

**CLIMATE CHANGE IMPACT ANALYSIS ON UPPER
BLUE NILE BASIN HYDRO CLIMATOLOGY, CROP
YIELD, HYDROPOWER, AND OPERATION POLICY OF
RESERVOIR SYSTEM**

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August 2024

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YIELD, HYDROPOWER, AND OPERATION POLICY OF
RESERVOIR SYSTEM**

by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



Indian Institute of Technology Delhi

August 2024

In loving memory of my Father

Certificate

This is to certify that the thesis, titled “**Climate Change Impact Analysis on Upper Blue Nile Basin Hydro Climatology, Crop Yield, Hydropower and Operation Policy of Reservoir System,**” being submitted by **Mr. Elias Jemal Abdella** to the **Indian Institute of Technology, Delhi** for the award of **Doctor of Philosophy** is a bonafide record of research work carried out by him under our joint supervision and guidance. In our opinion, the thesis work has reached the requisite standard, fulfilling the requirements for the Doctor of Philosophy degree. We certify that the results contained in this thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma,

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Acknowledgments

I sincerely thank my supervisors, Prof. A.K. Gosain and Prof. Rakesh Khosa, for their guidance, fruitful discussion, and support throughout this study. I am grateful for their care and immense patience. This research would not have achieved its objectives without their advice. Likewise, I am profoundly thankful to all other SRC committee members.

I would also like to thank my mother, all my family members, and friends for their concern and unbroken motivation. Their wholehearted and sincere commitment to my cause is beyond words, and I am very grateful.

My thanks are extended to Prof. Raghavan Srinivasan, Prof. Dhanya C T, Dr. Aniket Chakravorty, and Raktim Haldar for their generosity with their time and expertise in demystifying ArcSWAT and MATLAB. I also thank the staff members of the Civil Engineering Department, especially those working at the water resource simulation laboratory. I want to acknowledge the Ethiopian Ministry of Water, Irrigation and Electricity, the Ethiopian National Metrological Service Agency, and the Ethiopian Electric Power Corporation for their support in data provision. I also thank the Ministry of Education of Ethiopia for this research's financial support and funding. I thank everyone who has helped me directly or indirectly with any part of this research. Lastly, nothing is possible without the Almighty's wish, and I thank the Almighty for providing me with the courage, means, and blessings to complete my study.

(Elias Jemal Abdella)

Abstract

An effort has been made to understand the impact of climate change on hydro-climatology, yield, hydropower, and reservoir performance in the upper Blue Nile basin, Ethiopia. The projected change of the climate variables was assessed by using four CORDEX-AFRICA regional climate models for two climate change scenarios (RCP 4.5 and RCP 8.5). The bias inside the RCM models was corrected with the observed climate data. The spatial pattern of mean Blue-water-flow (which is the sum of the basin water yield and aquifer recharge, mm/year) for the baseline (1982 – 2005) was simulated using observed historical climate data. The future Blue-water-flow availability was simulated using an ensemble of the four bias-corrected RCMs; the outputs averaged for the period (2027 – 2050). The projected change of blue water flow is primarily due to the variation in temperature and rainfall under both RCP scenarios.

The impact of the changing climate on irrigation water demand and yield of sugarcane was also evaluated for the baseline and the two future RCP scenarios at 19 sites in the existing and proposed reservoir command areas. The projections of gross irrigation water demand (GID) for the dry season (November to May) are predicted to increase for almost all command areas compared to demand in the baseline period. Though minor drops in demands on the monthly scale were witnessed, the overall annual irrigation water demands for sugarcane are projected to grow in all command areas. The contribution of improved irrigation efficiency as an adaptation tool to save water was also assessed. The changes in yield, biomass, and water productivity are evident under the two RCP scenarios relative to the baseline period, and the result shows a difference in the impact of each scenario and the range of spatial variability in the command area. The most substantial projected change in sugarcane yield for RCP 8.5 and RCP 4.5 climate scenarios is estimated at the Lower Guder command area; the yield is expected to increase by 32.8% and

27.1%, respectively. The projected biomass and yield are generally higher under RCP 8.5; this could be due to the CO₂ effects on the crop that may, to some extent, compensate for the stress that the RCP 8.5 climate conditions impose on the crop, resulting in the small biomass and yield increases.

