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By

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ASSESSMENT OF GREEN HYDROGEN PRODUCTION POTENTIAL FROM JEBBA HYDROPOWER RESERVOIR IN THE NIGER RIVER BASIN AS AN OPTION FOR CLIMATE CHANGE MITIGATION

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THESE

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Dans la Spécialité:

Changements climatiques et Ressources en Eau

Par

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ÉVALUATION DU POTENTIEL DE PRODUCTION D'HYDROGÈNE VERT À PARTIR DU RÉSERVOIR HYDROÉLECTRIQUE DE JEBBA DANS LE BASSIN DU FLEUVE NIGER COMME OPTION D'ATTÉNUATION DU CHANGEMENT CLIMATIQUE

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Dedication.

This work is dedicated to the Almighty God, as well as my wonderful parents, wife, and son, who have supported me along the way.

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Synthèse de la Thèse

1. Résumé

La crise énergétique du Nigeria pourrait s'aggraver à mesure que la population du pays augmente et que le développement économique stimule la demande d'énergie. La demande d'énergie étant appelée à augmenter en raison de la croissance démographique et des variations climatiques, il est nécessaire d'évaluer avec précision la disponibilité future de l'eau pour la production d'énergie hydroélectrique, ainsi que l'impact du changement climatique sur la diminution des débits fluviaux, et d'estimer le potentiel de production d'hydrogène vert à partir des ressources hydroélectriques. Les objectifs de ce travail sont (i) d'évaluer l'impact du changement climatique sur les composantes du bilan hydrique dans le bassin du fleuve Niger, (ii) d'examiner les tendances récentes des variables hydroclimatiques, de la production hydroélectrique et du potentiel de production d'hydrogène vert à la centrale hydroélectrique de Jebba, (iii) d'analyser la production hydroélectrique future et le potentiel de production d'hydrogène vert des centrales hydroélectriques en cascade de Kainji-Jebba dans le cadre des scénarios SSP245 et SSP585, sur la période future 2025-2100, en utilisant 1984-2009 comme période de référence. Données principales : Les données utilisées comprennent les séries chronologiques de précipitations mensuelles, les températures maximales moyennes, les débits entrants et sortants des réservoirs, les pertes par évaporation, les débits des turbines, la production d'énergie, les précipitations quotidiennes observées et satellitaires, et les données climatiques pour analyser l'impact du changement climatique. Méthodologie utilisée : comprend (i) l'analyse de la variabilité interannuelle et des anomalies pluviométriques, (ii) l'analyse des tendances et de l'homogénéité des données à un niveau de signification de 5 %, (iii) l'étude de l'impact du changement climatique sur les composantes du bilan hydrique (précipitations, ruissellement, évapotranspiration) à l'aide de la modélisation de la surface du sol, (iv) évaluation de l'impact de la variabilité climatique sur la production d'hydroélectricité et d'hydrogène vert à l'aide du test de Mann-Kendall modifié (MMK), du coefficient de corrélation de Pearson et d'une analyse de sensibilité, (v) estimation du potentiel passé et futur de l'hydrogène vert, de la réélectrification, de la substitution des combustibles et des émissions de CO2 évitées à l'aide d'une analyse statistique, d'une modélisation hydrologique et d'une simulation de l'hydroélectricité. Les résultats montrent que les stations d'Ilorin et de Bida ont enregistré respectivement les anomalies négatives les plus élevées et les plus faibles. La plus longue période de sécheresse a été observée entre 1981 et 1989 dans le bassin du fleuve Niger, suivie par la période 1992-1996 à la station d'Ilorin. Les tests de tendance MMK et ITA révèlent une tendance similaire à l'augmentation des précipitations dans le bassin du fleuve Niger (NRB) et à la station d'Ilorin. Le test de Pettit pour les points de changement a montré que toutes les variables ont connu des années de changement, à l'exception des précipitations aux stations de Bida et Minna. Les projections des changements dans les précipitations, le ruissellement de surface et l'évapotranspiration dans le cadre du scénario à faibles émissions (RCP 2.6) indiquent que la région pourrait connaître des conditions hydrologiques relativement stables. En revanche, le scénario à fortes émissions (RCP 8.5) suggère une évolution vers des conditions plus sèches avec une disponibilité réduite de l'eau. L'étude montre que la production hydroélectrique du barrage au cours de la période étudiée (1988 à 2018) a augmenté de manière significative en raison des fluctuations des variables hydroclimatiques, en particulier la tendance à la hausse des débits d'entrée du réservoir et des débits des turbines. Ceci a directement influencé l'augmentation de la production d'énergie et a produit une tendance similaire à la hausse du potentiel estimé pour l'hydrogène vert, la ré-électrification, la quantité de combustible fossile (essence) qui peut être remplacée, et les émissions de CO_2 et de CO qui peuvent être évitées grâce à l'utilisation de l'hydrogène. En outre, les changements futurs dans les apports des réservoirs et la production d'énergie hydroélectrique mettent en évidence un changement temporel critique dû au changement climatique. La période de 2025 à 2065 offre une plus grande disponibilité de l'eau et de la production d'énergie pour la production d'hydrogène vert et la substitution de l'essence.

Mots-clés : Variabilité hydroclimatique, hydroélectricité, changement climatique, atténuation, hydrogène vert, barrage de Jebba, Nigeria.

2. Introduction

Les changements climatiques induits par l’homme, notamment la fréquence et l’intensité accrues des événements extrêmes, ont eu de vastes conséquences négatives, entraînant des pertes et des dommages pour l’environnement et les humains. Alors que les systèmes naturels et humains sont poussés au-delà de leur capacité d’adaptation, la hausse des phénomènes météorologiques et climatiques extrêmes a engendré des conséquences irréversibles. Les industries et les systèmes ont été touchés de manière disproportionnée à travers les secteurs et les régions. Cependant, la vulnérabilité a été atténuée grâce à certaines mesures de développement et d’adaptation (IPCC, 2022). Hamed et al. (2020) ont affirmé que le monde traverse des périodes difficiles marquées par des défis importants alors que la population mondiale augmente (dépassant les sept milliards de personnes), accompagnée de crises économiques croissantes, de la mauvaise gestion des ressources naturelles, d'événements météorologiques extrêmes, d'incertitudes, et de l'aggravation de la pauvreté et de la faim. L'Afrique a été décrite comme le continent le plus vulnérable aux impacts des changements climatiques, avec des ressources en eau de plus en plus fragiles (Serdeczny et al., 2016). Au-delà des relations traditionnelles d'influence et de contrainte, le lien énergie-eau est confronté à de nouvelles conditions et à de nouveaux défis. Les changements climatiques mondiaux critiques, l'augmentation continue de la température moyenne mondiale et les événements météorologiques extrêmes fréquents ont profondément transformé les systèmes hydrologiques mondiaux et modifié de manière significative la quantité globale et la répartition régionale des ressources en eau, en raison de la consommation massive de combustibles fossiles et des émissions continues de gaz à effet de serre (GES) (Sun et al., 2018).

Le Nigeria est particulièrement vulnérable aux changements climatiques, avec une vaste superficie géographique de 923 768 km² couvrant de nombreuses zones climatiques. Il est indéniable que le pays est au bord du danger en raison d'une série de problèmes environnementaux, dont beaucoup sont aggravés par les changements climatiques (Okedina et al., 2018). Face aux changements climatiques, le pays est confronté à une crise énergétique qui pourrait s'aggraver si aucune mesure n'est prise. Glassman et al. (2011) ont souligné que la production d'énergie nécessite une grande quantité d'eau et que l'approvisionnement en eau consomme également beaucoup d'énergie. Répondre aux futures demandes énergétiques dépend de la disponibilité de l'eau, et répondre aux besoins en eau exige des choix politiques énergétiques judicieux dans un monde où la pénurie d'eau constitue une préoccupation majeure et croissante. Les changements climatiques auront un impact significatif sur l'accessibilité et la disponibilité de l'eau pour la production d'énergie et d'autres usages, tant sur le plan qualitatif que quantitatif (IPCC, 2007). Le lien entre le nexus climat-eau-énergie, notamment les précipitations et la température dans les réservoirs hydroélectriques des bassins fluviaux du pays, comme la partie nigériane du bassin du fleuve Niger, influence fortement la disponibilité de l'eau ainsi que la production et l'approvisionnement en électricité. Fung (2009) a indiqué que l'effet des changements climatiques sur la disponibilité de l'eau dans les bassins fluviaux est déterminé par deux facteurs : les changements des variables climatiques qui influencent les processus hydrologiques, tels que les précipitations, le rayonnement solaire et la température, ainsi que la vulnérabilité du bassin à ces changements.

Olaoye et al. (2016) ont averti que la crise énergétique au Nigeria pourrait s'aggraver à mesure que la population du pays augmente et que le développement économique exige une demande énergétique accrue. Les efforts pour sauver la planète du réchauffement climatique ont conduit les nations à se tourner vers des sources alternatives pour répondre à leurs besoins énergétiques. Il est donc impératif de tirer parti des solutions d'énergie renouvelable, telles que l'énergie verte de l'hydrogène, comme stratégie d'atténuation des changements climatiques et pour répondre à l'industrialisation rapide et aux besoins énergétiques croissants du Nigeria.

L'objectif général est d'évaluer le potentiel de production d'hydrogène vert à partir du réservoir hydroélectrique de Jebba dans le bassin du fleuve Niger comme option pour l'atténuation des changements climatiques. Pour atteindre cet objectif général, l'étude vise spécifiquement à :

- Évaluer l'impact des changements climatiques sur les composantes du bilan hydrique (précipitations, ruissellement de surface et évapotranspiration) dans le bassin du fleuve Niger.
- Examiner les tendances récentes des variables hydroclimatiques, de la production d'énergie hydroélectrique et du potentiel d'hydrogène vert à la centrale hydroélectrique de Jebba.
- Analyser la production future d'hydroélectricité et le potentiel de production d'hydrogène vert à partir des centrales hydroélectriques en cascade de Kainji-Jebba, selon les scénarios SSP245 et SSP585, sur la période future de 2025 à 2100, en utilisant la période de base de 1984 à 2009.

3. Zone d'étude

Le bassin du fleuve Niger (BRN) est le deuxième plus grand fleuve d'Afrique, comme l'illustre la figure 1. Il couvre une superficie de 2,27 millions de km² et est situé entre les latitudes 5° N et 24° N et les longitudes 12° O et 17° E. Le bassin est caractérisé par un écoulement inhabituel à travers dix pays qui se partagent ses eaux, à savoir l'Algérie, le Bénin, le Burkina Faso, le Cameroun, le Tchad, la Côte d'Ivoire, la Guinée, le Mali, le Niger et le Nigéria. Parmi les bassins actifs, le Nigeria couvre une superficie de 562 372 km², soit 44,2 % de la superficie totale des bassins actifs. Traduit avec (Andersen & Golitzen, 2005), le bassin connaît deux variations saisonnières principales : un été pluvieux et un hiver sec, sauf au Nigeria, où l'on distingue quatre saisons. L'humidité annuelle, l'ensoleillement et la vitesse du vent dans le bassin varient en fonction de la saison et de la localisation. L'évapotranspiration est un facteur essentiel du cycle hydrologique du bassin, influençant la disponibilité de l'eau et les interactions entre la terre et l’atmosphère dans la région. L’évapotranspiration annuelle dans le bassin varie en fonction de plusieurs facteurs, notamment les précipitations, la température, l’humidité et la couverture végétale. Une partie importante du bassin comprend des réservoirs majeurs situés dans le bassin inférieur, notamment les réservoirs de Kanji, Jebba et Shiroro. L’étude de cas examinée dans cette recherche concerne le réservoir de Jebba au Nigeria. Le pays compte environ 60 grands barrages, parmi lesquels les trois plus importants (Kanji, Jebba et Shiroro) ont une capacité totale de stockage d’eau de 34 800 millions de mètres cubes (MCM), situés dans la zone étudiée (JICO, 2014). L’étude se concentre sur le deuxième plus grand barrage hydroélectrique du Nigeria, le réservoir de Jebba. Le barrage hydroélectrique de Jebba dispose de six turbines de production, chacune ayant une capacité nominale de 96,4 mégawatts, pour une puissance installée maximale de 578,4 mégawatts.

4. Matériel et Méthodes

Les données hydroclimatiques et de production énergétique pour le réservoir hydroélectrique de Jebba ont été obtenues auprès de Mainstream Energy Solution. Les données d’observation des précipitations des stations voisines du barrage de Jebba (Ilorin, Bida, Minna et Lokoja) ont été fournies par NiMET (Agence météorologique du Nigeria). Pour l’analyse à l’échelle du bassin, les données de précipitations issues de la version 2 de Climate Hazards Group Infrared Precipitation with Stations (CHIRPS), développées par le Climate Hazards Group de l’Université de Californie, ont été utilisées. La configuration du modèle CLM5 nécessite les données de forçage météorologique suivantes: rayonnement incident à ondes courtes et longues, température de l’air, humidité relative, vitesse du vent, pression et précipitations. Les données climatiques de forçage utilisées pour l’étude proviennent du jeu de données de projection de la phase 5 du Coupled Model Intercomparison Project (CMIP5) pour cinq modèles climatiques régionaux (RCMs) à une échelle temporelle journalière. Le jeu de données historiques pour la modélisation hydrologique et hydroélectrique comprend les précipitations, les températures minimales et maximales sur le bassin versant du barrage de Jebba, les apports d’eau au réservoir et le stockage du réservoir pour la centrale hydroélectrique. Les données de forçage climatique du CMIP6 ont été obtenues et sélectionnées à partir de l’archive des projections journalières globales et ajustées à une échelle fine de NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6). L’analyse statistique et l’analyse des tendances constituent des mesures essentielles pour l’étude des séries chronologiques climatiques (Hussain & Mahmud, 2019). Dans cette étude, des analyses statistiques et des tendances ont été utilisées pour caractériser, quantifier et valider la variabilité des précipitations dans le bassin du fleuve Niger et au barrage hydroélectrique de Jebba. Pour évaluer l'impact des changements climatiques sur les composantes du bilan hydrique, le CLM5 (Community Land Model version 5) a été utilisé comme modèle de surface terrestre pour simuler les interactions entre la surface terrestre et l'atmosphère en représentant des processus physiques et biogéochimiques critiques. Des versions simplifiées du modèle hydrologique HBV ont été implémentées en Python. Le modèle HBV a été choisi pour sa flexibilité, son efficacité computationnelle, son efficacité prouvée dans diverses conditions climatiques et physiographiques, ainsi que pour son application réussie dans plusieurs études de régionalisation précédentes. Le modèle hydroélectrique pour l'étude a été implémenté en Python en utilisant la règle d'exploitation du réservoir du barrage de Kainji telle que décrite dans Oyerinde et al. (2016).

