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Optimal Operation of Cascade Reservoir Systems under Climate Change: Case Study of Tekeze Hydropower Reservoir in the Tributary of the Blue Nile River

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ABSTRACT

Planning and optimal operation of reservoirs under the paradigm of climate change is one of the most momentous problems in the planning and management of water resources due to the rapid growth of economy and population. In this study, Soil and Water Assessment Tool (SWAT) and reservoir operation optimization (HEC-ResPRM) models have been employed in the three cascade hydropower reservoirs in Tekeze basin, Ethiopia to investigate the impact of planned cascade reservoirs' operation on the existing reservoir on the face of climate change. Results showed that an increase in rainfall and temperature in the future will be critical to future inflow in cascade hydropower reservoirs, with rainfall variability having a greater impact than temperature variability. HEC-ResPRM was prepared to reproduce optimum hydropower reservoir storage and water levels on the joint cascade operation of Tekeze reservoirs in each mode under climate change effect. Joint optimum operation of cascade reservoirs in different operation modes under climate change in both RCP4.5 and RCP8.5 climate scenarios affects existing reservoir operation in the future. Therefore, it is better to improve existing reservoir operation before investing into new planned cascade reservoirs and incorporate climate change scenarios in the planning, design, and operation of new reservoirs in Tekeze Basin. The results of this study can help the water resources planners and managers to plan and manage the future water resources of Ethiopian Rivers.

Keywords: Cascade reservoirs operation; HEC-ResPRM; SWAT; Climate change; Tekeze basin

INTRODUCTION

Reservoir planning and operation are some of the most complex problems for integrated water resource development and management that face difficult challenges. These are mainly due to growing water demand from increasingly populated and complex societies which requires a shift towards an integrated approach; and climate change which from a hydrological point of view makes the assumption of stationarity in long term weather conditions not valid any more [1]; and needs to follow new approaches, strategies, and tools. Reservoir planning and operation are vital to meet society's energy and water requirements by using our water resources more efficiently [2]. In this regard, reservoirs are one of the most crucial efficient infrastructure components for integrating water resources development and management [3]–[5].

Recent studies showed that efficient operation of water reservoir systems in a watershed having a cascade rolling pattern is a new and challenging active research area [6]. Most previous studies about the cascade reservoirs combined operation were limited to the reasonable allocation of water quantity [7]–[12].Nowadays, many studies around the world were carried out to identify the hydropower potential and to promote hydropower projects in large scale and small scale basins [13]. Ethiopia is fortunate to be blessed with an abundance of highlands watershed through steep and narrow river valleys which are considered as the water tower of East Africa with an estimated hydropower potential of 45,000 MW (160,000 GWh/year) with 299 potential sites in the 12 basins which has vast unexploited hydropower potential. There will be major cascade hydropower developments in the future in some major Ethiopian River Basins such as

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Abay(78,800GWh/yr), Tekeze (5,960GWh/yr), Omo-Gibe (35,000GWh/yr), Wabi-Shebelle (5,400GWh/yr), Genale-Dawa (9,300GWh/yr), Baro-Akobo (18,900GWh/yr) and Awash (4,500GWh/yr) [14], [15]. However, the present hydropower production is exposed to streamflow variations due to climate variability in the region [16].

Overall, several studies showed that the timing of streamflow and the overall magnitude of rainfall and streamflow expected to change due to climate variability and change [17], [18]which affects the overall hydropower reservoir planning and operation because hydropower is directly dependent on the magnitude and timing of streamflow [19]. In Ethiopia, most hydropower reservoir projects were planned, designed, and operated based on past climate history and the assumption that future hydrological patterns will follow historic patterns. Though, the concept of future hydrological conditions will remain unchanged and thereby predictable for the design and operation of hydropower reservoir schemes is no longer valid. Hydropower stations based on the past century's records of flow are unlikely to deliver the expected services over their lifetime under climate change scenarios. Therefore, it is better to incorporate climate change impacts in all aspects of water resources management during the planning, design, and operation of water resources projects [20]. Several researchers in the Eastern Nile tried to investigate climate change impacts on water resources by the trend analysis of historical data[18], [21]–[25]and future climate projections using a combination of hydrologic models and climate change scenarios[21], [26]–[30]. Specifically, climate change effects on the water resources of Tekeze have been discussed by Fentaw et al. [28]. They agree that climate change will contribute to the uncertainty in water resources planning and management in the basin. A recent study by Gizaw et al. [31] has also characterized the sensitivity of water resources to climate change in the different watersheds of the Ethiopian river basin including the Tekeze basin. On the other hand, very few studies were conducted in the applications describing the impact of climate change on reservoir operation in the Blue Nile.Abera et al.[16]investigated the operation of the Tekeze hydropower reservoir located at Eastern Nile under climate change conditions. They conclude that an increase in streamflow is the expected impact of climate change on water balance in the catchment area and eventually it will increase the water storage amount in the reservoir. So a typical method of evaluating effects of climate change and the future non-stationarity of hydrological regimes require the use of an ensemble of GCMs, climate scenarios, and regional climate models to provide inputs to a hydrological model [32]which is used for water resources system optimization [16], [33], [34]. Translating the impacts of climate change affected runoff on hydropower reservoir planning and operation requires coupling of hydrological models, and reservoir operation methods.

Numerous researchers have been developed, applied and reviewed time to time reservoir operation techniques for planning studies to formulate and evaluate alternative plans for solving water resources management problems; for feasibility studies of proposed construction of water resources projects as well as for re-operation of existing reservoir systems[8], [12], [35]. However, no general algorithm covers all types of reservoir operation problems. The choice for water resources reservoir operation problems usually depends on the availability of data, reservoir specific system characteristics, the objectives specified and the constraints imposed. Various optimization methods based on linear programming, non-linear programming, dynamic programming, genetic algorithm, artificial neural networks, particle swarm optimization, simulation, etc., has been used as a solution tool for water resource system planning and management are very common in the academic literature [5], [8], [36]. Optimization methods have been proven of much importance when used with simulation modeling and the combinations of simulation and optimization models give the best results[10], [16], [37].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 [38].Water resources reservoir operation problems expressed in standard mathematical programming forms based on optimization models and optimization algorithm solves them. Operation decisions are then determined as outputs of optimization models[8], [39].Even if various reservoir operation models and methods have been proposed and reviewed by many authors but it is difficult to find a single model or technique to solve the operation of a cascade multi-reservoir system [8].Indeed, for cascade reservoir systems, there is no alternative optimization methodology presently available which would not require similar or more significant assumptions of the HEC-ResPRM combination of simulation and optimization reservoir operation model and well-tested technology [40].

The purpose of this paper was to investigate the effect of new planned cascade hydropower reservoirs operation on the existing operational one in the face of climate change and develop joint operation models based on the objective function of maximizing existing hydropower reservoir storage and pool level.

