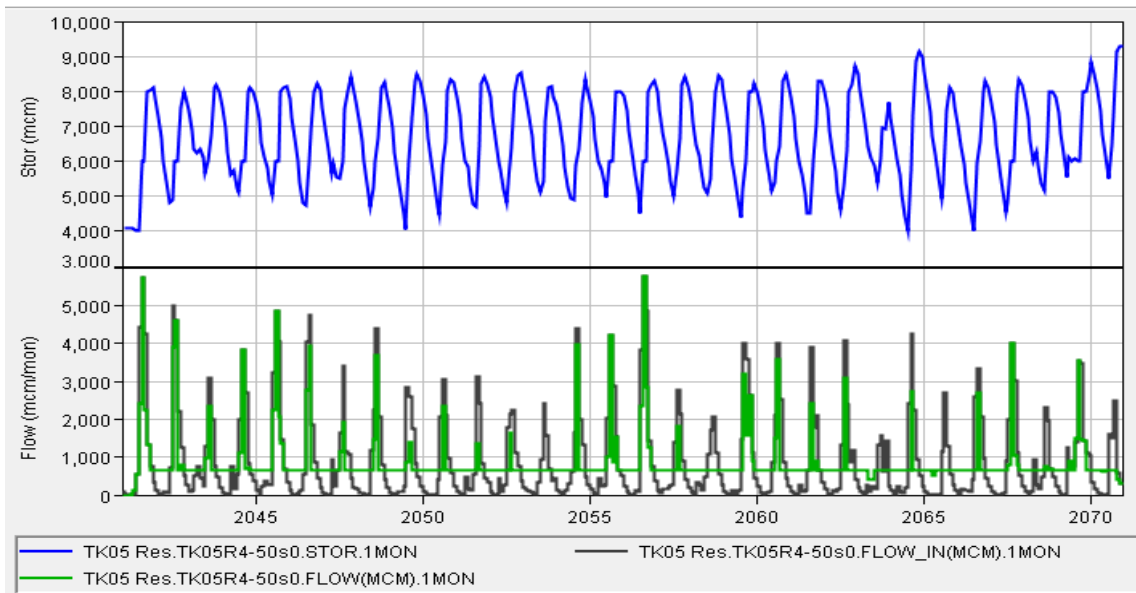
Appendix F6: Optimized storage versus release at Tekeze hydropower reservoir under RCP8.5 in 2050s



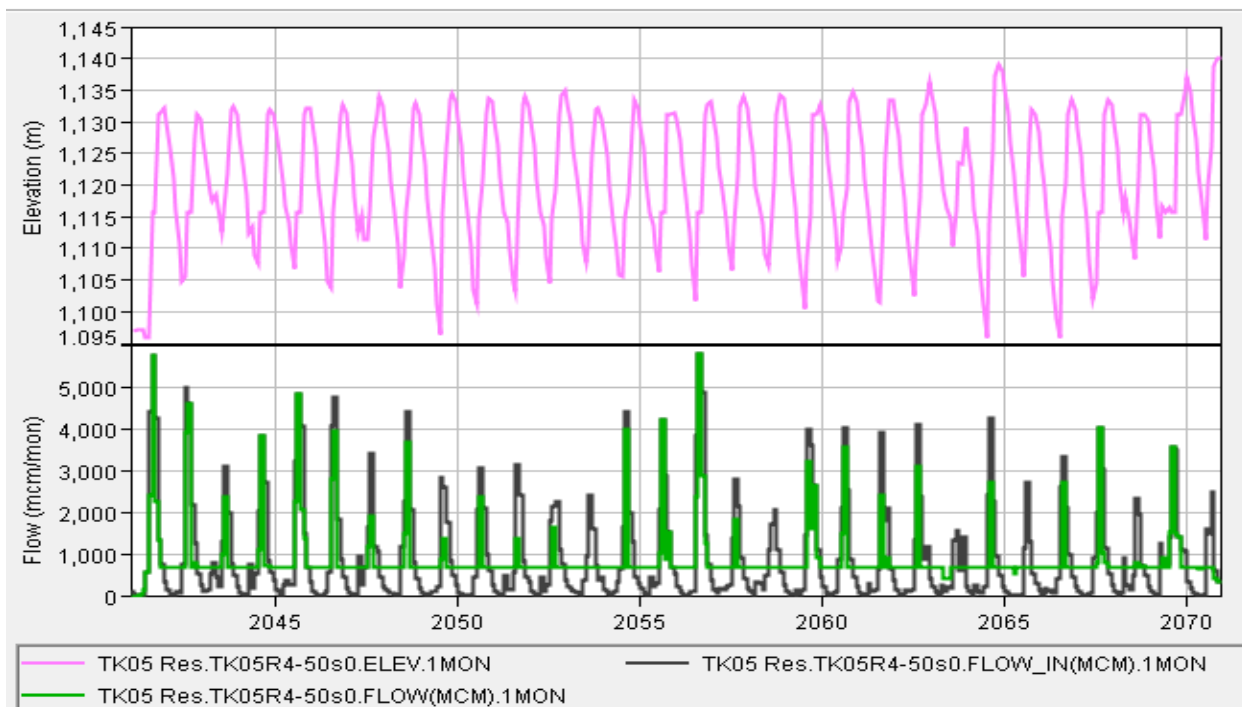
Appendix F7: Optimized pool level versus release at Tekeze hydropower reservoir under RCP8.5 in 2050s