5. Résultats et Discussion

La variabilité des précipitations annuelles a été caractérisée sur le bassin du fleuve Niger (NRB) et la station hydroélectrique de Jebba (JHS), et montre que les précipitations moyennes les plus faibles de 523,7 mm et 933,7 mm ont été enregistrées en 1983 et 2009, respectivement, tandis que les précipitations les plus élevées de 759,7 mm et 1462,8 mm ont été enregistrées en 1999 et 1991, respectivement. Les relevés mensuels des précipitations montrent une faible pluviométrie de novembre à Février; cependant, on observe une augmentation à partir de mars pour la NRB et la JHS. Les changements projetés dans les précipitations, le ruissellement de surface et l'évapotranspiration dans le cadre des différents scénarios RCP révèlent des impacts potentiels significatifs sur le bilan hydrique du bassin du fleuve Niger. La variabilité des précipitations dans le cadre du scénario RCP 2.6 devrait varier entre 550 mm et 750 mm par an. En revanche, dans le cadre du scénario RCP 8.5, les niveaux de précipitations pourraient diminuer de 420 mm par an. Dans le cadre du scénario RCP 2.6, le ruissellement de surface devrait varier entre 130 et 180 mm par an. Toutefois, dans le scénario RCP 8.5, on observe une diminution significative de l'écoulement de surface à partir de 2060, pour atteindre 90 mm à la fin du siècle. En outre, l'évapotranspiration, qui est une composante essentielle du cycle de l'eau, varie en fonction des différents scénarios. Selon le scénario RCP 2.6, l'évapotranspiration devrait se situer entre 380 et 420 mm par an. Cependant, comme pour les précipitations et le ruissellement, une diminution progressive de l'évapotranspiration est attendue dans le scénario RCP 8.5, avec des valeurs aussi basses' que 300 mm d'ici 2100. Dans le scénario à faibles émissions (RCP 2.6), la région pourrait connaître des conditions hydrologiques relativement stables. En revanche, le scénario à fortes émissions (RCP 8.5) suggère une transition vers des conditions plus sèches avec une disponibilité réduite de l'eau, ce qui pourrait avoir de profondes répercussions sur l'agriculture, l'approvisionnement en eau et la santé générale des écosystèmes de la région.

Les résultats de l'analyse des tendances des variables hydroclimatiques et de la production d'énergie des barrages hydroélectriques montrent une augmentation significative de la production d'énergie de 1988 à 2018 en raison d'une tendance à la hausse du débit entrant et sortant des réservoirs et du débit des turbines; cela indique que ces trois variables sont les principaux moteurs de la production d'énergie hydroélectrique. En outre, le débit des turbines, le débit entrant et le débit sortant du réservoir ont une corrélation plus forte avec la production d'énergie que d'autres variables telles que les précipitations, la température et les pertes par évaporation. L'augmentation de la production d'énergie a entraîné une tendance similaire à la hausse du potentiel estimé pour l'hydrogène vert, la réélectrification, comme le montre la figure ci-dessous, la quantité de combustible fossile (essence) qui peut être remplacée et les émissions de CO_2 et de CO qui peuvent être évitées grâce à l'hydrogène.

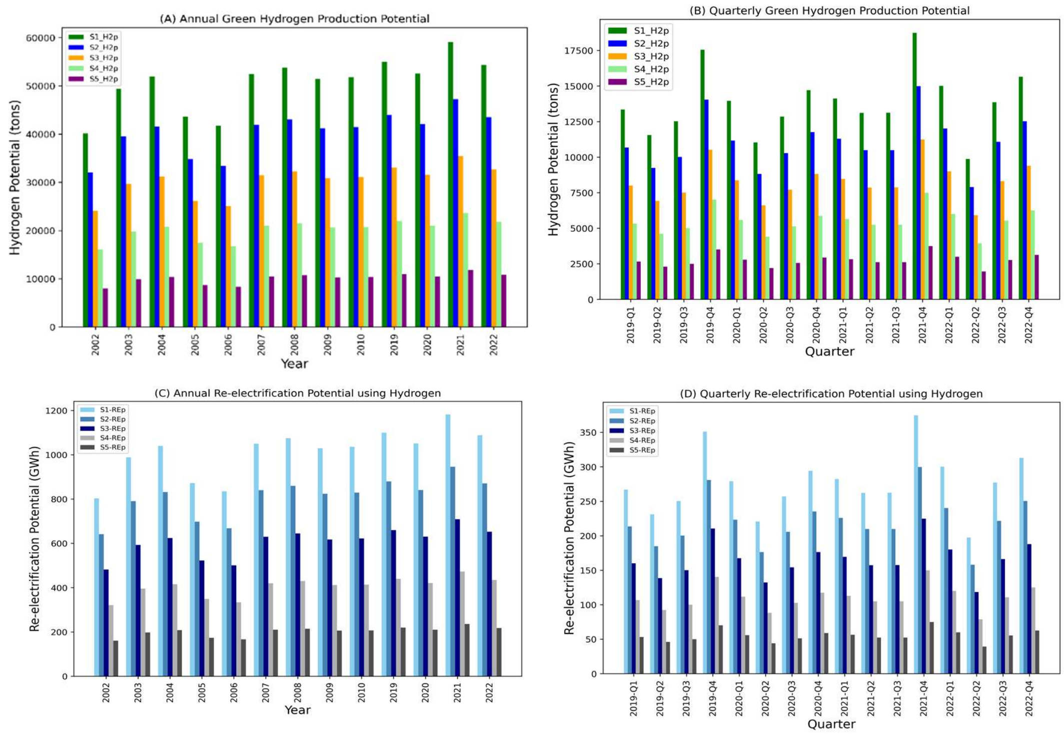

Figure i: Scénario 1 (S1) à Scénario 5 (S5) estimé **(a)** Potentiel annuel de production d'hydrogène vert (H2p**)**, (**b)** Potentiel trimestriel de production d'hydrogène vert **(**H2p**)**, **(c)** Potentiel annuel de ré-électrification (REp), et **(d)** Potentiel trimestriel de ré-électrification (REp) à la centrale hydroélectrique de Jebba.

L'analyse du débit du réservoir pour le barrage de Jebba dans le cadre des scénarios SSP245 et SSP585 révèle qu'entre 2025 et 2055, le débit du réservoir devrait augmenter, atteignant un pic d'environ 5000 (m^3/s) dans le cadre des scénarios SSP245 et SSP585. Cette augmentation initiale peut être attribuée à des précipitations accrues et éventuellement à un ruissellement plus important au cours de cette période. Toutefois, à partir de 2055 environ, on prévoit une diminution progressive du débit entrant, qui se prolongera jusqu'en 2100. Ce déclin indique une diminution à long terme des précipitations et du ruissellement, probablement influencée par la hausse des températures et l'évolution des conditions météorologiques associées à des concentrations plus élevées de gaz à effet de serre, en particulier dans le cadre du SSP 585. L'évaluation de l'impact du changement climatique met en évidence un changement temporel critique dans la dynamique des apports du réservoir et de la production hydroélectrique au barrage de Jebba. La période entre 2025 et 2055 semble offrir une fenêtre d'augmentation de la disponibilité de l'eau et de la production d'énergie, qui pourrait répondre aux besoins énergétiques croissants et maximiser la production hydroélectrique ainsi que la production d'hydrogène vert.

6. Conclusion

L’étude souligne l’importance de la variabilité des précipitations dans la détermination de la capacité de production hydroélectrique et la manière dont des problèmes liés au climat, tels que la sécheresse, peuvent affecter la production énergétique. Elle conclut que la variabilité des précipitations influence la disponibilité de l’eau à la centrale hydroélectrique, contribuant à la tendance croissante des apports au réservoir, des débits des turbines et de la production énergétique. Les changements projetés dans les composantes du bilan hydrique mettent en évidence l’importance des efforts d’atténuation du climat pour limiter les émissions de gaz à effet de serre et réduire la gravité des impacts climatiques futurs. En raison du vieillissement des centrales hydroélectriques, le pourcentage recommandé d’utilisation de l’hydroélectricité pour la production d’hydrogène vert est le plus bas, à savoir 20 %, ce qui peut constituer un point de départ pour orienter le pays vers la production et l’adoption de l’hydrogène vert en attendant les investissements nécessaires.

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List of Acronyms

CHIRPS: Climate Hazards Group Infrared Precipitation with Stations

CLM5: Community Land Model version 5

CMIP: Coupled Model Intercomparison Project.

CORDEX: Coordinated Regional Downscaling Experiment

ECOWAS: Economic Community of West African States

FAO: Food and Agriculture Organization.

GCM: General Circulation Model

GHG: Green House Gases

GDP: Gross domestic product

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

ITCZ: Intertropical Convergence Zone

MMK: Modified Mankendall Trend Test

MSWEP: Multi-Source Weighted-Ensemble Precipitation

NETP: Nigeria Energy Transition Plan

NIMET: Nigerian Meteorological Service Agency.

NRB: Niger River Basin

ITA: Innovative Trend Analysis

ITCZ: Intertropical Convergence Zone

SNHT: Standard Normal Homogeneity Test

SSP: Shared socio-economic Pathway

RCP: Representative Concentration Pathway

WMO: World Meteorological Organization

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CHAPTER 1: GENERAL INTRODUCTION

The general introduction presents an overall overview of the thesis. It describes the dissertation's content, beginning with the background and problem statement, as outlined in Section 1.1. Section 1.2 is the literature review, which provides a concise summary of the state of the art on green hydrogen production prospects in West Africa. Section 1.3 focuses on the research questions of the thesis, while Sections 1.4 and 1.5 focus on the main and specific objectives, respectively. The hypothesis and novelty are described in Sections 1.5 and 1.6, respectively. The scope of the thesis is detailed in Section 1.7, and the expected results are discussed in Section 1.8.

1.1 Context and Problem Statement.

1.1.1 Context of the study

Human-caused climate change, particularly more extreme and frequent catastrophic events, has wide-ranging negative effects and is associated with losses and damages to both humanity and the ecosystem (Parker et al., 2022). Human actions are the primary causes of climate change, largely due to the release of greenhouse gases (GHGs), such as methane and carbon dioxide, into the atmosphere (Driga & Drigas, 2019; Khetrapal, 2018; Chand, 2021). The burning of non-renewable energy sources (oil, coal, and gas) for energy generation, deforestation, industrial emissions, and changes in land cover and use are important factors that contribute to increased GHG concentrations in the atmosphere (Khetrapal, 2018; Thota, 2025; Sharma et al., 2025; Muhammad, 2024; Raghavendra, 2024). These gases trap heat, amplifying the natural greenhouse gas effects, which leads to increased temperatures and global warming (Driga & Drigas, 2019; Khetrapal, 2018; Chand, 2021). Since the mid-20th century, the impact of humans on the global climatic system has been unprecedented, causing changes on a global scale (Thota, 2025). This has led to human and ecological systems being forced beyond their capacity for adaptation, and some of the effects of the increase in weather and climatic extremes are irreversible. Industries and systems across various sectors and locations have been disproportionately affected. However, the vulnerability has been decreasing due to certain developments and adaptation strategies (IPCC, 2022). Hamed et al. (2020) alleged that the world is facing challenging times, with a growing population (exceeding seven billion people), deepening economic crises, resource depletion, extreme weather events, uncertainty, and rising rates of poverty and hunger. The African continent has been identified as the most susceptible to the effects of rising temperatures, with Africa's water resources being increasingly vulnerable

(Serdeczny et al., 2016). The energy-water nexus is confronted with novel circumstances and difficulties that go beyond the conventional impact and constraint interactions. Global non-renewable fuel consumption and ongoing emissions of greenhouse gases (GHG) have significantly altered global hydrological systems, the amount of water available globally, and the allocation of water resources across regions due to the critical global changing climate, the ongoing increase in the average temperature, and recurring severe weather conditions (Sun et al., 2018). Nigeria's massive geographic expanse of 923,768 sq km, which spans a variety of climatic regions, increases its susceptibility to a changing climate. There is no denying that a number of environmental problems are putting the nation at risk, several of which are being exacerbated by climate change (Okedina et al., 2018). In light of global climate change, the nation faces an energy security challenge that could worsen if no action is taken. Notably, Glassman et al. (2011) pointed out that producing energy requires a significant amount of water, and providing water in turn demands a substantial amount of energy. Water availability determines future energy demands, and in a world where water scarcity is a serious and growing issue, addressing water needs requires informed and prudent energy policy decisions. As noted by IPCC (2007), climate change will significantly impact water accessibility and availability for energy production and other uses, both qualitatively and quantitatively.

1.1.2 Problem statement

Nigeria has an abundance of renewable energy sources, hydroelectric potential, and natural resources. Nevertheless, in the history of energy generation, the nation cannot be considered to have ever had a sufficient supply of electricity (Olaoye et al., 2016). In the report by IEA, (2020), World Energy Outlook shows the proportion of the population across West African countries that had access to electricity from 2000 to 2019. According to the estimations, only nearly 60% of Nigerians had access to grid-electricity in 2019, a 20% increase from 40% in 2014. The relationship between the water-energy-climate nexus, especially rainfall and temperature in the hydropower reservoirs in the country's river basins, such as the lower Niger basin in the Niger River, greatly influences water resource availability and electricity generation and supply. Lopez et al., (2009) opined that the two main factors influencing the impact of changing climate on river basin water resource availability are the basin's susceptibility to these changes and fluctuations in the atmospheric factors, such as temperature, precipitation, and solar radiation, that affect hydrological processes.