Method and Material

To Study Area Description

The area of focus for this study is the three cascade hydropower reservoirs of Tekeze Basin, located at the most north-eastern portion of the Eastern Nile. Tekeze basin has a large elevation drop of the Semein Mountains offers significant potential sites with technical energy potential of 5,960GWh/year for cascade hydropower development which has the same geographical and climatic zone[16]. The three cascade hydropower reservoirs (Fig.1, Table 1) considered in this study found upstream of Embamadre streamflow gauged station with a catchment area of up to 43,000 km² and annual discharge of 4.4 billion m³/year[28]. Currently, Tekeze hydropower reservoir or TK05 (completed in 2009; 300 MW), the 2nd tallest arch dam in Africa is in operation for hydropower production. There are also two planned reservoir dams upstream and downstream of this existing hydropower reservoir. These TK07 (in planning; 321 MW) and TK04(in planning; 133 MW) reservoirs are in the planning stage located most downstream and upstream one, respectively. The characteristics of the three cascade hydropower reservoirs show in Table 1.

The climate of the basin in the North and East part is described as semi-arid, and partly humid in the South. Based on the data obtained from Ethiopian National Meteorological Service Agency (NMSA), the study region has an annual average rainfall of about 600mm in the lowlands and 1300mm in the Semein Mountains, where more than 70% of rainfall falls in the summer (*Kiremt*) season from July to August. The mean monthly minimum and maximum temperature may vary up to 3-21ºC and 19-43 ºC in the highland and lowland areas, respectively. Tekeze basin river flow pattern normally follows that of rainfall. The mean annual flow was 190m^3/s at Embamadre gauging station from 1994-2008 record periods.

The Study Framework

This research developed a framework for assessing the impact of planned cascade reservoirs on the operational one considering projected climate scenarios. This was accomplished based on the following some methodological frameworks shown in Fig. 2: (i) preparation of climate and spatial data into SWAT format; (ii) SWAT model setup including watershed delineation and hydrologic response units (HRUs) definition; (iii) Model calibration and validation; (iv) RCP climate scenarios data preparation (rainfall and temperature); (v) application to hydrological models for the assessment of the response of river's hydrologic system to change in RCP climate scenarios variables and (v) application to reservoir operation model in different modes of the cascade reservoirs.

Data Sources

The data required to cascade reservoir operations in this study are data to set up, calibrate and validate the hydrological model and data to parametrize the reservoir module with the three Tekeze cascade rservoirs characteristics.

Hydro-Climatic and Spatial Data

Hydro-climatic data from 1994 to 2008 for all stations showed in Fig.1 and 3acquired from the Ethiopian Ministry of Water, Irrigation and Electricity, and NMSA. Only the data from one hydrological station at Embamadre were available for calibration and validation of the SWAT model, which is located at downstream of the three cascade reservoirs. Both the temperature and precipitation data which have a long period of records with small data gaps were collected from the 21 stations located within and near Tekeze basin. All the climatic and hydrological data are available on the monthly and daily time scales. The three steps visual inspection, comparison to the nearest station with in the same zone and regression relations between neighboring stations were taken to detect outliers and fill in the missing gaps in these data series. Besides hydro-climatic data, data of topography (Digital Elevation Model) to delineate the watershed and generate the drainage pattern and associated physiographic attributes, soil and land use/land cover data are the main inputs for the SWAT model taken from the Ethiopian Ministry of Water, Irrigation and Electricity.

Future Climate data

This study uses future projections of precipitation and temperature (minimum and maximum) data from the newly available Coupled Model Inter comparison Project Phase 5 (CMIP5 model)[41], [42]used for impact and adaptation studies[43]–[46] which was obtained from Regional Climate Models (RCMs) ensemble outputs of Coordinated Regional Climate Downscaling Experiment on African domain (CORDEX-Africa) under two representative concentration pathways (RCP) climate scenarios (RCP4.5and RCP8.5).

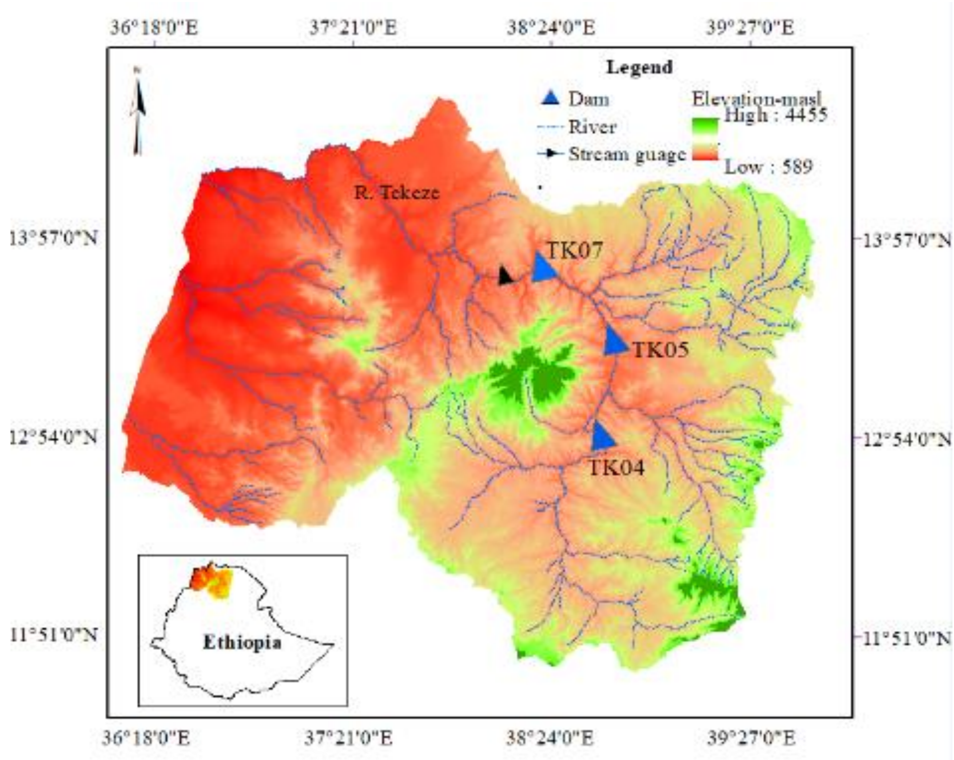

Fig. 1: Sketch of Tekeze river basin showing tributaries and positions of stream gauge and cascade hydropower reservoirs

Table 1: List of characteristic parameter values of Tekeze cascade reservoirs

Item	Unit	TK04	TK05	TK07
Catchment area	Km^2	21,188	29,692	47,723
Dam type		*RCCGD	Arch dam	*CFRD
Dam height	M	122	188	158
Full supply level	M	1275	1140	990
Minimum water level	m	1222	1096	901
Total storage	10^8m^3	38.02	92.93	93.8
Reservoir surface area	Km^2	73.38	147	135.47
Installed capacity	MW	133	300	321
Turbine discharge	m^3/s	105.6	220	160.1
Type of turbine		-	Francis	-
Commission year	Year	-	2009	-

*RCCGD-Roller Compacted Concrete Gravity Dam, *CFRD-Concrete Face Rock Fill Dam

The details of RCP4.5 and RCP8.5 climate scenarios are briefly described in the works of different researchers [42], [47]–[49].Precipitation and temperature data from these scenarios with a spatial resolution of 0.44°from 1951-2005 for baseline (past) used to calibrate and validate with observed data and 2041-2070 for future periods and bias-correction done using distribution mapping to improve on relevant biases which are expected to capture a reasonable range in climatic and hydrological projections in the Tekeze reservoir's watershed [28].