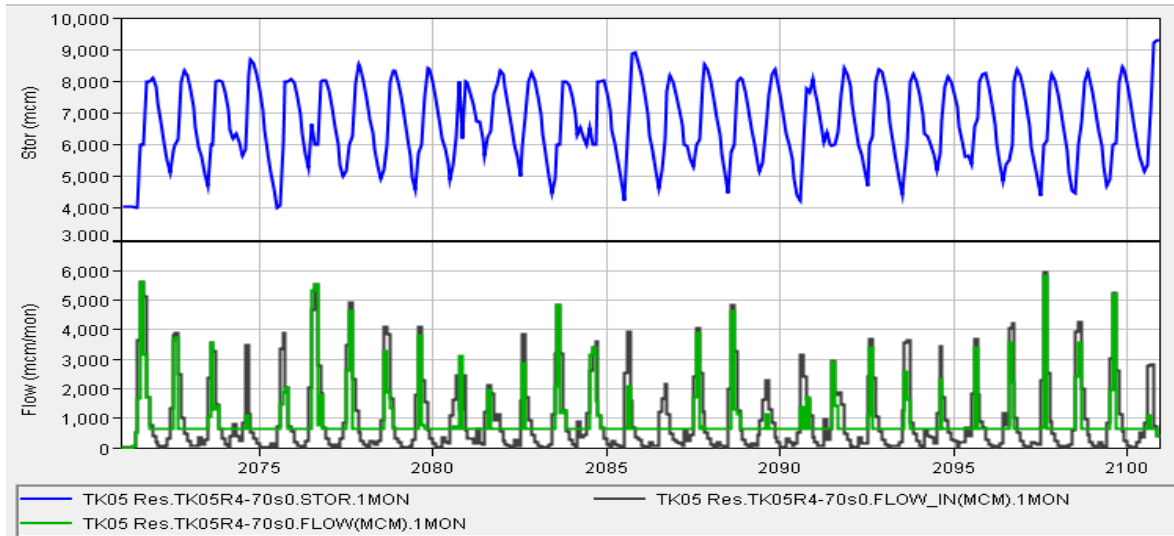
Appendix F8: Optimized storage versus release at Tekeze hydropower reservoir under RCP4.5 in 2050s