1.1.3 Justification of study

Nigeria's energy situation might get worse as the nation's population grows and its economy develops, increasing demand for electricity (Olaoye et al. 2016). In an effort to combat global warming, countries are utilizing alternative energy sources to meet their energy requirements. Consequently, it is essential to utilize renewable energy sources, such as green hydrogen energy, as a means of mitigating climate change and meeting Nigeria's rapidly increasing industrialization and energy demands. Given the growing population and changing climate, which will lead to a rise in energy consumption, a thorough evaluation of the future availability of water for hydroelectric power generation is necessary, as well as the impact of the changing climate on the dwindling streamflow, and the assessment of the hydropower resources' potential for green hydrogen production. Accurate analysis based on timely hydro-climatic and hydropower generation data, as well as future climate projections, is necessary to achieve this goal. In most cases, information on future changes in hydropower, streamflow, and potential green hydrogen production in hydropower resources in the Niger River Basin, particularly the Jebba Dam in Nigeria, is not readily available or does not exist. This is a significant research gap.

Therefore, this proposed study will contribute toward addressing this research gap. This study will address this gap by examining the suitability of different climate models and their ensembles in replicating in situ climatic scenarios to project future changes in streamflow, hydropower generation, and the potential for green hydrogen production at the Jebba Dam in the Niger River Basin. The climate model output will be used to forecast potential hydropower generation, study the interface between the climate-water-energy nexus, and estimate future potential for green hydrogen production from hydroelectric dam resources as an option for climate change mitigation. This research is significant for the study area because of its strategic location and importance to hydropower generation in Nigeria. The study will enable decision-makers and stakeholders to assess the future availability of water resources for hydroelectric energy generation and quantify potential green hydrogen production from hydropower resources, given a deeper understanding of the effects of a changing climate. The findings will inform policy-making and enhance the nation’s adaptation and mitigation strategies to meet the impending increase in electricity demand, avert an energy crisis, and collectively work towards achieving the nation's net-zero carbon neutrality.

1.2 Literature review

1.2.1 Concepts and Definitions

i. **Climate change:** this depicts long-term changes in the Earth's climate system, including variations in precipitation, temperature, wind patterns, and other elements (Basu et al., 2025). It is a lasting alteration in the condition of the climate, noticeable through changes in its average conditions and variations. This phenomenon can be triggered by natural forces such as the solar cycle or volcanic activity, or by persistent human-driven factors, including changes in land use or the atmosphere's composition (IPCC, 2013).

ii. **Climate model:** A climate model is a sophisticated computational tool that simulates the mathematical formulas that reflect the established principles of physics of the Earth's climate system (Yang et al., 2020). This system encompasses interacting components such as the atmosphere, oceans, land surface, and ice (Yang et al., 2020). These models are indispensable in climate science for predicting future climate scenarios, informing policy decisions, and guiding economic changes in response to climatic shifts (Elsherif & Taha, 2025). They capture a wide array of interacting dynamic processes through complex ordinary and partial differential equations (Elsherif & Taha, 2025).

iii. **Downscaling:** This is a scientific technique used to convert data from a coarse spatial resolution into a finer, more precise geographical or temporal resolution (Benestad, 2016; Ghosh et al., 2024). It enables the translation of large-scale climate outputs into localized projections using modeling or empirical relationships (IPCC, 2013).

iv. **Emission scenario:** This describes potential future releases of greenhouse gases and aerosols, constructed from consistent demographic, economic, and technological assumptions. Derived concentration scenarios are then used in climate models for projections (IPCC, 2013). They have been adapted to take into account advances in science and trends in world development (Burgess et al., 2023).

v. **Ensemble:** this is a set of climate model simulations used for predictions or projections, where variations in starting conditions and model design highlight uncertainties from model error and climate variability (IPCC, 2013).

vi. **Green hydrogen:** This is a type of hydrogen that is generated by utilizing renewable electricity to split water into hydrogen and oxygen, such as hydropower, photovoltaics, wind turbines, etc. (Abhinav & Emanuele, 2021). Its production is essentially emissions-free, making it a crucial facilitator of deep decarbonization in a number of industries (Pathak et al., 2025; Maka & Mehmood, 2024)

vii. **Greenhouse gases (GHG)**: these are natural or human-made gaseous constituents that absorb and release energy at certain wavelengths of terrestrial radiation, leading to the greenhouse effect. The main examples are water vapor, carbon dioxide, methane, nitrous oxide, and ozone (IPCC, 2013).

viii. **General Circulation Models (GCMs):** This mimics the flow of mass and energy from one section of the atmosphere to another using a system of mathematical equations. They split the atmosphere and ocean into three-dimensional cells, each of which transmits mass and energy to its neighbors based on the results of equations within the cell. In theory, these are the same models that are used to forecast the weather, but they are run on a larger (global) scale and for centuries instead of days (Lee Hannah, 2022).

ix. **Hydrological cycle:** This is often known as the water cycle, and is the continual circulation of water within the Earth-atmosphere system, principally driven by solar energy. This basic mechanism is crucial for maintaining life and regulating the climate (Moser et al., 2019). It encompasses several key phenomena, including runoff, infiltration, precipitation, condensation, evaporation, and subsurface flow.

x. **Hydropower:** This is a renewable source of electricity that relies on water and is environmentally friendly, especially in light of future climate change. It reduces carbon emissions by producing energy utilizing water turbines coupled with generators while optimizing the rotational speed of the water turbines through the use of a head. Since it has a greater energy density compared to other alternative sources, it is considered a valuable resource for development (Jung et al. 2021).

xi. **Projection:** This describes possible future states of a system, estimated using models. They differ from predictions because they rely on specific assumptions, such as societal or technological trends. (IPCC, 2013).

xii. **Socio-economic scenario:** this represents a possible future pathway based on key drivers such as population growth, GDP, and other social or economic variables that shape climate change outcomes (IPCC, 2013).

xiii. **Resolution:** In climate modeling, spatial resolution refers to the grid spacing (in meters or degrees) used for calculations, while temporal resolution indicates the time step between successive computations. (IPCC, 2013).

xiv. **Water security:** this is the sustained access to enough clean water, safe for all people, enabling livelihoods, well-being, and socioeconomic development. This concept also involves protecting against disasters linked to water crises and pollution, while safeguarding ecosystems in a peaceful and stable political environment (UN-Water, 2013).

1.2.2 Climate change impact on water resources

Climate change has a significant impact on water supplies in the Niger River basin, affecting water availability, flow regimes, and groundwater recharge (Boko et al., 2020; Nonki et al., 2019; Oguntunde & Abiodun, 2013; Oguntunde et al., 2018). It significantly contributes to alterations in water balance, streamflow, and lake water volume, thereby impacting ecosystems and energy production (Abera et al., 2024). Droughts and floods are becoming more often due to rising temperatures and changed precipitation patterns, which disrupt water supply systems, hydropower production, and agriculture (Abdoulaye et al., 2021; Aich et al., 2016). Likewise, rising temperatures intensify extreme precipitation events and floods, especially in small watersheds (Wang et al., 2025). As emphasized by Gain et al. (2012), the planet's ecosystem is impacted by climate change, and hence, the livelihoods and general well-being of people are often affected by water-related events (e.g., droughts and floods). In addition to changes in climate, current economic expansion, demographic shifts, and associated land-use changes all contribute to the rising demand for water supplies. Bates (2008) reported Intergovernmental Panel on Climate Change (IPCC) scientists anticipate that the current rise in greenhouse gas concentrations will directly affect the global hydrological cycle, affecting water availability and demand through changes in rainfall, evaporation, streamflow, and sea level rise, among other first-order effects. In light of this changing climate, the availability of water resources in West Africa is crucial for the overall well-being of the population and the region's economic development. Most notably, West Africa has already experienced a rise in sea levels, increased temperatures, significant shoreline erosion, dwindling water availability, erratic rainfall, and more as a result of climate change (Babalola et al., 2021). In this regard, understanding the future effects of climate change on the seasonality of river discharge is crucial for a more precise and quantitative understanding of the water available for various purposes. Most especially, because knowledge about the seasonality of river discharge is necessary for recognizing significant interannual hydrological processes. Evaluating the effects of a changing climate on water availability involves hydrologic modeling, statistical downscaling, and consideration of climate projections (Soriano & Herath, 2020). In an assessment conducted by Aich et al. (2016), utilizing a model based on ecohydrological processes (SWIM) to assess future flood risk, considering both land use and climate change. It was noted that climate change, combined with land-use changes, can increase flood risk in the Niger River Basin (Aich et al., 2016). Additionally, land use and climate change both significantly impact streamflow, necessitating a thorough examination for effective water resource management (Mahmood et al., 2024). Furthermore, Lawin et al. (2018) conducted a study to assess the impacts of climate and land-use change on future flows in the Bétérou basin. Based on the combination of climate change scenarios, RCP 4.5 and RCP 8.5, with land use/cover change scenarios, the future flows in the Ouémé River at the Bétérou outlet were estimated. Their results showed that the Ouémé River at the Bétérou outlet will have a higher discharge for all time horizons till 2050 and for all combined scenarios of climate change and land-use change, relative to the 2002–2004 baseline period. Furthermore, in West Africa, Babalola et al. (2021) did similar studies to assess the effects of climate change on the seasonal flow of two West African rivers, namely, the Hadejia-Jama'are, Komadugu Yobe, and Niger Basin. The findings of their multi-model median on climate change indicate that future river flow patterns in river basins will be altered over time due to climate change. Precipitation-influenced basins were seen to consistently raise streamflow quantities in the latter stages of the high-flow season.

1.2.3 Climate change uncertainties and their impact

There are several uncertainties regarding climate change projections that come from internal climate variability, climate models, and scenarios (Liu et al., 2022; Pan et al., 2024; Rahman et al., 2018). These uncertainties arise from various sources, including the choice of Representative Concentration Pathways (RCPs), Shared Socioeconomic Pathways (SSPs), and the climate models used, and internal climate variability (Liu et al., 2022; Okkan et al., 2023). Understanding and quantifying these uncertainties is crucial for developing effective climate change mitigation and adaptation strategies (Tao et al., 2018; Alizadeh et al., 2022;Koo et al., 2020). Some of these sources of uncertainty are;

i. **Scenario Uncertainty:** SSPs and RCPs represent different future socioeconomic development and greenhouse gas emission trajectories, leading to varying climate outcomes (Kim et al., 2014; Okkan et al., 2023). SSPs describe broad socioeconomic trends, while RCPs specify greenhouse gas concentration pathways (Okkan et al., 2023). The combination of SSPs and RCPs creates scenarios that explore a range of possible futures. For example, SSP1-2.6 represents a sustainable pathway with low emissions, SSP2-4.5 represents, middle of the road, signifying business as usual, SSP3-7.0 represents regional rivalry leading to low international priority to address climate change and environmental degradation, while SSP5-8.5 is a fossil-fueled development pathway with high emissions (Aryal et al., 2018; Georgopoulou et al., 2024). The choice of scenario significantly influences projected climate changes (Kim et al., 2014).

ii. **Climate Model Uncertainty:** Climate models, including General Circulation Models (GCMs), simulate the Earth's climate system and project future climate conditions (Okkan et al., 2023). However, these models have structural and parametric uncertainties that contribute to the variability in climate projections (Alizadeh et al., 2022; East et al., 2022). Different climate models may yield different results even when using the same scenario (Okkan et al., 2023). For example, variations in climate sensitivity (the degree to which the Earth's climate will warm in response to a doubling of atmospheric CO2 concentrations) among models contribute to the spread in projections (Scafetta, 2023).

iii. **Internal Climate Variability**: This refers to natural fluctuations within the climate system, such as El Niño-Southern Oscillation (ENSO) and other atmospheric and oceanic patterns (Liu et al., 2022; Rahman et al., 2018). This variability can influence regional climate and extreme weather events, adding uncertainty to climate projections, especially at shorter time scales (Liu et al., 2022; Rahman et al., 2018).

Uncertainties in climate change projections have significant implications for impact assessments and adaptation planning (Liu et al., 2022; Koo et al., 2020). For example, uncertainties in regional climate projections can affect assessments of water resource availability (Georgopoulou et al., 2024). Understanding the range of possible climate futures and their associated probabilities is crucial for making informed decisions about mitigation and adaptation strategies (Koo et al., 2020). It is impossible to overstate the uncertainty surrounding the evaluation of climate change's impact on water resources using climate models. However, in this study, the uncertainty range was minimized by analyzing the model ensemble mean for the selected General Climate Models (GCMs) and Regional Climate Models (RCMs).

1.2.4 Climate change adaptation and mitigation

Climate change adaptation refers to actions taken to minimize the negative impacts of climate change, while mitigation involves efforts to reduce or prevent the emission of greenhouse gases

(Bangar et al., 2020; Fotedar, 2025; Khan et al., 2023). Adaptation aims to reduce vulnerability and enhance the ability of communities and ecosystems to cope with the impacts of climate change (Khan et al., 2023). But, mitigation focuses on reducing greenhouse gas emissions and enhancing greenhouse gas sinks to limit the magnitude of climate change (Fotedar, 2025; Bangar et al., 2020). These strategies aim to address the root causes of climate change by decreasing anthropogenic impacts on the climate system (Fotedar, 2025). Both strategies are crucial for addressing the challenges posed by climate change, though they differ in their approach and goals (Harry & Morad, 2013). Although there has been an increase in highly severe emission control policies, it is expected that greenhouse gas concentrations will continue to rise in the short term (Abbas et al., 2018). This calls for probable solutions, such as adopting green hydrogen energy, which has net-zero carbon emissions and can gradually replace fossil fuels, thereby contributing significantly to greenhouse gas emissions.

1.2.5 Green hydrogen as an option for climate change mitigation.

The development of green hydrogen aligns well with the global strategy to reduce greenhouse gas emissions, protect the environment, and fight climate change. Green hydrogen technologies, which produce no greenhouse gases, enable the decarbonization of many human activities, including transportation, industry, manufacturing, and energy storage, while also offering economic opportunities for West African nations (Ballo et al., 2022). Green hydrogen has the potential to be a major driver in the worldwide shift toward sustainable energy and net-zero-emission economies (Abhinav & Emanuele, 2021). There is widespread enthusiasm globally to realize hydrogen's long-held promise as a clean energy source. Due to their large renewable energy potential, West African countries can meet their electricity needs by developing green hydrogen (Ballo et al., 2022). For example, hydropower capacity is enough to fulfill all energy demands in West African nations (Karaki, 2017). According to Sadik-Zada (2021), the widespread production and availability of green hydrogen can help to fill the gap between Europe's and Africa's energy transition and sustainability and development goals, respectively.