Reservoir Characteristics Data

The three cascade reservoir characteristics data like background map of the watershed, reservoir outlet capacities, elevation-area-storage curve, current outflow energy relationship, and current and future reservoir inflow time series were used for input to HEC-Res PRM model to perform the optimal operation of cascade reservoirs. Table 1 summarizes the reservoir characteristics data for the three cascade reservoirs in the Tekeze basin. The current operational reservoir, Tekeze

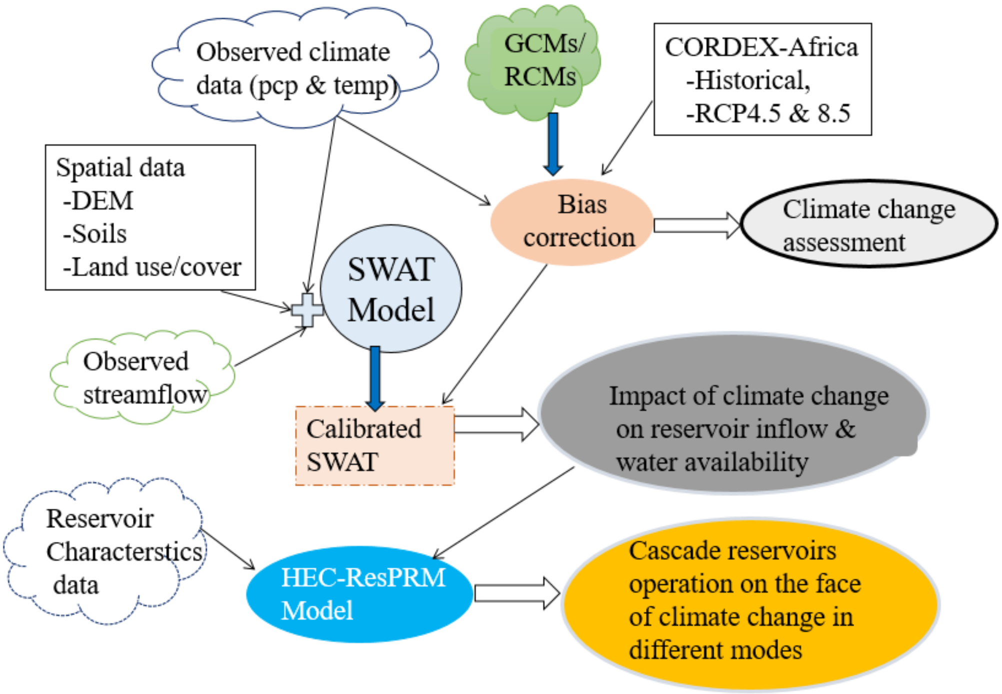

Fig. 2: Framework of the study for the assessment of cascade reservoirs effect on the operational reservoir under climate change

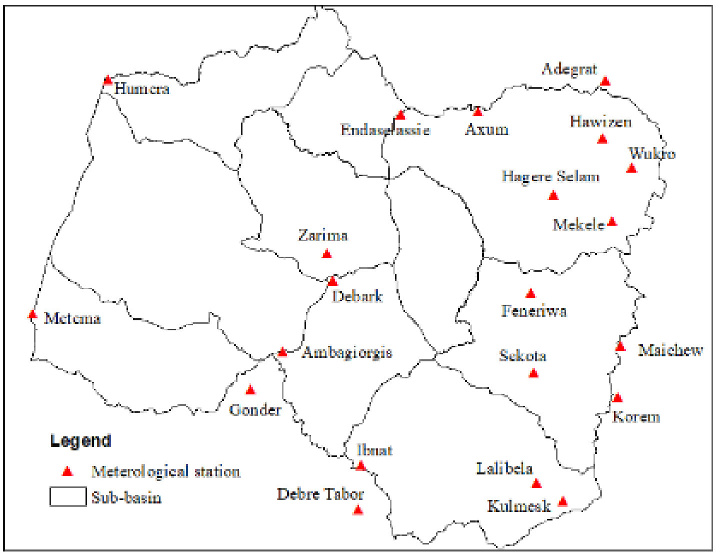

Fig. 3: The Tekeze river basin showing sub-basins and spatial distribution of meteorological stations

hydropower reservoir (TK05) storage, and pool level data from 2009-2017 were used for purpose of comparison. All these reservoirs' characteristics data were collected from Ethiopian Electric Power Corporation, and the Ministry of Water, Irrigation and Electricity.

Hydrological Model

A hydrological model was used to produce inflow projections and to assess climate change impacts on the hydrological regime of Tekeze reservoir watershed. The Soil and Water Assessment Tool (SWAT), one of the more widely used models in the world [50]and in Ethiopia [51], [52]was applied for the simulation of river flow in the Tekeze reservoir watershed. For this study, the 2050s future streamflow generated from the calibrated and validated SWAT model based on bias corrected CORDEX-Africa two RCPs (RCP4.5 & RCP8.5) climate scenarios were used [16], [28]. SWAT is a physically-based, semi-distributed, continuous time, hydrologic model used for long-term hydrological simulations of