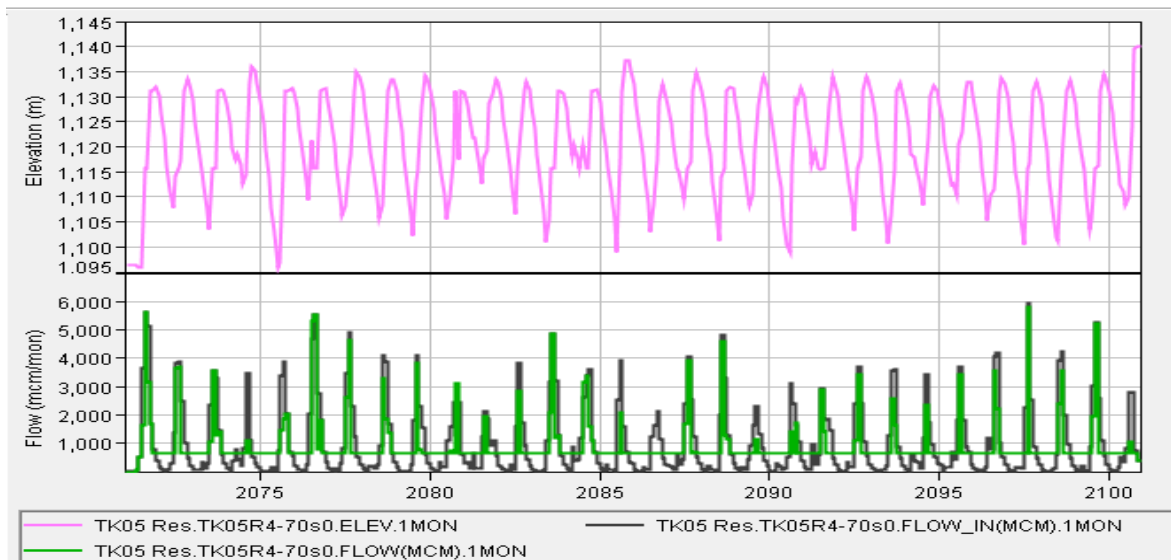
Appendix F9: Optimized pool level versus release at Tekeze hydropower reservoir under RCP4.5 in 2050s



Appendix F10: Optimized storage versus release at Tekeze hydropower reservoir under RCP4.5 in 2080s



Appendix F11: Optimized pool level versus release at Tekeze hydropower reservoir under RCP4.5 in 2080s



Appendix F12: Optimized Tekeze hydropower reservoir (TK05) pool level (m.a.s.l) using HEC-ResPRM optimization model under climate change a) RCP4.5 climate scenario b) RCP8.5 climate scenario