1.2.6 Status of green hydrogen energy in West Africa

In a law and policy review conducted by Ballo et al. (2022), it was stated that currently, the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) produces the Atlas of Green Hydrogen Generation Potential (H_2Atlas) in fifteen (15) West African countries. According to the H_2Atlas–Africa project funded by the Federal Ministry of

Research, Technology, and Space, BMFTR's Energy and Hydrogen Technologies Department (H2Atlas-Africa, 2021). Many ECOWAS countries have excellent prerequisites for producing green hydrogen. The area is projected to generate as much as 165,000 terawatt-hours of green hydrogen annually, which is roughly 1,500 times greater than Germany's anticipated hydrogen demand by 2030. Notably, around 75% of the land in ECOWAS member states is considered appropriate for wind turbine installations. By harnessing renewable energy, countries in West Africa have the capacity to generate as much as 165,000 terawatt-hours of green hydrogen per year, with about 120,000 terawatt-hours achievable at costs below €2.50 per kilogram, significantly lower than the €7–10 per kilogram range in Germany (Meza, 2021). Green hydrogen presents a significant opportunity for the ECOWAS region, positioning it as a potential global hub while enabling member states to address their energy demands and gain economic advantages through exports (Ballo et al., 2022). The study considers the production of green hydrogen from hydropower resources, and its utilization as displayed in Figure 1.

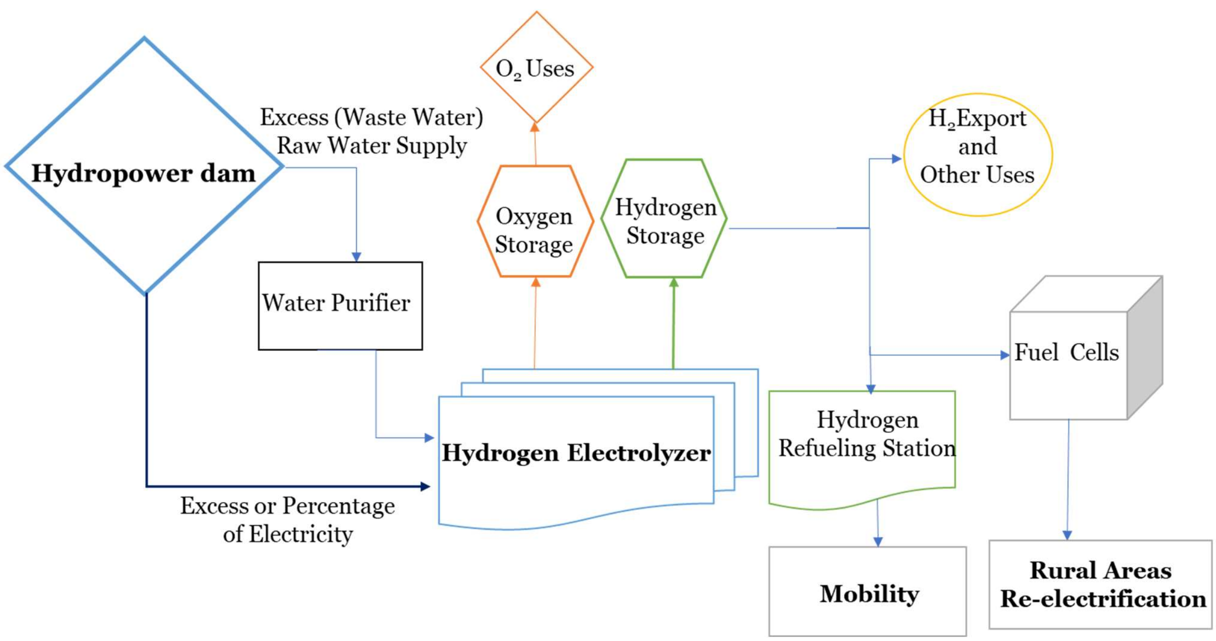


Figure 1: Concept of Hydrogen Production from Hydropower Plant and Utilization.

1.3 Research questions

The broad question is: What is the potential for green hydrogen production from the Jebba hydropower reservoir in the Niger River Basin as a strategy for mitigating climate change?

In detail, the study seeks to address the following questions:

1. Would climate change have a significant impact on the water balance components (precipitation, runoff, and evapotranspiration) in the Niger River Basin?
2. What are the recent trends in hydroclimatic variables (temperature, rainfall, turbine discharge, reservoir inflow and outflow, and evaporation loss), and how do these trends influence hydropower generation for green hydrogen production at the Jebba hydropower dam?
3. Would the impact of climate change increase hydropower energy generation, which would simultaneously increase green hydrogen production potential for climate change mitigation?

1.4 Thesis objectives

1.4.1 General Objective

The general objective is to assess the potential for green hydrogen production from the Jebba hydropower reservoir in the Niger River Basin as an option for climate change mitigation.

1.4.2 Specific Objectives

To achieve the general objective, the study specifically attempts to;

1. Evaluate the impact of climate change on the water balance components (precipitation, surface runoff, and evapotranspiration) in the Niger River Basin.
2. Examine the recent trends in the hydroclimatic variables, hydroelectric energy generation, and green hydrogen potential in the Jebba hydropower station.
3. Analyze future hydroelectric generation and green hydrogen production potential from the Jebba hydropower station under SSP245 and SSP585 scenarios over the future period of 2025-2100, using a base period of 1984-2009

1.5 Novelty

Insufficient information and limited quality research data have hampered strategic planning and evaluation of hydropower resources for potential climate change mitigation in Nigeria. The existing observational hydroclimatic data are insufficient for investigating probable climate extremes that could significantly impact the capacity of hydropower reservoirs. Adaptation and mitigation have not received considerable attention due to the lack of a climate change impact assessment of the hydropower energy system, particularly for the Jebba hydropower dam. To understand the future climate extreme events at a river basin, it is necessary to use downscaled climate model outputs to represent the basin's intrinsic water-energy nexus and predict future changes in hydropower generation as a renewable energy source. Given this, there is a need to fill this research gap, as it is necessary to put preventive measures in place to avert an impending energy crisis and ensure energy security. Furthermore, in the face of variability in water resources availability, the study also objectively addresses the feasibility of green hydrogen energy production from hydropower resources as an alternative to fossil fuels, which has been proven to be an adaptable mitigation strategy for greenhouse gas emissions in different nations because of its net-zero carbon emission. The above-mentioned areas of study have not been adequately addressed in the study area; hence, they were given priority in this thesis. This will improve our understanding of the future availability of water resources for hydropower and green hydrogen production as an option for climate change mitigation in Nigeria.

1.6 Scope of the thesis

The study examined the interplay between climate change and water resources (streamflow prediction) for hydropower and green hydrogen energy potential generation in Nigeria's Niger River basin area, with the Jebba Dam reservoir as the primary focus. It focused on the trend test and detection of abrupt change points in the observation time series. Other elements include the statistical analysis of the hydroclimatic variables such as precipitation and temperature in the river basin, analysis of reservoir inflow and hydropower generation in the hydropower reservoir at both historical and future time slices under CMIP6 climate scenarios (the shared socio-economic pathways-SSPs) for probable climate change at the end of the century (21st Century). This also includes the river basin's land surface modeling to assess the impact of climate change on water balance components (precipitation, evapotranspiration, and runoff) under RCP2.6 and RCP8.5. Additionally, the scope includes evaluating future changes in streamflow, hydropower, and green hydrogen production potential as options for climate change mitigation and energy security in Nigeria under the SSP245 and SSP585 scenarios**.** The study is limited to one hydropower dam, the Jebba Dam; however, it provides a detailed framework and preliminary insights that can be applied to other hydropower dams across the country. Scaling up this approach will enable a comprehensive evaluation of Nigeria's hydropower potential for green hydrogen production, supporting the transition to a clean and renewable energy system. Future research could explore forecasting hydropower demand under various scenarios, taking into account factors such as population growth, industrial development, and climate change. These projections would help understand how hydropower generation could meet electricity and green hydrogen production needs.

1.7 Expected results and benefits

At the end of this thesis, the following results will be obtained;

1. Impact of climate change on the water balance components (precipitation, runoff, and evapotranspiration) in the Niger River Basin are analyzed.
2. Recent trends in hydroclimatic variables and the effect on hydropower generation for green hydrogen production in the Jebba hydropower station are evaluated.
3. Future changes in the reservoir inflow, hydropower generation, and green hydrogen production potential for achieving net-zero carbon emissions and climate change mitigation in Nigeria are projected.

This research is expected to benefit the country by obtaining relevant information and data concerning the impact of climate change on water balance components and hydropower generation in the Niger River Basin, with a focus on Jebba Reservoir. The expected variations in green hydrogen production potential may contribute to shaping policy and regulatory measures that advance national energy transition and efforts to combat climate change.

1.8 Outline of the thesis

Chapter 1 provides a comprehensive introduction to the subject, summarizing the relevant literature. This chapter explored the concepts and definitions of climate change, water resources, hydropower generation, and green hydrogen production. Furthermore, the problem statement, justification of the study, general and specific objectives, and expected results are covered. Chapter 2 describes the study area and its hydroclimatic characteristics. Chapter 3 describes the data collected for the study. Chapter 4 detailed the impact of climate change on the water balance components —namely, runoff, evapotranspiration, and precipitation —using a land surface model, the Community Land Model 5 (CLM5). Chapter 5 describes the recent analysis of hydroclimatic trends and energy generation, as well as the potential for green hydrogen production. The trend analysis was performed on both annual and monthly timescales, utilizing the Modified Mann-Kendall test and Pearson correlation coefficient to analyze the data. Chapter 6 projected future changes in streamflow, hydropower generation, and green hydrogen production potential at the Jebba hydropower dam from 2025 to 2100 under the SSP245 and SSP585. Chapter 7 summarizes the results, concludes the thesis, and presents the perspective of the work based on the results obtained.

CHAPTER 2: STUDY AREA

This chapter establishes the essential geographical, climatic, and hydrological context for the research study area. It begins by defining the primary study area, detailing the regional location of the Niger River Basin. Following this description, the chapter provides a detailed explanation of the basin's key climatic characteristics. This section focuses specifically on rainfall patterns, temperature regimes, and the resulting runoff dynamics, as these factors are the fundamental drivers of the region's water resources. Finally, the chapter narrows its focus from this broad basin-level context to the specific site of investigation, presenting a comprehensive description of the Jebba hydropower dam.

2.1 Location

The Niger River Basin (NRB) is the largest river basin in West Africa and the third-longest river in Africa, as seen in Figure 2, spanning 2.27 million square kilometers and situated between latitudes 5° N and 24° N and longitudes 12° W and 17° E. The basin is delineated by an unusual flow through ten shared countries, including Guinea, Mali, Niger, Nigeria, Benin, Burkina Faso, Cameroon, Chad, and Côte d'Ivoire. Out of the active river basins, Nigeria has 562,372 km², accounting for 44.2% of the total active basins. According to (Andersen & Golitzen, 2005). The basin exhibits two distinct seasonal variations: a rainy summer and a dry winter. Nigeria, which has two major seasons, is also characterized by these seasonal patterns, with the rainy season (April-October) and the dry season (November-March). The annual humidity, sunshine, and wind speed in the basin vary depending on the season and location. Evapotranspiration is a crucial factor in the hydrologic cycle of the basin, influencing water availability and land-atmosphere interactions in the region. The annual evapotranspiration in the Basin varies depending on several factors, including rainfall, temperature, humidity, and vegetation cover.

2.2 Main Climatic Characteristics of the Niger River Basin

2.2.1 Rainfall:

The annual rainfall in the Basin ranges from less than 100 millimeters (4 inches) in the Sahel zone to over 1,200 millimeters (48 inches) in the tropical Guinea zone (Andersen & Golitzen, 2005). According to Animashaun et al. (2020), It was noted that the basin experiences high rainfall variability, ranging from 250-750 mm/yr in the Sahelian zone to over 2,000 mm/yr close to the river mouth in the Guinean zone.

2.2.2 Temperature

The coastal regions have an average annual temperature range of 21°-28 °C, which is 70°-82°F, while the inland northern regions have a range of 12°-29 °C, which is 54°-84°F, that fluctuates with the seasons. The climate of the Basin is affected by the movement of air masses from the Intertropical Convergence Zone (ITCZ). During the summer, the rise of the Saint Helena high-pressure area marks the onset of the monsoon season, characterized by humid, unstable air and cooler temperatures. The winter season is dry and characterized by the influence of the Saharan high-pressure zone and the north-eastward harmattan wind, bringing hot and dry air with high temperatures; for example, the relative humidity can drop to 15-10%, contributing to the dry conditions, while the daytime temperature can be range between 30-40°C and night time temperature can cool to as low as 10 -15°C (Andersen & Golitzen, 2005).