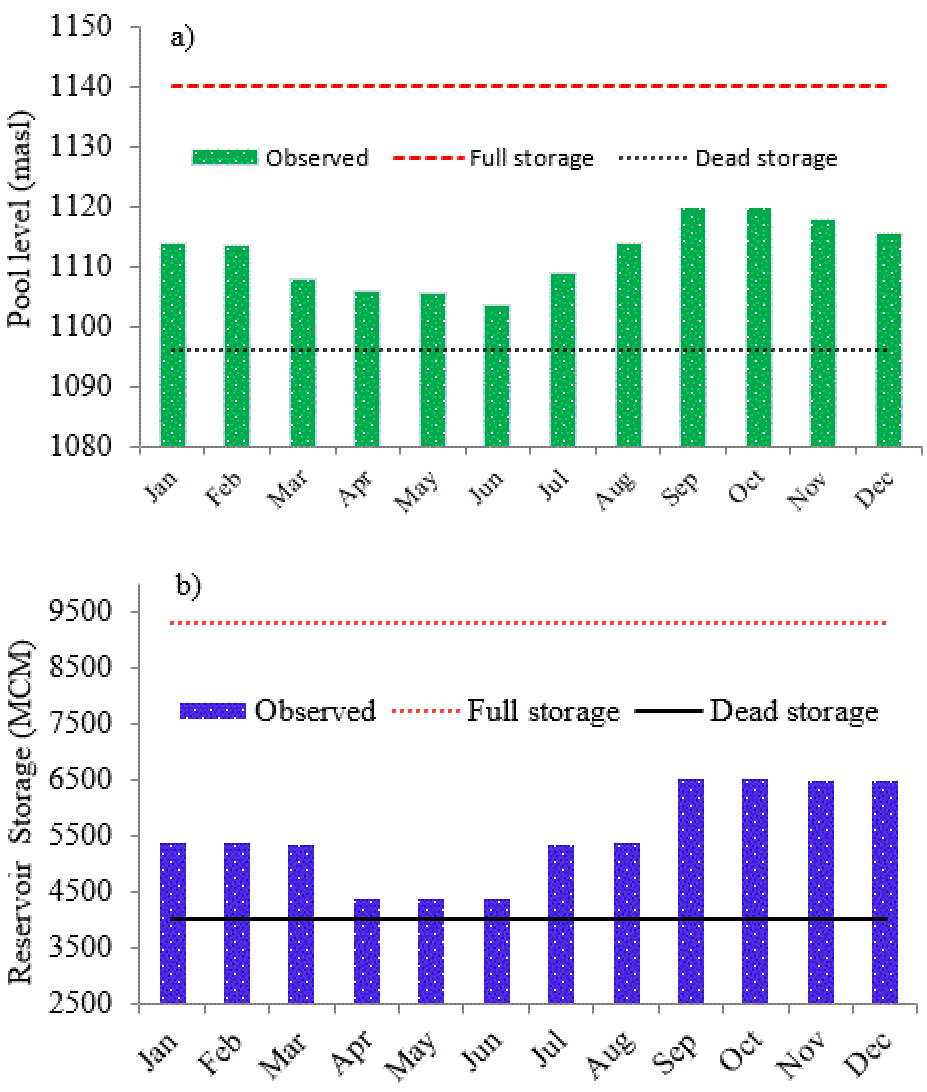

Fig. 4: Tekeze Hydropower reservoir (TK05) mean monthly observed data (2009-2017) (a) reservoir pool level (elevation) and (b) reservoir storage

Table 2: SWAT model calibration and validation period performance

Calibration			Validation		
R^2	E_{NS}	PBIAS	R^2	E_{NS}	PBIAS
0.73	0.71	0.53	0.80	0.79	0.45
Good	Good	Very good	Very good	Very good	Very good

watersheds [53].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. Further details on SWAT operation and the deriving algorithms may be found in [54] and other user manuals. 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 [55]

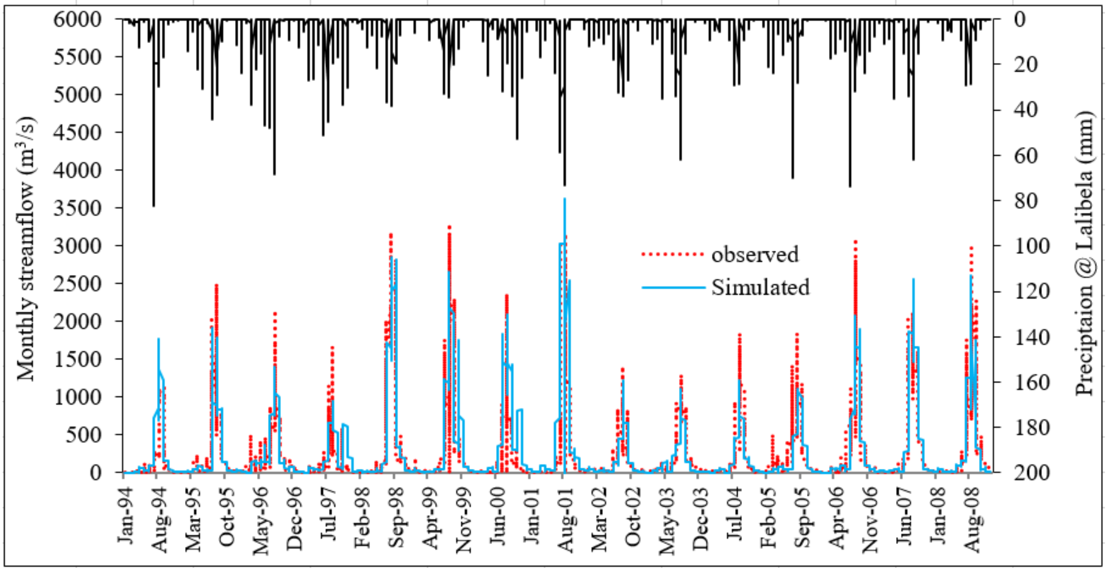

Fig. 5: Plot of precipitation, observed and simulated streamflow data for the calibration (1994-2002) and validation (2003-2008) periods at Embamadre station in a monthly time scale

at each HRU using water balance equation, which contains precipitation, surface runoff, evapo-transpiration, infiltration and subsurface inflow. The water balance equation of the hydrologic cycle is shown in eq. (1):

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

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). For this study, the methods of the Soil Conservation Service (SCS) curve number procedure were used to estimate surface runoff.

SWAT model has been structured for the entire Tekeze basin upstream of Embamadre hydrological station. According to Fentaw et al. [28], Tekeze basin has been apportioned into 23 sub-watersheds, and 277 Hydrological Response Units (HRUs)that integrate unique land use, soil type and slope, which are the basic elements of hydrological calculation. Sensitivity analysis was conducted to identify the most influential hydrological parameters such as CN2, SOL-AWC, ESCO, GW-DELAY, GW-REVAP, SOL-K and GWQMN for streamflow simulation, which were adjusted during calibration. Calibration is the process when observed and generated values are fitted as much as possible, searching for the best optimization of an objective function; R^2, Nash-Sutcliffe efficiency (E_{NS}) and Percentage of bias (PBIAS) for this case [56]. The SWAT model calibrated monthly streamflow data for a period of nine years (1994-2002). After calibration, the model was validated using the monthly discharge data of six years (2003-2008). The R^2 values are 0.73 and 0.80 for calibration and validation periods, respectively, indicating that the simulation exhibits a strong correlation with the observation findings. The E_{NS} values for calibration and validation are 0.71 and 0.79, respectively exhibiting the high credibility of the simulation. The PBIAS values are also within a reasonable range. Then the SWAT model forced to run for historical and future climate scenarios to generate cascade reservoirs inflow of 2050s (2041-2070) for both RCP4.5 and RCP8.5 scenarios. The basic assumption on the use of SWAT for climate change impact assessment is that land cover and soil properties and their hydrological behavior remain unchanged in the future.