a) RCP4.5 climate scenario (2050s)												
Year/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2041	1096.60	1095.90	1095.90	1104.60	1101.80	1098.10	1102.60	1121.70	1131.00	1134.00	1132.90	1131.30
2042	1128.10	1123.60	1118.50	1113.10	1107.40	1104.00	1107.60	1121.30	1132.30	1133.00	1131.30	1127.80
2043	1123.20	1118.00	1112.50	1106.60	1101.10	1102.80	1115.60	1117.10	1131.30	1133.60	1132.50	1129.40
2044	1124.90	1120.00	1114.40	1110.80	1105.90	1114.80	1115.60	1128.20	1136.10	1136.20	1134.20	1130.70
2045	1126.10	1121.10	1115.60	1115.40	1110.70	1108.20	1110.50	1124.70	1133.50	1134.00	1131.90	1128.40
2046	1123.70	1119.30	1115.60	1111.60	1106.90	1102.30	1106.50	1124.00	1131.30	1133.50	1132.90	1130.20
2047	1125.90	1121.20	1115.60	1109.90	1103.30	1107.30	1115.60	1115.60	1131.30	1131.70	1131.30	1128.40
2048	1124.10	1120.90	1118.40	1115.60	1111.60	1106.50	1115.60	1115.60	1131.30	1131.60	1131.90	1129.10
2049	1125.10	1120.80	1115.60	1115.60	1111.50	1112.00	1117.50	1126.00	1133.30	1133.70	1131.80	1130.20
2050	1126.00	1121.10	1115.60	1112.60	1111.60	1107.20	1109.30	1115.60	1131.30	1134.10	1133.60	1132.20
2051	1128.70	1124.10	1119.20	1117.10	1115.60	1113.10	1112.90	1123.40	1130.80	1132.30	1130.80	1127.40
2052	1122.80	1117.60	1111.90	1112.90	1108.70	1108.00	1115.60	1115.60	1131.30	1131.80	1132.00	1129.80
2053	1125.80	1121.10	1115.60	1112.30	1110.20	1109.90	1115.60	1119.60	1131.00	1133.30	1132.80	1129.90
2054	1125.40	1120.80	1115.60	1111.10	1105.30	1104.80	1115.60	1115.60	1131.30	1126.10	1127.20	1125.20
2055	1121.50	1120.10	1116.20	1115.60	1125.60	1123.60	1115.60	1115.60	1131.30	1129.40	1132.60	1131.30
2056	1127.90	1123.50	1118.40	1114.30	1109.10	1108.70	1115.60	1120.00	1131.30	1134.40	1133.20	1130.20
2057	1125.70	1120.90	1115.60	1110.20	1103.80	1097.80	1115.60	1122.30	1131.60	1132.90	1131.30	1127.90
2058	1123.30	1118.20	1112.80	1109.00	1104.90	1107.70	1115.60	1124.20	1130.90	1132.60	1131.40	1128.40
2059	1124.80	1120.30	1116.20	1114.40	1109.70	1106.20	1115.60	1131.30	1133.60	1133.20	1131.10	1127.40
2060	1122.80	1117.70	1112.00	1105.70	1099.40	1104.50	1115.60	1126.70	1133.90	1133.60	1131.30	1127.40
2061	1122.60	1117.40	1114.00	1108.80	1115.30	1112.10	1115.60	1126.90	1136.70	1138.60	1137.10	1135.00
2062	1131.30	1126.60	1124.60	1123.50	1119.90	1115.50	1113.40	1122.00	1126.80	1126.30	1124.80	1122.10
2063	1117.90	1115.60	1113.20	1111.60	1110.40	1111.50	1114.20	1123.90	1132.40	1134.50	1132.90	1129.40
2064	1124.70	1120.20	1115.60	1110.20	1103.70	1096.90	1101.90	1115.70	1131.30	1133.50	1132.60	1129.90
2065	1125.70	1120.90	1115.60	1110.10	1103.50	1107.00	1115.60	1115.60	1135.90	1138.70	1137.90	1135.10
2066	1131.30	1127.80	1122.90	1118.90	1113.20	1107.50	1113.50	1125.40	1131.90	1131.30	1130.00	1131.20
2067	1130.00	1128.20	1125.20	1124.00	1121.20	1118.80	1115.60	1129.00	1127.90	1126.50	1124.50	1121.80
2068	1118.60	1112.90	1107.70	1104.10	1097.80	1095.90	1115.60	1115.60	1131.30	1132.80	1131.60	1128.60
2069	1124.10	1119.10	1115.60	1112.90	1110.10	1105.50	1115.60	1115.60	1131.30	1131.30	1131.70	1129.60
2070	1125.60	1120.90	1116.30	1111.20	1105.30	1100.10	1115.60	1130.50	1138.10	1140.00	1140.00	1134.70