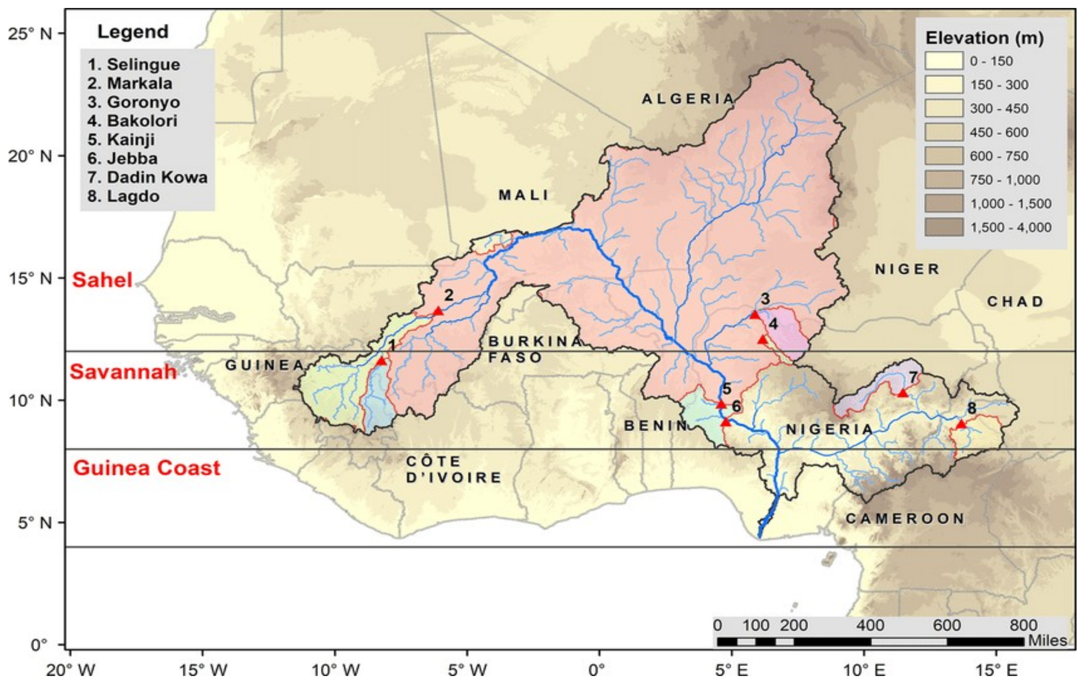


Figure 2: Map of Niger River Basin showing hydropower dams(Yue et al., 2022), the study focuses on the 6th dam (Jebba Dam).

2.2.3 Runoff

The quantity of water that flows into the river and its tributaries over one year, known as annual runoff, is subject to various factors such as precipitation, evapotranspiration, soil moisture, and land use practices. Due to the large variability in rainfall, the annual runoff in the Basin varies greatly from year to year. The average river flows in the Niger Basin, according to a report by the Nigeria Hydrological Services Agency, (2020), the low flow discharge measurement at

Jiderebode was 663 m^3/s, Kainji Dam was 1,250 m^3/s in February, 2018 and Baro was 3,540.422 m^3/s as at March 2018. However, at the Lokoja gauging station which is a critical station located at the confluence of the Niger and Benue Rivers, the river flow has an average daily streamflow of 6,332 (m^3/s) which was recorded over a long-term period of 1915-2019, according to the study by (Afolabi, 2025), while the river flow measured at the Onitsha monitoring station before 1960 and between 1980 and 2004, are 7000 m^3/s and 4720 m^3/s, respectively (Andersen & Golitzen, 2005). Moreover, the annual discharge ranges between 193 km^3/yr in Gaya (Abdoulaye et al., 2021; Dai & Trenberth, 2002) and 183 km^3/yr at the confluence of the Niger and Benue rivers (Abdoulaye et al., 2021; Ogilvie et al., 2010). A significant part of the basin has major reservoirs in the lower basin, namely, Kanji, Jebba, and Shiroro reservoirs. The case study being investigated for this study is the Jebba reservoir.

2.3 Jebba hydropower reservoir

Nigeria has around 60 significant dams, with the most notable three (Kanji, Jebba, and Shiroro) with a total storage capacity of 34,800 (MCM: million cubic meters), located in the region under study (JICA, 2014). The study focuses on Nigeria's second biggest hydropower dam, the Jebba Dam, as displayed in Figure 3. Jebba hydropower dam has six-generation turbines, each with a rated capacity of 96.4 megawatts, for a maximum installed output of 578.4 megawatts. Jebba Dam is about 100km downstream of the Kainji Dam, and it is a cascaded dam on the Niger River Basin, with outflow from the Kainji Dam serving as the primary inflow to the dam, as seen in Figure 4.

2.3.1 Climate

The Jebba Dam is located in a transitional climatic zone influenced by dry continental trade winds during the dry season and moist maritime equatorial air during the wet season. Rainfall occurs mainly between April and October, driven by moist air masses from the south. In contrast, the period from November to March is typically dry, influenced by Saharan winds from the north. The climate is classified as hot equatorial, characterized by high temperatures, with the warmest month recording an average daily maximum of about 33.5 °C and a mean annual temperature of roughly 30 °C. Annual precipitation in the lake area is approximately 1,000 mm, concentrated almost entirely between mid-April and mid-October (Liman et al., 2023). A large portion of it is linked to line squalls that occur in the late afternoon as well as the early morning.

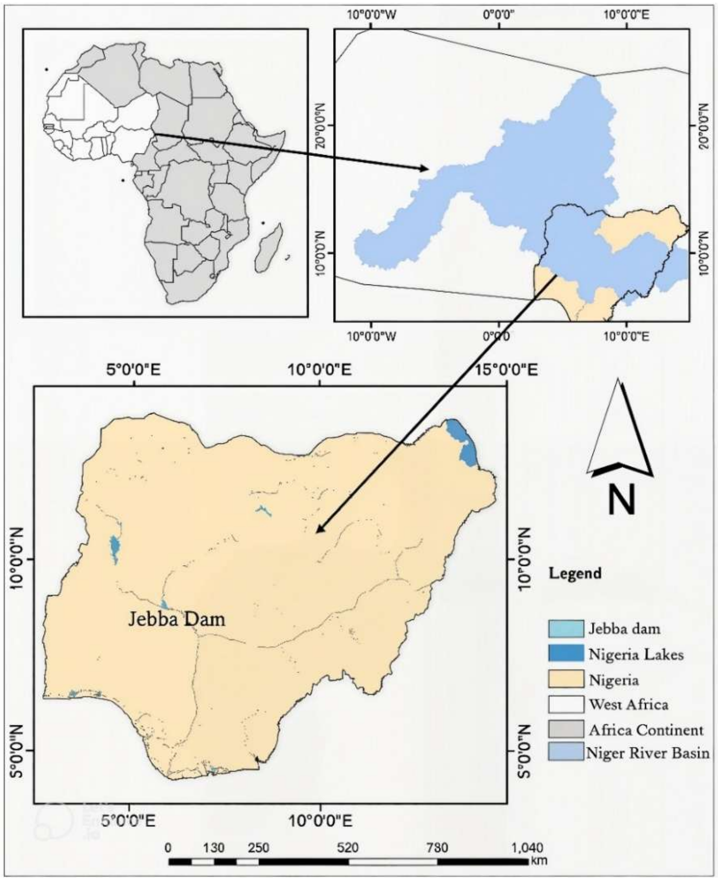


Figure 3: Jebba Dam in Nigeria

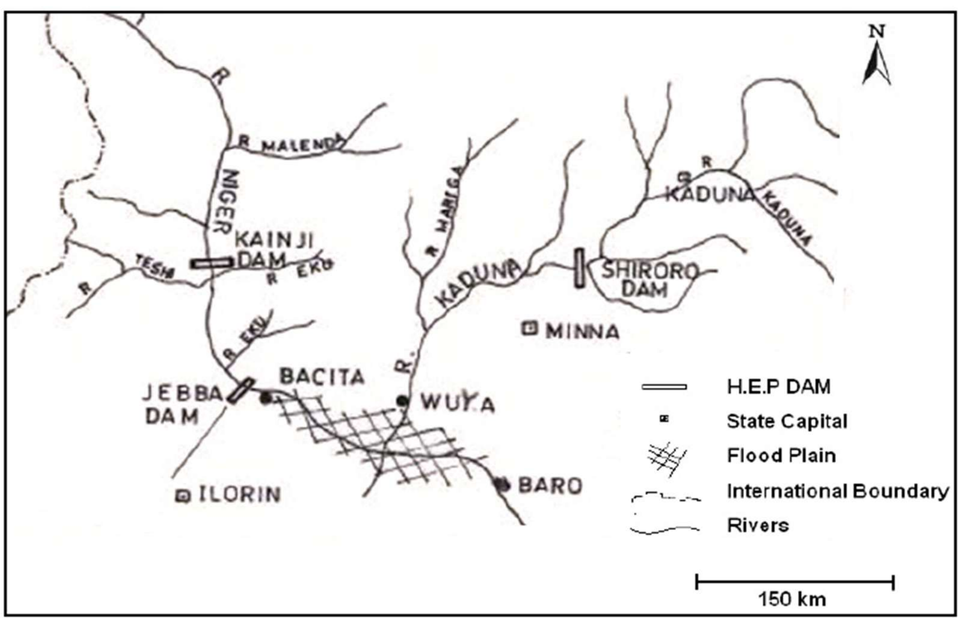


Figure 4: Map of Cascaded Jebba Dam showing inflow from Kanji dam (Olukanni & Salami, 2012).

2.3.2 Geology

Jebba Dam lies within the African basement complex terrain, characterized by diverse rock formations, including granite, diorite, hornblende-biotite gneiss, mica quartzite, pegmatite, and dolerite (the latter two occurring as intrusive rocks). Upstream at the Kainji Dam, these lithologies are well-exposed. Granite gneiss dominates the region, covering roughly half of the area, while diorite and quartzite account for about 10%. The remaining 30% is made up of dioritic and hornblende-biotite gneiss. In addition, both concordant and discordant pegmatite veins, ranging from 3 to 25 cm in thickness, are found within the gneiss (Olatunji & Abdulfatai, 2022).

2.3.3 Hydrology and Water Resources

Approximately half of Jebba Lake's annual inflow originates from releases at Kainji Dam, as seen in Figure 3. This inflow results from basin runoff south of Niamey, forming the so-called "white flood", which enters the lake from mid-August through December. The floodwaters are highly turbid and greyish in appearance, rising sharply to a variable peak before receding by late September or early October. The remaining inflow comes from rainfall in the Niger headwaters located in the Guinea Highlands. After flowing through the plains around Timbuktu, this clearer water, termed the "black flood", arrives later. It begins rising in October and persists until May, with its peak occurring in February and tapering off toward late April. In years of high discharge, the total annual flow can reach about 80,000 million m^3, with roughly 47,000 million m^3 contributed by the white flood and the remaining 33,000 million m^3 from the black flood. While the black flood is relatively stable each year, the white flood can decrease by up to one-third during dry periods (Ugbor et al., 2023). The major rivers feeding the dam catchments include the Niger, Olli, Kaduna, and Gurara, along with their numerous tributaries. Both Kainji and Jebba reservoirs, situated along the Niger River, provide the main water supply for the Kainji and Jebba hydropower plants. Notably, Kainji Lake functions as the head reservoir supporting power generation at both stations.

2.3.4 Vegetation

The vegetation of Jebba Dam lies within the Northern Guinea Savanna. The tree vegetation of the area exhibits a notably uniform floristic composition, with only minimal influence from variations in structure. Most species are characteristic of the savanna, showing fire resistance or tolerance and the ability to regenerate effectively through coppicing or root suckers. In certain parts of the Southern Guinea Zone, fire-sensitive species are mainly found in the lower layers of mature savanna woodland, although they are generally scarce. This overall uniformity in species composition is largely attributed to the limited variation in moisture availability across habitats. The soils, which are often deep, porous, and well-drained, create favorable conditions for plant growth.

2.3.5 Land Use

The floodplains surrounding the Jebba Reservoir are highly fertile and widely cultivated, with soil fertility continually renewed by seasonal flooding. The relatively flat terrain also enhances accessibility, supports construction, ensures a reliable water supply, and facilitates other services. Consequently, despite the risks associated with flooding, communities have historically settled in these areas. Currently, about 14 settlements with a combined population of approximately 6,099 people, originating from the initial 42 villages, are situated within the Jebba Dam floodplain. Generally, agricultural lands downstream of the dams remain prone to flood-related damage. Therefore, promoting sustainable development in the project area requires that communities living along the floodplains are fully engaged and adequately informed.

2.3.6 Demography

An estimated 437,212 people reside within the dam catchments, which span Niger, Kwara, and Kebbi States. These populations are distributed across 438 settlements and 44,432 households. A recent flood risk assessment revealed that about 103 communities, with a combined population of 131,918, are vulnerable to flooding. These at-risk settlements are predominantly inhabited by farmers and fishermen living close to the reservoirs or along the Niger River. The dominant religions in the project area are Islam and Christianity, with a smaller proportion practicing African Traditional Religion; however, Muslim communities form the majority around both dam sites. Social organization in the area is strongly tied to informal work exchange networks, which play a vital role in farming, fishing, and women’s processing activities. In addition, informal savings and credit associations, locally referred to as adashe or esusu, are more widespread in the southern Jebba area compared to the northern Kainji zone, where cooperative societies are less common.

2.3.7 Economic activities and socio-economic status, and vulnerability

The socio-economic profile of households within the dam catchment areas reveals an average annual income of approximately 28,675 Naira. Livelihood strategies vary across communities, with multiple activities contributing to household earnings. Although crop farming is the most widespread occupation, fishing represents the most significant source of income at the aggregate level, reflecting the dependence of riparian communities on aquatic resources.

2.4 Partial Conclusion

This chapter provides an overview of the study area, covering its location, climate, geology, hydrology, vegetation, land use, economic activities, and socioeconomic conditions. The Niger River Basin (NRB), spanning 2.27 million km² across West Africa, displays diverse climatic and hydrological features. Rainfall varies from less than 100 mm in the Sahel to over 1,200 mm in the Guinea zone, significantly affecting evapotranspiration and runoff patterns. Seasonal variations marked by dry harmattan winds in winter and moist equatorial air in the rainy season further shape the basin's hydrological cycle. River flow fluctuates greatly across gauging stations. For example, average low flows recorded in 2018 ranged from 663 m^3/s at Jiderebode to 3,540.4 m^3/s at Baro, while long-term data at Lokoja indicated an average streamflow of 6,332 m^3/s (1915–2019). The Onitsha station recorded flows of 7,000 m^3/s before 1960 and 4,720 m^3/s between 1980 and 2004. This study specifically focuses on the Jebba hydropower dam in Nigeria, the country's second-largest hydropower plant, which features six turbines with a total capacity of 578.4 MW. Located within the Northern Guinea Savanna, the region experiences distinct dry and wet seasons. Approximately half of Jebba's inflow comes from Kainji Dam, with peak inflows occurring between August and December. The vegetation surrounding the dam is fairly uniform, and the floristic structure remains consistent across different physiographic areas. Socioeconomic assessments of the catchment area, which includes parts of Niger, Kwara, and Kebbi states, reveal a population of over 437,000 across 438 settlements. Of these, around 132,000 residents in 103 communities are vulnerable to flooding. The average household income per year is 28,675 Naira, with contributions from farming, fishing, and trading.