The impact of the changing climate on the performance of the Lake-Tana-multipurpose-reservoir system was also investigated, and adaptive strategies for likely future scenarios were developed. The projected change in the mean monthly inflow during the main rainy season (June to September) generally decreases for RCP 4.5 and RCP 8.5 scenarios in the range of -1% to -15% and -0.3% to -11%, respectively. The mean monthly evaporation loss is projected to increase in every month. In the main rainy season (June to September), the projected increase in evaporation loss ranges from 3% to 4% for RCP 4.5 and 4% to 5% for RCP 8.5; this rise is primarily attributable to the projected increase of the mean monthly temperature throughout the basin. The performance assessment was conducted for two different reservoir operation policies viz. standard-operating-policy (SOP) and optimal-operating-policy (OOP). The monthly scale optimal operating policy was formulated using Linear Programming (LP) optimization technique to maximize reliabilities with respect to the multiple reservoir purposes. Under SOP, the reservoir could be unable to keep the storage above the buffer level for almost three successive months, starting from mid-March to the end of May. When the reservoir is operated under OOP, the storage level remains above the buffer level to satisfy all the demands. The three performance indices (reliability, vulnerability, and resiliency) of the reservoir operation were calculated for both policies under the baseline and two RCP scenarios. Under SOP, reliability and resiliency in reference to hydropower show a decline for both RCP scenarios, while vulnerability increases for the two scenarios. The effect of

applying OOP in improving the performance indices shows that OOP achieves higher hydropower reliability and resiliency for historical and future climate scenarios.

सारांश

इथियोपिया के ऊपरी ब्लू नाइल बेसिन में जल-जलवायु विज्ञान, उपज, जल विद्युत और जलाशय प्रदर्शन पर जलवायु परिवर्तन के प्रभाव को समझने का प्रयास किया गया है। जलवायु चर के अनुमानित परिवर्तन का मूल्यांकन दो जलवायु परिवर्तन परिदृश्यों (आरसीपी 4.5 और आरसीपी 8.5) के लिए चार कॉर्डेक्स-अफ्रीका क्षेत्रीय जलवायु मॉडल का उपयोग करके किया गया था। आरसीएम मॉडल के अंदर पूर्वाग्रह को मनाया जलवायु डेटा के साथ ठीक किया गया था। बेसलाइन (1982 - 2005) के लिए औसत ब्लू-वाटर फ्लो (जो बेसिन जल उपज और एक्वीफर रिचार्ज, मिमी/वर्ष का योग है) का स्थानिक पैटर्न मनाया गया ऐतिहासिक जलवायु डेटा का उपयोग करके अनुकरण किया गया था। भविष्य के ब्लू-वाटर-फ्लो की उपलब्धता को चार पूर्वाग्रह-सही आरसीएम के एक समूह का उपयोग करके अनुकरण किया गया था, आउटपुट अवधि (2027 - 2050) के लिए औसत था। नीला-जल-प्रवाह का अनुमानित परिवर्तन मुख्य रूप से आरसीपी दोनों परिदृश्यों के तहत तापमान और वर्षा में अनुमानित भिन्नता के कारण है।

सिंचाई के पानी की मांग और गन्ने की उपज पर बदलती जलवायु के प्रभाव का मूल्यांकन बेसलाइन और मौजूदा और प्रस्तावित जलाशय कमांड क्षेत्रों में 19 साइटों पर बेसलाइन और दो भविष्य के आरसीपी परिदृश्यों के लिए भी किया गया था। शुष्क मौसम (नवंबर से मई) के लिए सकल सिंचाई जल मांग (जीआईडी) के अनुमानों को बेसलाइन अवधि में मांग की तुलना में लगभग सभी कमांड क्षेत्रों के लिए बढ़ने का अनुमान है। हालांकि मासिक पैमाने पर मांग में मामूली गिरावट देखी गई थी, लेकिन सभी कमांड क्षेत्रों में गन्ने के लिए समग्र वार्षिक सिंचाई पानी की मांग बढ़ने का अनुमान है। पानी बचाने के लिए एक अनुकूलन उपकरण के रूप में बेहतर सिंचाई दक्षता के योगदान का भी आकलन किया गया। उपज, बायोमास और जल उत्पादकता में परिवर्तन आधारभूत अवधि के सापेक्ष दो आरसीपी परिदृश्यों के तहत स्पष्ट हैं, और परिणाम प्रत्येक परिदृश्य

के प्रभाव और कमांड क्षेत्र में स्थानिक परिवर्तनशीलता की सीमा में अंतर दिखाता है। आरसीपी 8.5 और आरसीपी 4.5 जलवायु परिदृश्यों के लिए गन्ने की उपज में सबसे महत्वपूर्ण अनुमानित परिवर्तन लोअर-गुडर कमांड क्षेत्र में अनुमानित है; उपज में क्रमशः 32.8% और 27.1% की वृद्धि होने की उम्मीद है। अनुमानित बायोमास और उपज आम तौर पर आरसीपी 8.5 के तहत अधिक होती है; यह फसल पर CO₂ प्रभावों के कारण हो सकता है जो कुछ हद तक उस तनाव की भरपाई कर सकता है जो RCP 8.5 जलवायु परिस्थितियों में फसल पर थोपता है और इसके परिणामस्वरूप छोटे बायोमास और उपज में वृद्धि होती है।