Year/Month	b) RCP8.5 climate scenario (2050s)										
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2041	1097.10	1097.10	1097.10	1095.90	1095.90	1115.60	1115.60	1131.30	1131.40	1132.10	1129.90
2042	1121.10	1115.60	1110.60	1104.80	1105.60	1115.60	1115.60	1127.90	1131.30	1130.30	1127.30
2043	1118.80	1117.60	1118.60	1116.60	1112.80	1115.60	1121.90	1131.90	1132.60	1131.30	1127.90
2044	1118.10	1112.40	1113.30	1108.80	1107.50	1115.60	1115.60	1131.30	1132.00	1131.30	1129.20
2045	1120.40	1116.70	1114.10	1110.70	1106.80	1115.60	1115.60	1131.30	1132.10	1132.30	1130.00
2046	1121.10	1115.60	1110.20	1104.80	1103.80	1115.60	1122.40	1131.30	1132.80	1131.40	1128.00
2047	1118.20	1112.50	1115.10	1111.50	1111.50	1115.60	1127.60	1131.30	1134.00	1132.50	1129.30
2048	1120.70	1115.60	1110.10	1103.60	1108.80	1115.60	1121.60	1132.10	1133.00	1131.30	1127.80
2049	1118.10	1112.40	1107.00	1101.30	1096.50	1115.60	1125.50	1133.40	1134.50	1133.20	1130.40
2050	1121.20	1115.60	1110.00	1103.50	1101.10	1114.60	1120.70	1131.40	1133.60	1133.10	1130.30
2051	1121.20	1115.60	1114.20	1109.80	1104.40	1103.30	1119.70	1132.80	1134.10	1132.50	1130.20
2052	1121.10	1115.60	1113.60	1108.60	1104.50	1115.00	1119.30	1131.30	1134.30	1134.90	1132.90
2053	1125.80	1121.60	1116.40	1110.80	1107.80	1110.60	1125.10	1131.90	1132.20	1130.30	1128.60
2054	1119.80	1114.20	1109.30	1105.80	1105.50	1114.70	1118.60	1128.90	1133.40	1132.10	1129.50
2055	1121.00	1115.60	1113.80	1110.00	1106.20	1115.60	1115.60	1131.30	1131.30	1131.30	1130.40
2056	1123.00	1117.90	1112.40	1107.30	1101.70	1115.60	1115.60	1131.30	1132.60	1133.20	1131.30
2057	1122.80	1118.90	1114.40	1110.50	1106.60	1113.30	1121.50	1132.40	1134.00	1132.30	1129.00
2058	1119.80	1117.10	1113.80	1109.00	1107.20	1111.40	1120.60	1131.30	1134.30	1133.60	1130.90
2059	1121.70	1116.40	1111.80	1105.80	1100.60	1108.60	1115.60	1131.30	1131.30	1132.70	1131.30
2060	1123.60	1118.50	1113.20	1108.10	1110.20	1115.60	1119.40	1133.30	1134.60	1133.20	1130.30
2061	1121.10	1115.60	1112.40	1107.00	1101.70	1101.50	1115.60	1124.70	1133.40	1133.40	1131.30
2062	1122.80	1117.60	1112.90	1107.70	1102.60	1109.30	1118.20	1131.30	1132.60	1136.20	1134.50
2063	1127.20	1122.40	1119.20	1116.30	1114.70	1110.40	1116.20	1123.60	1123.30	1129.10	1125.80
2064	1116.20	1112.50	1107.10	1101.00	1095.90	1113.50	1126.00	1137.20	1139.10	1138.00	1135.10
2065	1126.60	1121.60	1117.40	1111.60	1105.70	1110.50	1127.30	1131.90	1131.10	1128.30	1124.20
2066	1115.10	1110.30	1105.00	1099.00	1095.90	1115.20	1120.60	1131.30	1133.40	1131.90	1128.90
2067	1119.80	1114.10	1108.20	1102.10	1104.50	1115.60	1115.60	1131.30	1133.50	1132.60	1129.80
2068	1120.60	1115.60	1118.00	1114.60	1110.10	1108.20	1121.60	1131.30	1131.30	1130.10	1126.80
2069	1117.30	1111.70	1116.70	1115.60	1116.50	1115.60	1115.60	1131.30	1131.30	1134.40	1136.90
2070	1127.00	1122.10	1117.00	1111.40	1119.80	1126.10	1138.80	1140.00	1140.00	1137.20	1137.05

Appendix F13: Mean monthly reservoir power storage for future time periods (rule curve) under: (a) RCP4.5 climate scenario; and (b) RCP8.5 climate scenario.