Following this partial conclusion, this chapter lays the foundation for the next chapter, which discusses the data, materials, and methodologies used in this research.

CHAPTER 3: DATA, MATERIALS, AND METHODS

This chapter outlines the various types of data collected, the sources and methods used to collect and analyze them, as well as the tools and materials employed. It is divided into three sections. The first section deals with data collection, sources, and pre-processing. The second section deals with the materials and model description. The last section describes the trend analysis of hydroclimatic variables, the impact of hydroclimatic trends on energy generation using the Pearson correlation coefficient, and methods for analyzing climate change impacts on future changes in water balance components and predicting future changes in hydropower generation and green hydrogen production potential.

3.1 Data

3.1.1 Hydroclimatic and hydropower data

Hydroclimatic and power generation data for the Jebba hydropower reservoir were sourced from Mainstream Energy Solution, the operator of the Jebba Hydropower Station. The dataset includes monthly records of rainfall, mean maximum temperature, reservoir inflow and outflow, evaporation losses, turbine discharge, and electricity generation. Observed rainfall data for Jebba dam neighboring stations (Ilorin, Bida, Minna, and Lokoja) were obtained from NiMET (Nigerian Meteorological Service Agency). For basin-scale analysis, the rainfall data from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) version 2, developed by the Climate Hazards Group of the University of California, was used. The daily rainfall dataset was downloaded at a basic scale using the feature of a custom polygon region for the Niger River Basin (NRB) in the Google Climate Engine App, accessed via the link https://app.climateengine.com/climateEngine. The length of the data collected was from 1981-2022. The CHIRPS dataset provides quasi-global rainfall coverage between 50°S and 50°N, extending from 1981 to the present. It integrates satellite imagery at a 0.05° × 0.05° spatial resolution with ground-based station observations to generate gridded precipitation time series, making it suitable for applications such as trend detection and seasonal drought monitoring (Chris, Funk et al., 2014). It can be freely accessed at http://chg.geog.ucsb.edu/data/chirps/. To ensure data quality, the datasets were visually inspected to identify outliers, and the data was graphically visualized using time series plots in Microsoft Excel. Additionally, the CHIRPS rainfall dataset was selected based on three criteria: its long-term data availability (1981-2022), which spans more than 40 years; zero percentage of missing data; and good representativeness of the entire river basin. Table 1 presents the spatial and temporal resolution of the datasets used in the study and their corresponding years of record.

Table 1**:** Hydroclimatic data for trend analysis

Variable	Data Type	Resolution	Temporal	Spatial	Source
Max. Temperature	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Reservoir Inflow	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Reservoir Outflow	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Lake evaporation	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Turbine Discharge	Observed	Monthly	1984 – 2009	Jebba Dam	JHS
Energy generated	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Rainfall	Observed	Monthly	1988 – 2018	Jebba Dam	JHS
Rainfall	Observed	Daily	1992 – 2021	Ilorin Station	NiMET
Rainfall	Observed	Daily	1992 – 2021	Bida Station	NiMET
Rainfall	Observed	Daily	1992 – 2021	Lokoja Station	NiMET
Rainfall	Observed	Daily	1992 – 2021	Minna Station	NiMET
Rainfall	Satellite	Daily	1981 – 2022	Niger River Basin	CHIRPS

JHS: Jebba Hydropower Station; **NiMET;** Nigeria Meteorological Agency: **CHIRPS:** Climate Hazards Group Infrared Precipitation with Stations

3.1.2 Land Surface Modelling Data

The CLM5 model setup requires meteorological forcing inputs, including incident shortwave and longwave radiation, air temperature, relative humidity, wind speed, atmospheric pressure, and precipitation, as outlined in Table 2. The meteorological forcing data used for the study was the Coupled Model Intercomparison Project Phase 5 (CMIP5) projection dataset for five Regional Climate Models (RCMs) at a daily time scale, which was obtained from Earth System Grid Federation as outlined in Table 3. Additionally, land surface information, soil information, and vegetation were obtained from CLM5 input files. The dataset was used to set up the CLM5 simulations.

Table 2**:** Community Land Model data requirement for each grid cell

S/N	Data Category	Type of Data	Data Source
1.	Meteorological data	Air temperature, relative humidity, air pressure, wind speed, global radiation, precipitation, and incoming longwave radiation	CMIP5 Climate Model data,
2.	Soil information	Sand content, clay content, and organic matter content	FAO (Food and Agriculture Organization), satellite and field data
3,	Vegetation type	plant functional type and leaf area index	MODIS (Moderate Resolution Imaging Spectroradiometer)

Table 3**:** CMIP5 Regional Climate forcing dataset for CLM5.

S/N	Model Name	Model Full Name	Source
1	MPI-CCLM5	Max Planck Institute Consortium for Small-scale Modeling Climate Limited-area Modeling version 5	ESGF
2	MPI-REGCM4	Max Planck Institute Regional Climate Model version 4	ESGF
3	MPI-REMO2015	Max Planck Institute Regional Model version 2015	ESGF
4	NOR-CCLM5	Norwegian Consortium for Small-scale Modeling Climate Limited-area Modeling version 5	ESGF
5	NOR-REGCM4	Norwegian Regional Climate Model version 4	ESGF

ESGF: Earth System Grid Federation; https://esgf-metagrid.cloud.dkrz.de/search/cordex-dkrz/

3.1.3 Hydrological and hydropower model dataset

The historical dataset includes precipitation, minimum and maximum temperatures over the Jebba dam catchment, reservoir inflow, and reservoir storage for the hydropower station. The precipitation data over the catchment were obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) dataset, while the minimum, maximum, and mean temperatures were obtained from the ERA-5 (fifth-generation ECMWF atmospheric reanalysis of the global climate). The observed reservoir inflow, reservoir storage, and hydropower energy generation data were obtained from the |Jebba Hydropower Station Authority for 1984-2009, as outlined in Table 4.

Table 4: Hydrological and Hydropower Modelling Data

S/N	Data	Periods	Source
1	Precipitation	1984-2009	MSWEP: https://www.gloh2o.org/mswep/
2	Minimum Temperature	1984-2009	ERA5: https://app.climateengine.org/climateEngine
3	Maximum Temperature	1984-2009	ERA5: https://app.climateengine.org/climateEngine
4	Mean Temperature	1984-2009	ERA5: https://app.climateengine.org/climateEngine
5	Reservoir Inflow, Storage for Kainji and Jebba Dam	1984-2009	Kainji Hydropower Station Authority Jebba Hydropower Station Authority
6.	Hydropower Generation for Kainji and Jebba Dam	1984-2009	Kainji Hydropower Station Authority Jebba Hydropower Station Authority

MSWEP: Multi-Source Weighted-Ensemble Precipitation, ERA5: ECMWF Reanalysis v5.

3.1.4 Climate forcing dataset

The CMIP6 climate forcing dataset was obtained and selected from the archive of NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) (https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/index.html) based on the best-performing data over Nigeria for the climate change impact analysis, using the historical (1984-2009) and future data of SSP245 and SSP585 (2025-2100) as outlined in Table 5. SSP245 and SSP585 were chosen because it aligns more with the possible assumptions in Nigeria, in which SSP245 represent, middle of the road, signifying business as usual assuming that social, economic, and technical developments in Nigeria don't significantly deviate from past trends., and SSP585 was chosen is a fossil-fueled development pathway with high emissions, assuming that Nigeria as a nation adopts an energy-intensive lifestyles and continues to exploit its vast abundant supply of fossil fuels in tandem with the drive for economic and social progress. The variables selected include precipitation, maximum temperature, minimum temperature, and Mean temperature. The data was statistically downscaled using the Bias-Correction Spatial Disaggregation (BCSD) method, and the spatial resolution was 0.25 degrees x 0.25 degrees

Table 5: CMIP6 Climate Model Forcing Data.

S/N	Model Name	Model Full Name
1	ACCESS-CM2	Australian Community Climate and Earth System Simulator Coupled Model Version 2.
2	ACCESS-ESM1-5	Australian Community Climate and Earth System Simulator Earth System Model Version 1.5.
3	BCC-CSM2-MR	Beijing Climate Center Climate System Model version 2, Medium Resolution.
4	CanESM5	Canadian Earth System Model version 5.
5	INM-CM5-0	Institute of Numerical Mathematics Coupled Model, Version 5.0.
6	IPSL-CM6A-LR	Institut Pierre-Simon Laplace Coupled Model, Version 6A, Low Resolution
7.	MIROC6	Model for Interdisciplinary Research on Climate, Version 6.
8.	MRI-ESM2-0	Meteorological Research Institute Earth System Model, Version 2.0

3.2 Methods

3.2.1 Statistical Tests

Statistical and trend analysis is one of the most critical measures in studying climate time series data (Hussain & Mahmud, 2019). In a study done by Tadese et al., (2019) Statistical and trend analysis were used to characterize, quantify, and validate the variability and trend of hydro-climatic variables in the Awash River Basin, Ethiopia. Methods such as coefficient of variation (CV), standardized anomaly index (SAI), and graphical methods were used to test for variability of rainfall and streamflow in the study area.

3.2.2 Coefficient of Variation and Standardized Anomaly Index

In this study, the coefficient of variation was employed as a statistical indicator to quantify the degree of variability in rainfall relative to the mean. It is the ratio of the standard deviation to the mean, as calculated using equation (1). For this study, a CV of < 20, ≥ 20 ≤30, and > 30 was considered normal, moderate, and highly variable, respectively. In previous studies, such as (Asfaw et al., 2018; Bekele et al., 2017; Bewket & Conway, 2007; Tadese et al., 2019b) CV was used to characterize rainfall variability.

$$\mathrm{CV} = \frac{\sigma}{\bar{x}} \times 100\ \% \qquad (1)$$

Where σ and $\bar{x}$ denote the standard deviation and mean of rainfall, respectively.

The Standardized Precipitation Index (SPI) or Standardized Anomaly Index (SAI) are methods recommended by the World Meteorological Organization (WMO) and are widely applied for assessing precipitation deficits across varying timescales, typically ranging from 3 to 48 months (Svoboda et al., 2012). SPI has been used in previous studies to analyze the interannual rainfall variability (Lawin et al., 2019). This study obtained the SPI for the annual rainfall records using equation (2).

$$I(i) = \frac{x_i - \overline{x_m}}{\sigma} \qquad (2)$$

Where $I(i)$, x_i, $\overline{x_m}$, and σ are the standardized index of the year I, the value for the year I, the average, and the standard deviation of the time series, respectively. Table 6 presents the guidelines for analyzing and interpreting SPI values (Svoboda et al., 2012).

Table 6: Standardized precipitation index (SPI) values and their meaning

SPI Value	**Meaning**
2.0 and plus	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near Normal
−1 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

3.2.3. Trend Analysis

i. Modified Mann-Kendall trend test: Trend analysis commonly employs both parametric and non-parametric approaches. Parametric tests require data to be independent and normally distributed, whereas non-parametric methods also assume independence but are more robust to outliers (Hamed & Rao, 1998). Nonetheless, parametric tests generally exhibit greater statistical power compared to non-parametric methods (Hussain & Mahmud, 2019). Several tests are used worldwide for trend analysis. One is the Mann–Kendall test (Mann, 1945; Kendall, 1975). Mann–Kendall test is a popular non-parametric method for detecting significant trends in time series. On the other hand, the original Mann-Kendall test did not account for serial correlation or seasonality effects (Bari et al., 2016; Hirsch et al., 1982). In many practical applications, the observed data exhibit autocorrelation, which may distort the interpretation of trend test outcomes (Cox et al., 1955). Conversely, time series related to water quality, hydrology, climate, and other natural processes are typically characterized by seasonal patterns. To address the limitations of the conventional Mann–Kendall test in handling such data, several modified versions of the test have been developed (Hamed & Rao, 1998). The Modified Mann–Kendall (MMK) test, which adjusts the variance of the test statistic (S), offers robustness against autocorrelation and does not rely on any specific distributional assumptions (Hamed & Rao, 1998). In this study, the Modified Mann–Kendall (MMK) test was applied to detect monotonic trends within the time series of hydro-climatic variables and hydropower generation (Yangouliba et al., 2022). Several studies have applied this approach to identify trends in various climatic and hydrological parameters, including precipitation, temperature, and streamflow (Pingale et al., 2016; Aziz & Obuobie, 2017; Abungba et al., 2020). The MK statistic (S) was calculated using equation (3), following the method Mann and Kendall described (Mann, 1945; Kendall, 1975).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}\left(x_j - x_k\right) \tag{3}$$

Where x_j and x_k are sequential data values for time series data of length n. The test statistic represents the number of differences for all the differences between adjacent points in the time series considered (Biggs, 2009) and equates to the sum of the Sgn series, which is defined in equation (4) as:

$$\mathrm{Sgn}(x_j - x_k) = \begin{cases} 1 \text{ if } x_j > x_k \\ 0 \text{ if } x_j = x_k \\ -1 \text{ if } x_j < x_k \end{cases} \quad (4)$$

The mean and variance of S, $E(S)$, and $V(S)$, respectively, under the null hypothesis, H_0, of randomness, given the possibility that there may be ties in the x values (Biggs, 2009), are given as;

$$E(S) = 0 \quad (5)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i[(t_i-1)(2t_i+5)]}{18} \quad (6)$$

Where t_i is the extent of any given tie. $\sum t_i$ denotes the summation of all ties and is only used if the data series contains ties. The standard normal variate Z is calculated using equation (7), as stated by (Biggs, 2009).