झील-ताना-बहुउद्देशीय-जलाशय प्रणाली के प्रदर्शन पर बदलती जलवायु के प्रभाव की भी जांच की गई, और संभावित भविष्य के परिदृश्यों के लिए अनुकूली रणनीति विकसित की गई। मुख्य वर्षा ऋतु (जून से सितम्बर) के दौरान औसत मासिक अंतर्वाह में अनुमानित परिवर्तन सामान्यतः आरसीपी 4.5 और आरसीपी 8.5 दोनों परिदृश्यों के लिए क्रमशः -1% से -15% और -03% से -11% की रेंज में घटता है। औसत मासिक वाष्पीकरण हानि हर महीने में बढ़ने का अनुमान है। मुख्य वर्षा ऋतु (जून से सितम्बर) में वाष्पीकरण हानि में अनुमानित वृद्धि आरसीपी 4.5 के लिए 3% से 4% और आरसीपी 8.5 के लिए 4% से 5% तक होती है; यह वृद्धि मुख्य रूप से पूरे बेसिन में औसत मासिक तापमान की अनुमानित वृद्धि के कारण है। प्रदर्शन मूल्यांकन दो अलग-अलग जलाशय संचालन नीतियों जैसे मानक-संचालन-नीति (एसओपी) और इष्टतम-संचालन-नीति (ओओपी) के लिए आयोजित किया गया था। मासिक पैमाने पर इष्टतम परिचालन नीति रैखिक प्रोग्रामिंग (एलपी) अनुकूलन तकनीक का उपयोग करके तैयार की गई थी ताकि कई जलाशय उद्देश्यों के संबंध में विश्वसनीयता को अधिकतम किया जा सके। एसओपी के तहत, जलाशय मार्च के मध्य से मई के अंत तक लगभग तीन लगातार महीनों तक बफर स्तर से ऊपर भंडारण रखने में असमर्थ हो सकता है। जब जलाशय को ओओपी के तहत संचालित किया जाता है, तो जलाशय में भंडारण स्तर सभी मांगों को पूरा करने के लिए बफर स्तर के शीर्ष से ऊपर रहता है। जलाशय संचालन के तीन प्रदर्शन सूचकांक (विश्वसनीयता, भेद्यता और लचीलापन)

की गणना बेसलाइन और दो आरसीपी परिदृश्यों के तहत दोनों नीतियों के लिए की गई थी। एसओपी के तहत पनबिजली के संदर्भ में विश्वसनीयता और लचीलापन दोनों आरसीपी परिदृश्यों के लिए गिरावट दिखाता है, जबकि दो परिदृश्यों के लिए भेद्यता बढ़ जाती है। प्रदर्शन सूचकांकों में सुधार में ओओपी लागू करने के प्रभाव से पता चलता है कि ओओपी ऐतिहासिक और भविष्य के जलवायु परिदृश्यों दोनों के लिए उच्च जल विद्युत विश्वसनीयता और लचीलापन प्राप्त करता है।

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List of Abbreviations and Acronyms

AgMIP	Agricultural Model Intercomparison and Improvement Project
AOGCMs	Atmosphere-Ocean General Circulation Models
AVHRR	Advanced Very High-Resolution Radiometer
CERES	Crop Environment Resource Synthesis
CFSR	Climate Forecast System Reanalysis Global weather data
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Downscaling Experiment
CRGE	Climate Resilient Green Economy
DAAC	Distributed Active Archive Centre
DEM	Digital Elevation Model
DSN	Digital Stream Network
DSSAT	Decision Support System for Agro-technology Transfer
EPIC	Environmental Policy Integrated Climate
EROSDC	Earth Resources Observation Systems Data Center
ESD	Empirical Statistical Downscaling
ESMs	Earth System Models
GCMs	Global Climate Models
GHG	Greenhouse Gas
GIS	Geographic Information System
GLCC	Global Land Cover Characterization
GLUE	Generalized Likelihood Uncertainty Estimation
HRU	Hydrological Response Unit

HWSD	Harmonized World Soil Database
IAMs	Integrated Assessment Models
IDW	Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
LP	Linear Programing
MCMC	Markov chain Monte Carlo
MoWEI	Ethiopian Ministry of Water, Energy and Irrigation
NASA	National Aeronautics and Space Administration
NASA	National Aeronautics and Space Administration
NCEP	National Centre for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
ParaSol	Parameter Solution
PSO	Particle swarm optimization
RCMs	Regional Climate Models
SOTER	Soil and Terrain
SRTM	Shuttle Radar Topographic Mission
SUFI2	Sequential Uncertainty Fitting
SWAP	Soil, Water, Atmosphere and Plant
SWAT	Soil and Water Assessment Tool
USDA-SCS	U.S. Department of Agriculture's Soil Conservation Service
USGS	United States Geological Survey
WOFOST	World Food Studies