HEC-ResPRM Optimization Model

The U.S. Army Corps of Engineer's Reservoir Evaluation System Perspective Reservoir Model (HEC-ResPRM) is a combination of simulation and optimizationmodel developed to assist planners, operators and managers with reservoir operation plan and decision making. 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. It also uses HEC's data storage system (HEC-DSS) to store and retrieve 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. 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).

HEC-ResPRM is monthly network flow programming model which gives optimal values of release and storage by minimizing penalty functions [40], [57]. Network flow programming considered as a computationally efficient form of linear programming, which is well suited for reservoir systems, as a general configuration of a reservoir system can be represented as a capacitated network [10]. The optimization problem is generally to maximize flow or minimize the cost of flow in the network. Optimization problem represented by the network with cost associated with flow as follows:

$$Minimize: \sum_{t}^{n} C_t Q_t \text{ (For all nodes)} \quad (2)$$

$$Subject\ to: \sum Q_t - \sum a_t Q_t = 0 \text{ (For all nodes)} \quad (3)$$

$$L_t \leq Q_t \leq U_t \text{ (For all arcs)} \quad (4)$$

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). Eq. (2-4) is 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.

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 existing hydropower reservoir began to operation. 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 2050s (2041-2070) future RCP4.5 and RCP8.5 climate scenarios data to get optimized Tekeze cascade reservoirs storage and pool level based on different operation modes to investigate the effects of cascade planned hydropower reservoirs on the operational reservoir on the face of climate change.

RESULTS AND DISCUSSIONS

Land Use Land Cover Change Analysis

The Water Resources Response to Climate Change

Tekeze Basin, part of Eastern Nile is still lagging behind most regions of the world in general scientific research including climate change [28]. Scientific researchers such as Fentaw et al. (2018) have discussed the impact of climate change on precipitation and temperature, key climatic derivers of hydrological responses. Their results showed that an increase in rainfall and minimum and maximum temperature in the basin.

Table 3 shows the change in precipitation, maximum and minimum temperature in 2050s for both RCP4.5 and RCP8.5 scenarios that would be critical to future inflow in Tekeze cascade reservoirs, with rainfall variability having a more significant impact than temperature variability. The overall annual increase in precipitation under both RCP4.5 and RCP8.5 climate scenarios will provide more water to Tekeze River.

Seasonal and annual streamflow change

Streamflow projections followed that of precipitation to a great extent with some changes between RCP4.5 and RCP8.5 climate scenarios. For 2050s, both the scenarios produce moderate increases in annual and for both dry and wet seasonal streamflow's except a decrease of streamflow for RCP8.5 climate scenario for the small rainy season over Tekeze reservoirs watershed which is due to projected increase in precipitation.

Table 3: Mean precipitations and temperature variations in the Tekeze Reservoirs watershed

Season/Scenario	Change in Precipitation (%)		Change in Min. Temperature (ºC)		Change in Max. Temperature (ºC)	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Dry-*Bega*	-23.36	5.72	1.71	2.35	0.12	0.60
Wet-*Kiremt*	24.61	31.32	1.95	2.62	1.30	1.81
Small Rainy-*Belg*	-31.48	-25.85	1.01	1.72	1.10	1.70
Annual	32.64	38.58	1.57	2.23	0.80	1.40

Projected annual streamflow may increase up to 39.19% for RCP4.5 and to 10.68% for RCP8.5 climate scenarios (Fig. 6). Due to these future changes of streamflow which is an input for cascade reservoirs planning and operation, climate change scenarios should incorporate into the operation of hydropower dams and reservoirs in Tekeze basin.

Reservoir's inflow:
The estimation of streamflow coming to the reservoir system is the important factor; hence, the estimation of credible flows for the basin is essential. Each cascade reservoirs inflow data for each month for the past period (1994-2017) and future 2041-2070 for both RCP4.5 and RCP8.5 climate scenarios, have been estimated from the calibrated and validated SWAT model of Tekeze reservoir watershed [16], [28].

Impact of Planned Reservoirs on Operational Reservoir under Climate Change

The historical data of Tekeze cascade reservoirs were selected for comparative study with the objective to maximize TK05 reservoir storage reservoir in millions cubic meter (MCM) and water levels in meter above sea level (masl) for 2050s time periods under RCP4.5 and RCP8.5 climate scenarios. The proposed HEC-ResPRM optimization model has been successfully applied to the three cascade reservoirs system of Tekeze watershed and monthly data is used in this study.
For comparative study, four different operation modes were selected and described as listed below:

- Mode I: Optimal operation of only TK05 reservoir (existing hydropower reservoir)
- Mode II: Joint optimal operation of two cascade reservoirs (TK04 & TK05)
- Mode III: Joint optimal operation of two cascade reservoirs (TK05 & TK07)
- Mode IV: Joint optimal operation of three cascade reservoirs (TK04, TK05 & TK07)

Choosing maximum reservoir storage/pool level of existing reservoir as the objective function, the results of monthly reservoir storage and water levels calculated by these four operation modes are discussed. In the future 2050s time periods under RCP4.5 and RCP8.5 climate scenario, the simulated increase in precipitation and streamflow expresses themselves as higher reservoir storage during main rainy (*Kiremt*) and dry (*Bega*) seasons, with a clear shift towards earlier increase in precipitation and reservoir storage during July to November. The addition of upstream reservoirs in Mode II and Mode IV will increase future monthly reservoir storage in the operational Tekeze arch dam hydropower reservoir (TK05) without impacting seasonality.
Tekeze hydropower reservoir system HEC-ResPRM results indicate the operational procedures that are often qualitatively used in TK05 hydropower reservoir different from those used currently. The two most differences are the storage allocation among the two cascade planned reservoirs. Whereas the simulation of current policies shows a linear balancing of storage among each month of the year, HEC-ResPRM results indicate a significantly different, non-linear, storage allocation rule. Comparison of TK05 reservoir pool levels (water levels) estimated using the different operation modes by considering the planned cascade reservoirs impact in the face of climate change are shown in Fig. 7(a) and (b). Mode II and IV have good optimum hydropower reservoir storage; this indicates that it is better to construct the upper (TK04) reservoir first.