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR}(S)}} \text{ if } S > 0 \\ 0 \text{ if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{VAR}(S)}} \text{ if } S < 0 \end{cases} \quad (7)$$

This test offers two main advantages. Firstly, it is non-parametric, meaning it does not assume a normal distribution of the data. Secondly, it is relatively insensitive to sudden shifts that may occur in a non-homogeneous time series (Adonadaga, 2014). In this test, the null hypothesis (H_0) indicates that no trend exists, implying the data are independent and randomly distributed, while the alternative hypothesis (H_1) suggests the presence of a trend (Vukialau-Taoi et al., 2023). The non-parametric trend analysis has a Python package called pyMannKendall, written entirely in Python. This package integrates nearly all variants of the Mann–Kendall tests and was designed to assist researchers in performing trend analysis using Python. The package employs a vectorized approach to enhance computational efficiency and currently includes 11 Mann–Kendall test variants along with 2 functions for estimating Sen's slope. A brief description of all the functions can be found in (Hussain & Mahmud, 2019). This study utilized the pyMannKendall package in Python to carry out the trend analysis.

ii. Homogeneity test: A homogeneity test was done to detect change points in the hydro-climatic data. Three homogeneity tests, namely Pettitt's test, Standard Normal Homogeneity Test (SNHT), and Buishand's range statistics, were used in the study. These methods have been utilized in prior studies, such as Taxak et al. (2014). The Pettitt test is a rank-based technique used to detect significant shifts in the mean of a time series when the exact change point is not predetermined (Pettitt, 1979). It is known for its robustness to changes in the distributional form of the data and its relative power compared to tests such as Wilcoxon-Mann-Whitney and cumulative sum and deviation. It has also been widely applied in detecting changes in climatic and hydrological time series data (Zhang et al., 2016). On the other hand, the SNHT uses a series of ratios to compare the observations of a measuring station to the average of several stations, which are then standardized to obtain the x_i series. The null and alternative hypotheses are given as follows;

Ho: The T variables Xi follow an N (0, 1) distribution.

Ha: Between times 1 and n, the variables follow an N(μ1,1) distribution, and between n+1 and T, they follow an N(μ2,1) distribution. The Pettitt's statistic is defined by;

$$T_0 = \max_{1 \le t \le T} [v z_1^2 + (n - v) z_1^2] \quad (8)$$

With

$$\begin{cases} z_1 = \frac{1}{v} \sum_{i=1}^{v} x_t \\ z_2 = \frac{1}{n-v} \sum_{t=v+1}^{T} x_i \end{cases} \quad (9)$$

The T_0 statistic is obtained by comparing the likelihoods of two competing models. The model corresponding to H_a estimates i_1 and i_2 while defining the n parameter to maximize likelihood. The SNHT method is particularly sensitive to breaks occurring at the start and end of a time series (Costa & Soares, 2009). Buishand's range test is suitable for variables following any distribution form, and its properties have mainly been studied in normal cases. For this study, Buishand focuses on the two-tailed test and the Q statistic (Buishand, 1982).

For Q statistic, the null and alternative hypotheses are given by;

$$S_0^* = 0, S_k^* = z_1 = \sum_{i=1}^{k} (x_i - u), k = 1,2, \dots .T \quad (10)$$

And

$$S_0^* = S_k^* / \sigma \quad (11)$$

The Buishand's Q statistics follow;

$$Q = \max_{1 \le t \le T} |S_k^{**}| \quad (12)$$

These methods have been used previously to analyze climate data and investigate hydro-climatological climate change signals and variability (Taxak et al., 2014)**.** The homogeneity tests have a Python package called Pyhomogeneity implemented in pure Python, which combines almost all types of homogeneity tests (Pettit's, SNHT, Buishard). A brief description of all can be found in (Hussain & Mahmud, 2019). This study used the Pyhomogeneity Python package for change point detection analysis.

iii. The Innovative Trend Analysis (ITA) is a novel trend detection technique introduced by Şen (2012). This method involves generating subsection time series plots on a Cartesian plane, where a trend-free series aligns along a 45° straight line. The method splits the time series into two equal halves, arranges each in ascending order, and then places the first half on the X-axis and the second half on the Y-axis. The time series is considered trend-free when the data points lie along the 1:1 line. Points located above this line indicate an upward trend, while those below suggest a downward trend. (Şen, 2014; Cui et al., 2017). The absolute value of the difference between the y and x values of a point is the distance from the 1:1 line (Wu & Qian, 2017; Cui et al., 2017). The difference represents the strength of either an upward or downward trend, while the mean difference reflects the overall trend of the time series. The trend indicator is determined using equation 13.

$$D = \frac{1}{n} \sum_{i=1}^{n} \frac{10(y_i - x_i)}{\bar{x}} \quad (13)$$

Here, D represents the trend indicator, where positive values signify an increasing trend and negative values denote a decreasing trend. The parameter n refers to the number of observations in each sub-series, while $\bar{x}$ indicates the mean of the first sub-series (Wu & Qian, 2017; Cui et al., 2017). When the original time series contains an odd number of observations, the first data point is omitted before splitting, ensuring the most recent data is fully utilized.

3.2.4 Pearson Correlation Coefficient

A Pearson correlation matrix was developed to assess the relationship between energy generation and various hydro-climatic variables, including precipitation, temperature, reservoir inflow and outflow, turbine discharge, and evaporation loss. Other studies have employed a similar method (Liman et al., 2021; Obahoundje et al., 2022). The correlation function in Python was applied, and the results were visualized through a heatmap. Additionally, a Random

Forest (RF) model was developed to perform a sensitivity analysis of energy production at the hydropower station. This method helps reveal the potential links between uncertainties in output variables and those in one or more input variables, essentially showing how much the predictors (input variables) influence the target variable (energy generation) (Obahoundje et al., 2022). Since it offers a robust, internally cross-validated measure of variable importance (Polewko-Klim et al., 2020), the RF method can serve as a more reliable tool for sensitivity analysis when aligning with production histories (Aulia et al., 2019). The percentage increase in Mean Squared Error (%IncMSE) is considered the most effective and informative approach for identifying key variables in RF. Further details on the Random Forest method can be found in the study by Polewko-Klim et al. (2020). In this study, the percentage increase in Mean Squared Error (%IncMSE) was used to identify the variables that most significantly affect energy generation at the Jebba hydropower station. (Obahoundje et al., 2022; Polewko-Klim et al., 2020).

3.2.5 Land Surface Modelling

CLM5 refers to the Community Land Model version 5. It is a widely used land surface model developed by the National Center for Atmospheric Research (NCAR). CLM5 simulates the interactions between the land surface and the atmosphere by representing key physical and biogeochemical processes. It includes representations of processes such as energy and water balance at the land surface, vegetation dynamics and photosynthesis, soil hydrology and water movement, carbon cycling, and exchange between the land surface and the atmosphere, as seen in Figure 5. CLM5 represents the land surface with one vegetation layer, up to five snow layers, and 20 soil layers. Each grid cell is partitioned into land units such as vegetated areas, lakes, urban regions, glaciers, and croplands. The default spatial distribution and seasonal patterns of plant functional types in CLM5 are based on MODIS satellite land surface datasets (Lawrence et al., 2019). It uses the simplified TOPMODEL (Niu et al., 2005), to parameterize surface and subsurface runoff. Surface runoff is simulated using the saturation-excess mechanism, while subsurface runoff is generated under saturated soil column conditions. The model is also coupled with a river routing module to represent the dynamics of runoff. In CLM5, soil evaporation is influenced by soil resistance, which is linked to the presence of a dry surface layer (DSL) (Lawrence et al., 2019). In the model, a dry surface layer (DSL) develops near the soil surface when the water content of the top layer falls below a threshold (SWCth), defined as 80% of that layer's porosity.($SWC_{sat,1}$). The formation of the DSL generates soil resistance, limiting soil evaporation. Meanwhile, CLM5 uses Richard's equation and Darcy's law to describe changes in soil water content (SWC) and soil water flux. The Community Land Model version 5 parameterizes interception, throughfall, canopy drip, snow accumulation, and meltwater transfer between snow layers, infiltration, evaporation, surface runoff, sub-surface drainage, redistribution within the soil column, and groundwater discharge and recharge to simulate changes in canopy water, $\Delta W_{\text{can, liq}}$, canopy snow water $\Delta W_{\text{can, sno}}$, surface water ΔW_{sfc}, snow water ΔW_{sno}, soil water $\Delta w_{\text{liq},i}$, and soil ice $\Delta w_{\text{ice},i}$, and water in the unconfined aquifer ΔW_a, (all in kg m^{-2} or mm of H_2O) (Lawrence et al., 2019). The total water balance of the system is evaluated using equation 14;

$$\Delta W_{\text{can, liq}} + \Delta W_{\text{can, sno}} + \Delta W_{\text{sfc}} + \Delta W_{\text{sno}} + \sum_{i=1}^{N_{\text{levsoi}}} \left(\Delta w_{\text{liq},i} + \Delta w_{\text{ice},i}\right) + \Delta W_a = \begin{pmatrix} q_{\text{rain}} + q_{\text{sno}} - E_v - E_g - q_{\text{over}} \\ -q_{h2o} - q_{\text{drai}} - q_{\text{rgwl}} - q_{\text{snwcp, ice}} \end{pmatrix} \Delta t \tag{14}$$

Where q_{rain}, is the liquid part of precipitation, q_{sno} is the solid part of precipitation, E_v, is ET from vegetation. E_g is ground evaporation. q_{over} is surface runoff q_{h2osf} , is runoff from surface water storage, q_{drai}, is sub-surface drainage, q_{rgwl}, and $q_{\text{snwcp, ice}}$, are liquid and solid runoff from glaciers and lakes, and runoff from other surface types due to snow capping (all in kg m^{-2} s^{-1}), N_{levsoi}, is the number of soil layers (note that hydrology calculations are only done over soil layers 1 to N_{levsoi}; ground levels $N_{\text{levsoi}} + 1$ to $N_{levgrnd}$, are currently hydrologically inactive and Δt is the time step (s) (Lawrence et al., 2019).

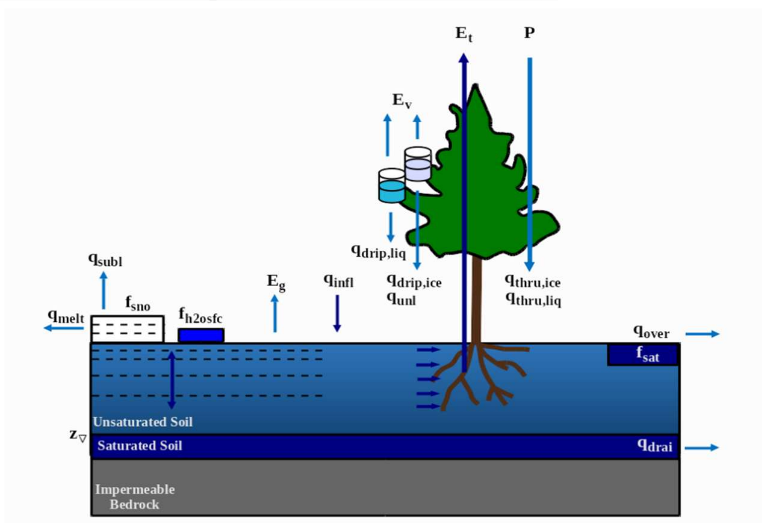


Figure 5: Hydrologic processes represented in CLM5 (Lawrence et al., 2019)

3.2.6 Hydrological Modeling

The lumped HBV hydrologic model was implemented in Python. HBV was selected due to its flexibility, computational efficiency, demonstrated reliability across diverse climatic and physiographic settings, and its successful use in numerous past regionalization studies. Furthermore, HBV includes 14 adjustable parameters, making it moderately complex and representative of a "typical" hydrologic model. Operating on a daily time step, it features two groundwater reservoirs and one unsaturated-zone store, while channel routing delays are simulated using a triangular weighting function. The model inputs consist of daily precipitation, potential evaporation, and air temperature. For more details concerning HBV, see (Bergström, 1992). For the Jebba catchment, the model was calibrated and validated using periods with concurrent observed discharge and input data, applying a lumped approach to minimize computational demand and the performance evaluation using the Kling-Gupta efficiency (KGE), which is a hydrologic science metric that compares simulations to observations. The values range from -Inf to 1, with the value closest to 1 being the best, as seen in Table 7. Equation 15 displays the formula used to calculate the KGE criterion.

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma sim}{\sigma obs} - 1\right)^2 + \left(\frac{\mu sim}{\mu obs} - 1\right)^2} \quad (15)$$

Where σobs is the standard deviation in observations, σsim the standard deviation in simulations, μsim the simulation mean, and μobs the observation mean.

Table 7: KGE performance evaluation interpretation

KGE Value	**Performance**
0.7 < KGE < 1.00	Very Good
0.6 < KGE < 0.7	Good
0.5 < KGE < 0.6	Satisfactory
0.4 < KGE < 0.5	Acceptable
0.4 ≤ KGE	Unsatisfactory

3.2.7 Hydropower Modeling

The hydropower model for the study was implemented in Python using the reservoir operation rule of the Kainji dam as described in (Oyerinde et al., 2016). Daily hydrological records (reservoir inflow, storage, and water level) for the Kainji and Jebba reservoirs were obtained from Kainji and Jebba Hydroelectric PLC for the period 1984–2009, which represents the maximum available dataset. These data were used to construct a hydropower production model designed to simulate future energy generation at both reservoirs. The reservoir water balance was represented as follows:

$$\frac{\partial S}{\partial t} = I - D + P - E \quad (16)$$

S is the reservoir storage at time t (m^3)

I is the reservoir inflow (m^3/s)

D is the amount of water released out of the reservoir to the turbines (m^3/s)

P is the lake area precipitation (m^3)

E is lake evaporation (m^3)

D was calculated by simulating the reservoir management of the dam. The rule consists of two segments:

(1) Rule at reservoir storage below optimal level (80% full): Logarithmic behaviour

$$D = D_{min} + \ln\left(kS^{\propto} + 1\right) \text{ at } S < S_{\text{optimal}} \quad (17)$$

(2) Rule at reservoir storage above optimal level (80% full): Exponential behaviour

$$D = \exp\left(b\left(S - S_{\text{optimal}}\right)^2\right) \text{ at } S \geqslant S_{\text{optimal}} \quad (18)$$

D_{min} = Minimum environmental flow (20% of average annual reservoir inflow) (m^3/s).

S = reservoir storage (m^3)

$$k = \frac{1}{S_{\text{optimal}}}\left[\exp\left(1 - D_{min}\right) - 1\right] \quad (19)$$

b and $\propto$ are model parameters.