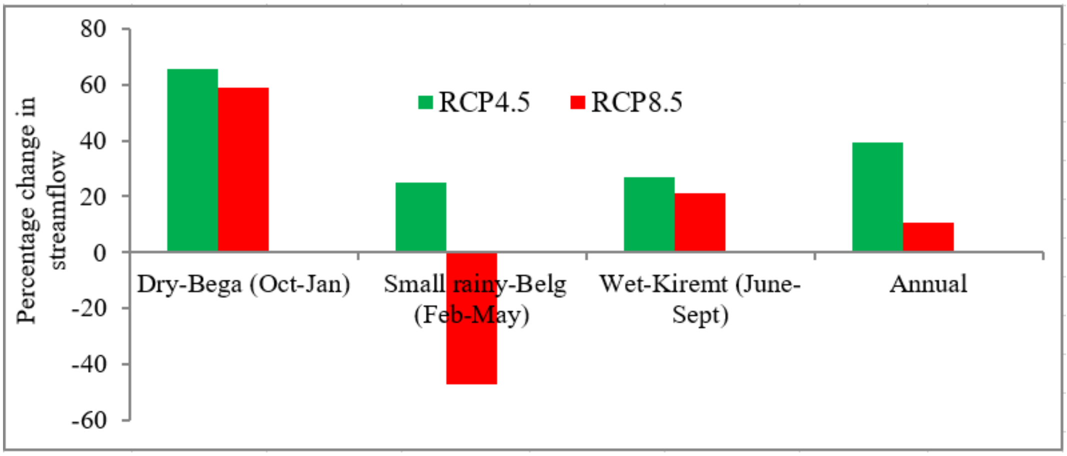

Fig. 6: Seasonal and annual evaluation of streamflow in RCP4.5 and RCP8.5 climate scenarios in the Tekeze Reservoir watershed (2041-2070)

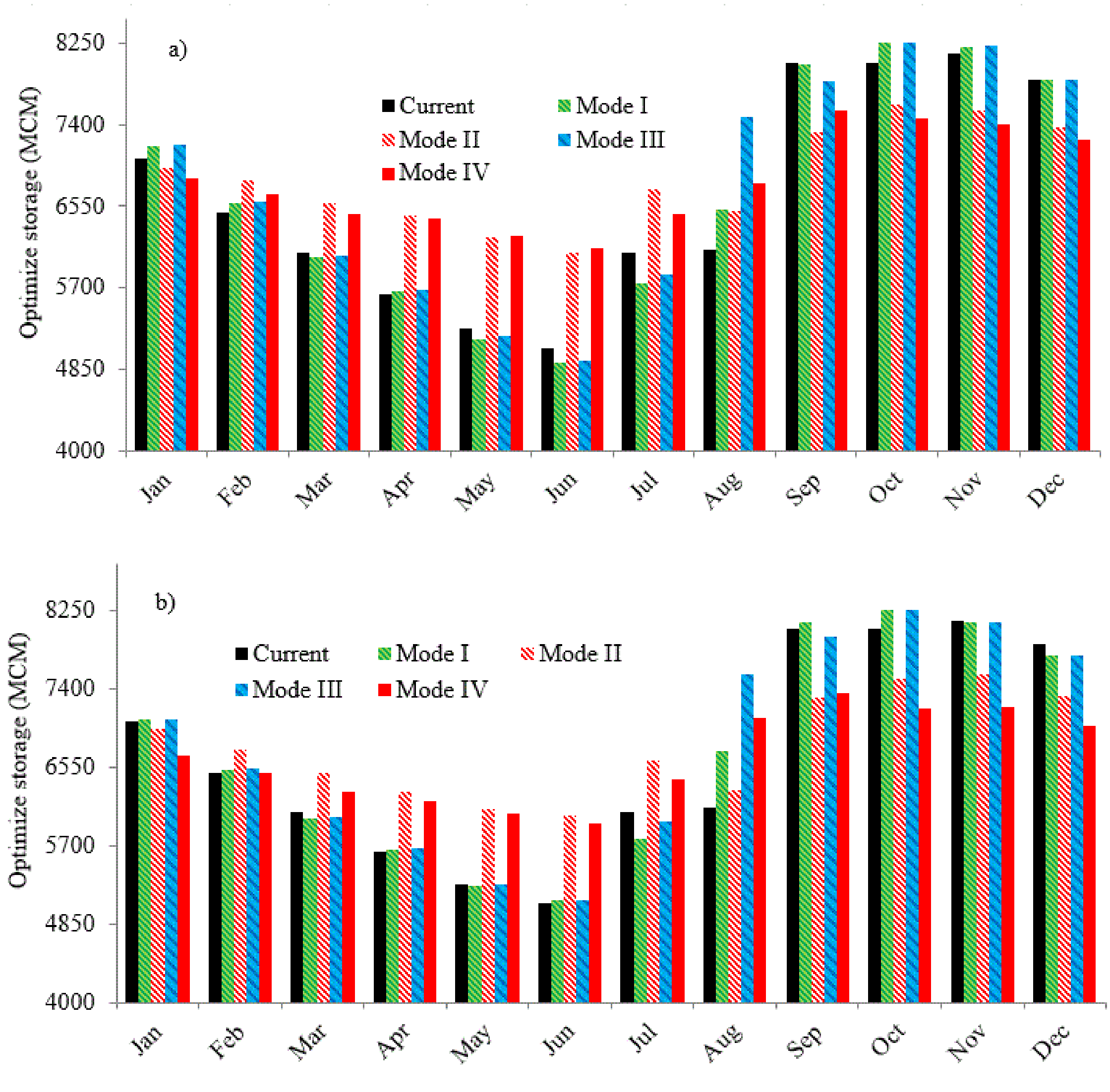

Fig. 7: Comparison of mean monthly optimized TK05 reservoir storage for the four operation modes under (a) RCP4.5 and (b) RCP8.5 climate scenarios

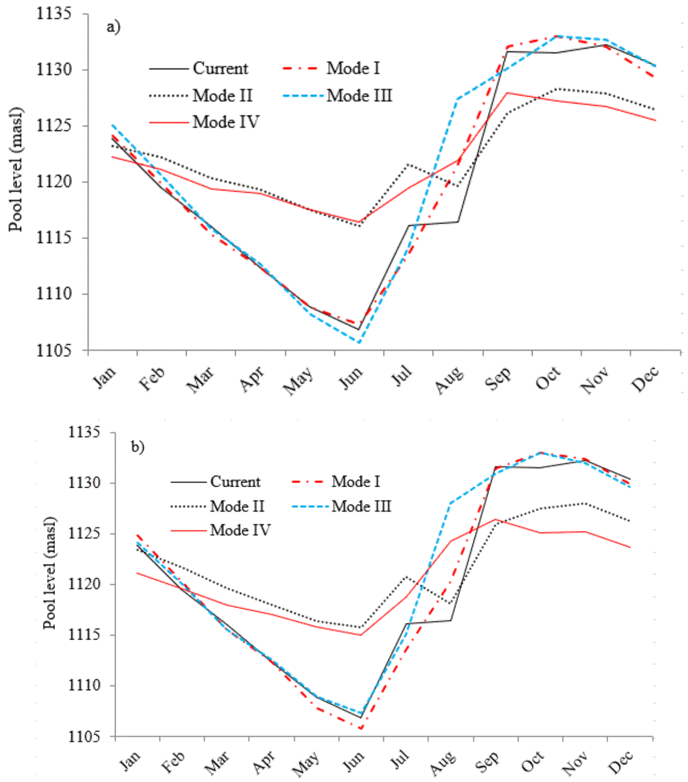

Fig. 8: Water levels of TK05 reservoir in different operational modes under (a) RCP4.5 and (b) RCP8.5 climate scenarios

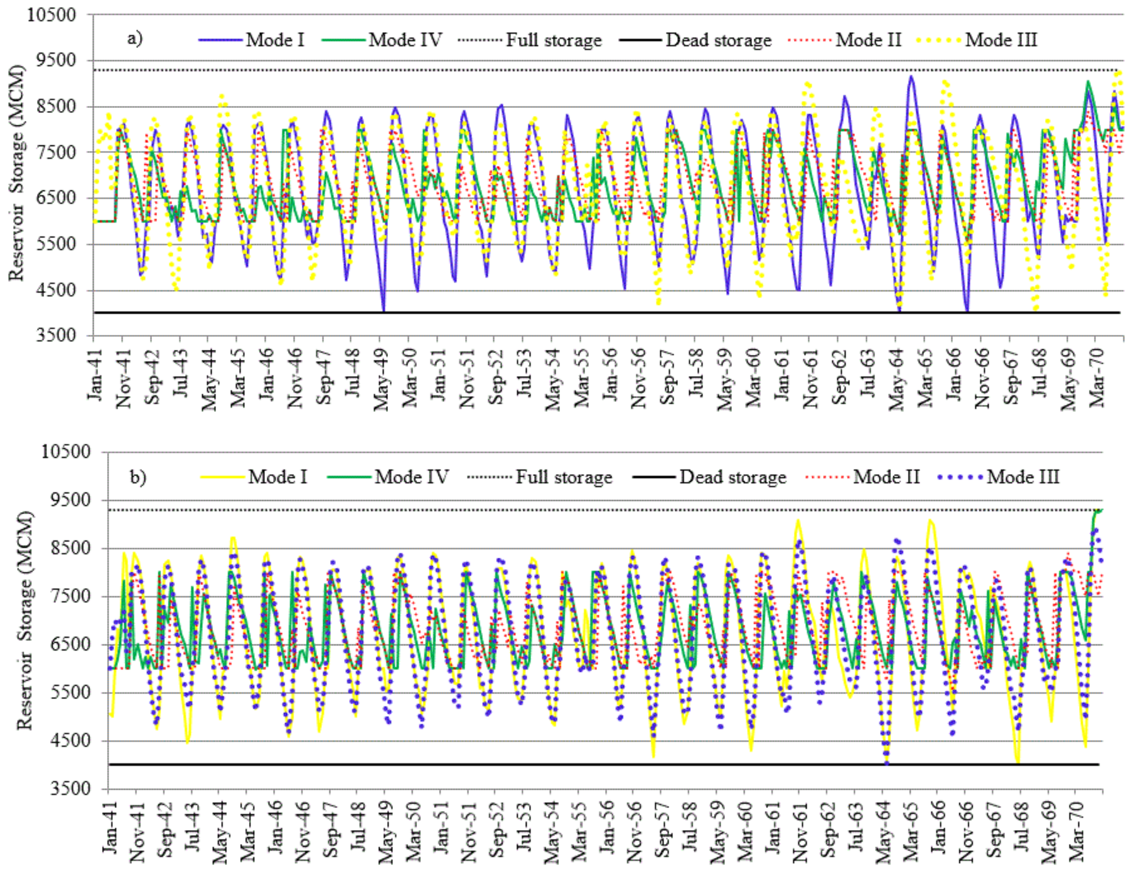

Fig. 9: Monthly reservoir storage of TK05 under different operational modes (a) RCP4.5 and (b) RCP8.5 climate scenarios

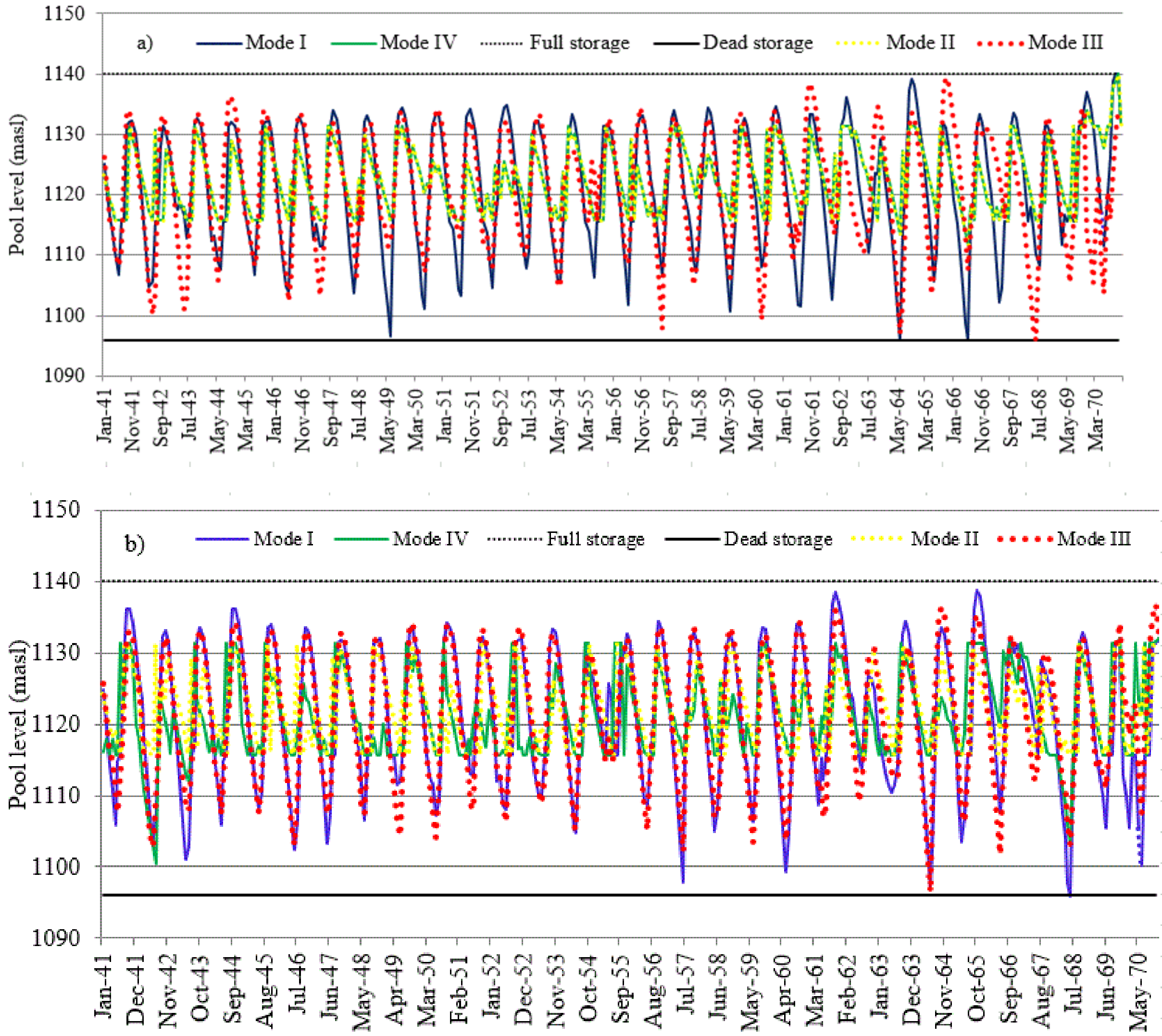

Fig. 10: Monthly reservoir pool level of TK05 under different operational modes (a) RCP4.5 and (b) RCP8.5 climate scenarios

As shown in Fig.7 (a) and (b), the outputs of the Tekeze reservoir operation under mode II and IV are larger than that of other operational modes during dry season months, and less than that after the end of main rainy seasons. Also, the outputs of Tekeze hydropower reservoir storage under operation mode II is larger than that of operational mode IV for all months.

According to Fig. 8 (a) and (b), the output of operational mode (mode II and IV) the reservoir has a high-water level when TK05 reservoir is unfilled during dry months compared to other operational modes. The result also showed that, when the main rainy season (*Kiremt*) ends (September-December) the reservoir water levels of mode II and mode IV decreased compared to other operational modes for both RCP4.5 and RCP8.5 climate scenarios which is due to the optimum reservoir water level distributed in the dry months for these two operational modes. This result concludes that planned reservoir operation on the face of climate change can alter the existing operational Tekeze hydropower reservoir water levels.

According to the above optimization results of TK05 due to the effect of cascade reservoirs in the face of climate change, it can be found that the storage and water levels have high variations. The long-term monthly reservoir storage and water levels variations of TK05 reservoir in different modes derived from HEC-ResPRM model under the two climate scenarios with different operational modes are summarized in (Fig. 9 (a) and (b) and 10(a) and (b)). In general, this study showed that the output of TK05 reservoir under different operational modes depends on the amount of water stored and the water head (pool level), and this amount of water is determined by the climate conditions in both RCPs climate scenarios. The storage and water levels of reservoir directly affected and changed the reservoir output. Therefore, it is more convenient to take the storage and water levels as the decision variables to carry out the reservoir operation.

Finally, climate change and the increasing present and future water demand will squeeze the reservoir water storage and water levels which operates with current operating procedure. Based on the hydrologic modeling using SWAT under climate change scenarios and reservoir optimization operation modeling using HEC-ResPRM, this study provides reasonable operating policies by evaluating the impact of planned cascade reservoir operations in the existing reservoir in the face of climate change. Moreover, the optimized results that were obtained should be competent in delivering better operation choices in response to wet and dry months' circumstances and which operation modes may highly impact Tekeze Hydropower Reservoir. Therefore, incorporate climate change scenarios in to the planning and design of new hydropower reservoirs in Ethiopia, especially in Tekeze basin is necessary. This optimal reservoir operation under climate change hopefully will create more room for water to be utilized in best time estimated for maximum benefit of the stakeholders.

CONCLUSIONS

In this research, the impact of projected climate change on the water resources of Tekeze reservoirs watershed and planned reservoirs impact on operational reservoir were assessed. The Soil and Water Assessment Tool (SWAT) was used to simulate watershed hydrological process to determine current and future reservoirs inflow, and HEC-ResPRM a network flow-based reservoir system operations optimization monthly model was applied in order to determine the impacts of planned cascade reservoirs operation on the existing reservoir operation on the face of climate change. Simulations with the calibrated model for the 2050s under RCPs (RCP4.5 and RCP8.5) based on CMIP5 which were used as an input for reservoir operation model. HEC-ResPRM was prepared to reproduce optimum hydropower reservoir storage and pool level on the joint operation of Tekeze cascade reservoirs in each mode under climate change effect.

The SWAT model was able to reproduce the current hydrological condition of the reservoir's watershed with a good performance and forced to run for future climate scenarios to generate cascade reservoirs inflows of 2050s. Based on the 2050s projection, average annual precipitation will increase up to 32.64% for RCP4.5 and 38.58% for RCP8.5 scenarios and also an increase in temperature with higher variation of minimum temperature up to 1.57 ^{o}C and 2.23 for RCP4.5 and RCP8.5, respectively, compared to maximum temperature change. Compared to the baseline period (1994-2008), future water resources in the Tekeze reservoirs watershed will experience a considerable change as a result of the changing precipitation and temperature. In 2050s, streamflow presents a high variability under the RCP4.5 and RCP8.5 scenarios up to 39.19 and 10.68 percent, respectively.

This study found that the impact of climate change and hydrological variability would be increase in precipitation, temperature and streamflow in the Tekeze reservoirs watershed under RCP4.5 and RCP8.5 climate scenarios that has an impact on the cascade reservoirs operation. As a result, the future scenarios lead to optimized reservoir storage and pool levels that greatly exceed those observed historically, indicating a shift in current water system behavior. Proposed, upstream reservoirs optimal operation (Mode II and IV) in the Tekeze basin would have a limited impact on the reservoir storage and pool level of existing downstream hydropower reservoir (TK05) under historical and future periods as compared to other cascade joint operational modes in the face of future climate scenarios. Therefore, it is recommended to construct upstream hydropower reservoir (TK04) first before other planned TK07 reservoir by incorporating climate change impact scenarios.

More importantly, the combination of semi distributed hydrological model and reservoir operation optimization model lays the foundation for additional studies that reduce uncertainties related to model structure and parameter values and account for errors in precipitation forcing and stream discharge measurements, possibly using ensemble approaches. In addition, the combined tools used here can be readily transferred to water resources managers in the Tekeze basin since these are based on long term ground observations and account for best available information on the hydrological and reservoir system.

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Conflict of Interest

The author declares no conflict of interest.