The reservoir level of the dam was estimated from reservoir storage using the level-storage relationship of a dammed river shown below:

$$\text{Reservoir level} = \sqrt[m]{\frac{\text{Storage}}{C_v}} \quad (20)$$

Where m and C_v are constants calibrated as additional model parameters.

Energy production was calculated from the simulated reservoir level using the hydropower equation (21):

$$P = e\rho Dgh \quad (21)$$

Where,

P is power in watts (W)

e is the dimensionless efficiency of the turbine (taken as 80% of installed capacity.

ρ is the density of water (kg/m^3).

D is the water released to the turbine (m^3/s).
g is the acceleration due to gravity (m/s^2).
h is the water level above the turbine (reservoir level) (m).

3.2.8 Green Hydrogen Production Potential from Hydropower Energy

There are two approaches to evaluate the green hydrogen potential of hydropower resources (Thapa et al., 2021a). The first approach assumes that a fixed proportion of the available commercial hydropower potential is allocated to hydrogen production via electrolysis, following a methodology similar to that applied in a study from Venezuela (Posso & Zambrano, 2014). The second method estimates hydrogen production potential from surplus electricity that would otherwise be curtailed due to low demand or increased generation during high inflow periods in the rainy season. Previous studies using this approach have shown that converting excess hydro-energy into hydrogen is highly effective and adds substantial value to otherwise underutilized energy (Bhatt, 2017; Padilha et al., 2009) This study employed the first approach, and the electrical energy generated can also be calculated using equation 22 (Posso et al., 2015).

$$E_{EG} = HP \times CF \times Op.hrs \tag{22}$$

E_{EG} is the total electrical energy generated yearly in GWh, HP is the hydroelectric potential, CF is the capacity or plant factor, and $Op.hrs$ is the operating hours. Equation 23 obtains the hydropower energy utilized for each of the assumed scenarios.

$$E_{sc} = E_{EG} \times \text{Scenario}\,\% \tag{23}$$

Where E_{sc} is the electrical energy assumed to be utilized for hydrogen production for each scenario in GWh. Based on a similar study done in Nepal (Thapa et al., 2021b), the following five different scenarios were assumed for the estimation of hydrogen production potential from hydroelectric energy generated;

Scenario 1 (S1-H2p) - 100% hydropower electricity was used.
Scenario 2 (S2-H2p) - 80% hydropower electricity was used.
Scenario 3 (S3-H2p) - 60% hydropower electricity was used.
Scenario 4 (S4-H2p) - 40% hydropower electricity was used.
Scenario 5 (S5-H2p) - 20% hydropower electricity was used.

The hydrogen potential (H_{2p}) in Kg H_2/year is estimated using equation 24. In each scenario, it is assumed that a specific percentage of the generated power is used for producing green hydrogen.

$$H_{2p} = \frac{E_{sc}}{\text{Electrolyzer Efficiency}} \quad (24)$$

For the green hydrogen production projection, the following four different scenarios were assumed for the estimation from the hydroelectricity projection, and as displayed in Figure 6.

S1-245: 20% excess under SSP 245(High hydropower demand and Low Renewable Supply)

S2-245: 40% excess under SSP 245(Low hydropower demand and High Renewable Supply)

S1-585: 20% excess under SSP 545 (High hydropower demand and Low Renewable Supply)

S2-585: 40% excess under SSP 545 (Low hydropower demand and High Renewable Supply)

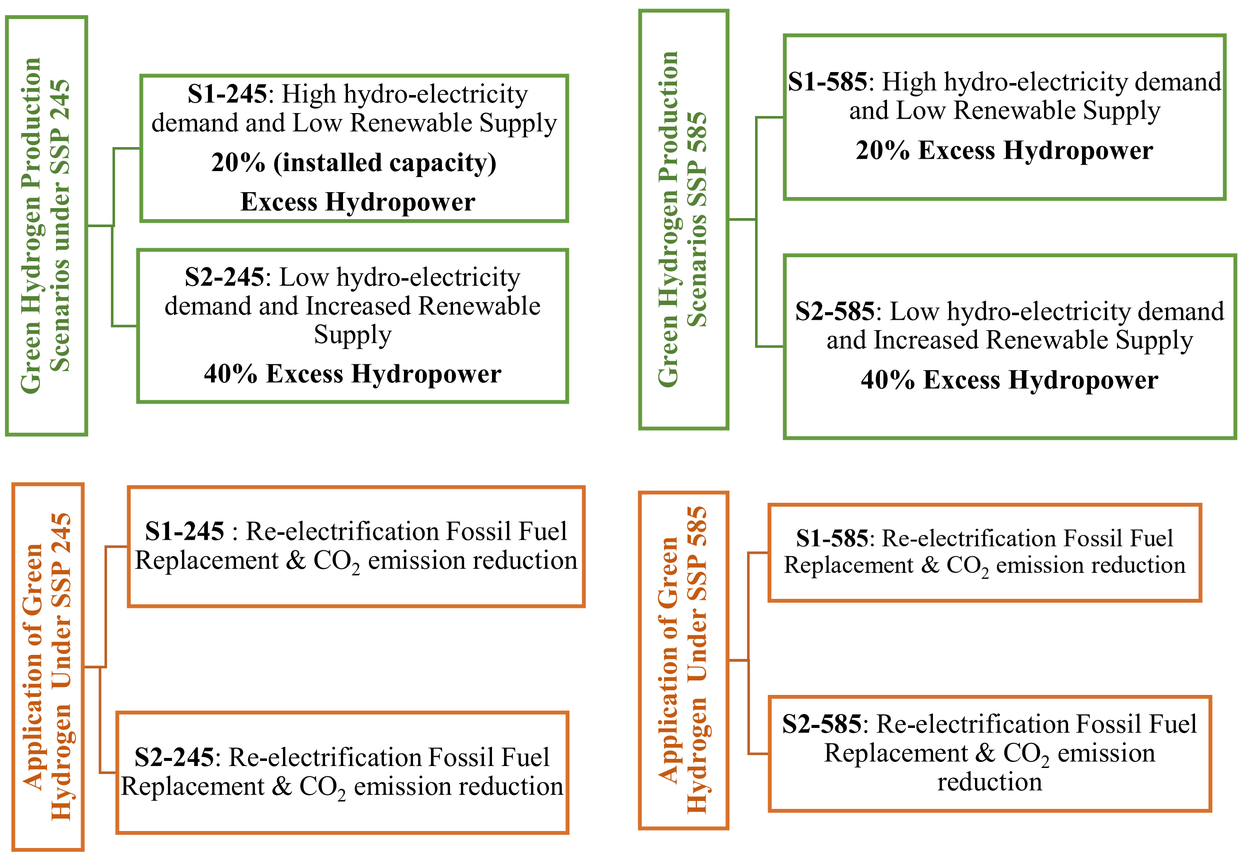


Figure 6: Assumed Scenarios for Green Hydrogen Production from Jebba Hydropower Dam

3.2.9 Re-electrification potential using hydrogen

Hydrogen energy can be harnessed to supply electricity to remote communities that lack grid access. In addition, hydrogen-based power offers a sustainable alternative to fossil-fuel sources in industrial and commercial sectors, replacing diesel or petrol-powered generators (Thapa et al., 2021b). Hydrogen derived from hydropower can be converted back into electricity through the use of fuel cells. The IEA (IEA 2019) It is projected that by 2030, if 1% of the global installed gas-fired power capacity (approximately 25 GW) were fueled with hydrogen (or ammonia), it could generate roughly 90 TWh of electricity annually at a 40% load factor, which would require approximately 4.5 million tons of hydrogen (MtH_2). Based on these assumptions, Zhou et al. (2020) estimated that with current technology, 1 kg of hydrogen can produce about 20 kWh of electricity (derived from 4.5 MtH_2 generating 90 TWh). As a consequence, assuming that fuel cells now have a 60% efficiency (Thapa et al., 2021b). Therefore, the potential for re-electrification with hydrogen is assessed using equation 25, based on the assumption that 1 kg of hydrogen yields approximately 20 kWh of energy.

$$\mathrm{RE_P} = \mathrm{H}_{2p} \times 20/1000\ (\mathrm{GWh}) \qquad (25)$$

Where $\mathrm{RE_P}$ is the Re-electrification potential. The same scenarios assumed for calculating the hydrogen potential from hydropower energy are used to analyze the re-electrification potential from hydrogen.

3.2.10 Estimation of fossil fuel (petrol) replacement.

In the study by (Thapa et al., 2021b), one tonne of green hydrogen can substitute for 3.785 liters of petrol, as each kilogram of hydrogen carries roughly the same energy content as one U.S. gallon of gasoline (Ale & Bade Shrestha, 2008; United States Department of Energy, 2008). In this study, equation 26 is used to analyze the amount of gasoline fuel in liters that would be displaced (Thapa et al., 2021b).

$$\mathrm{PR} = \mathrm{H_{2p}} \times 3.785\ (\mathrm{kL}) \qquad (26)$$

Here, PR denotes the petrol (gasoline) replacement potential. To estimate the volume of petrol displaced, the same five scenarios, corresponding to the percentage of hydropower energy utilization applied in the hydrogen production and re-electrification potential calculations, were adopted. The results for each scenario are presented as Sx-PR.

3.2.11 Estimation of greenhouse gases avoided.

Burning fossil fuels to provide electricity, transportation, industry, and other uses has sparked worries worldwide since it releases greenhouse gases, including CO2, CH4, CO, and N2O, which are to blame for the current global warming (Ayodele et al., 2019). For example, incomplete combustion of fossil fuels releases harmful gases such as carbon monoxide (CO). Consequently, countries worldwide are implementing measures to curb the emission of gases and pollutants that drive climate change. Among the various greenhouse gases, carbon dioxide (CO_2) alone accounts for nearly 77% of total global emissions (Adeoti et al., 2014). In this study, both CO and CO_2 emissions are considered. In contrast, hydrogen fuel cells primarily emit water, which is environmentally harmless and recognized as a promising solution to the climate change challenge. The avoided GHG emissions (CO_2 and CO) from replacing petrol combustion with hydrogen-based fuel cells were quantified using equation 27. (Ayodele et al., 2019):

$$\mathrm{CO_{2E}/CO_{E}} = \mathrm{PR} \times SE_F \tag{27}$$

$\mathrm{CO_{2E}/CO_{E}}$ is the amount of CO_2 and CO emissions that would be prevented, and SE_F is the specific emission factor of the associated greenhouse gas. The CO_2 emission factor of petrol (or gasoline) fuel is 2.3 kg per Litre (Ayodele & Ogunjuyigbe, 2015), whereas the CO emission factor is 0.00413 kg per Litre(Ayodele & Ogunjuyigbe, 2015). To estimate the amount of CO_2 and CO that would be prevented using hydrogen to replace petrol (or gasoline) fuel, the same five assumed scenarios with the equivalent percentage of hydropower energy utilization as used in the calculation of the hydrogen and the re-electrification potential were used in the estimation, and the results were obtained for each scenario as Sx-CO_{2E} and Sx-CO_E for CO_2 and CO emissions respectively.

3.3 Partial Conclusion

The objective of this chapter was to provide a methodological framework. Firstly, the data that will be used throughout the study was outlined, namely daily rainfall data from four Jebba dam neighboring rain gauge stations for the period of 1992-2021, which was obtained from the Nigeria Mereological Agency (NiMet) due to a lack of in-situ data that will cover the entire basin, satellite data namely; Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) version 2 developed by the Climate Hazards Group of the University of California was used. The daily rainfall dataset was downloaded at a basic scale utilizing the feature of custom polygon region for Niger River Basin (NRB) in the Google Climate Engine App using the link https://app.climateengine.com/climateEngine. The length of the data collected was from 1981-2022. Monthly hydroclimatic and hydropower data, namely, rainfall, average maximum temperature, reservoir inflow, reservoir outflow, evaporation loss, turbine discharge, and energy generation, were also obtained for the Jebba hydropower reservoir. Other data, which includes CMIP5 climatic data for climate change analysis, were obtained from the Earth System Grid Federation (ESGF) Website using the link; https://esgf-metagrid.cloud.dkrz.de/search/cordex-dkrz/, while the CMIP6 climatic data were obtained from the archive of NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) using the link; https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/index.html). Secondly, the computer software used in the study includes the Community Land Model 5, which was set up and used on a High-Performance Computer (HPC), while the Python programming language was used to set up and run the hydrological and hydropower model. Lastly, the methodologies used for the studies include statistical, anomaly, trend, and homogeneity test analyses of the rainfall data. Land surface modeling for assessment of changes in water balance components (rainfall, evapotranspiration, and runoff), Pearson correlation coefficient and sensitivity analysis of hydroclimatic variables and energy generation, hydrological modelling for assessment of changes in reservoir inflow, hydropower modelling for assessment of changes in energy generation, and projection of green hydrogen production potential, re-electrification potential, fossil fuel replacement potential, and greenhouse gases that would be avoided.

Following the description of the materials and method, the next chapter discusses the results of the first objective of the work, specifically the impact of climate change on the water balance components (precipitation, evapotranspiration, and runoff) in the Niger River Basin.

CHAPTER 4: IMPACT OF CLIMATE CHANGE ON THE WATER BALANCE COMPONENTS IN THE NIGER RIVER BASIN

Chapter 4 presents the results of the evaluation of the impact of climate change on the water balance components in the Niger River Basin using statistical and trend analysis for historical periods and the Community Land Model 5 for future changes from 2025-2100. Section 4.1 presents the results of the annual and monthly characteristics of rainfall in the study area. Section 4.2 The Seasonal Temporal Variability of Rainfall, Section 4.3 Inter-annual Variability of Rainfall, Section 4.4 Modified Man-Kendall and Innovative Trend Analysis of Rainfall, 4.5 Homogeneity Test and change year detection, 4.6 Changes in Water Balance components under RCP 2.6 and RCP 8.5, Section 4.9 Spatial variability of precipitation, surface runoff, and evapotranspiration under RCP 2.6 and RCP 8.5. The major results are summarized in a paper currently under revision for publication in the Taylor and Francis Journal.

4.1 Annual and Monthly Characteristics of Rainfall

The mean annual rainfall characteristics show the lowest rainfall record of 523.7mm in 1983 and 933.7mm in 2009, while the highest rainfall record was 759.7mm in 1999 and 1462.8mm in 1991, over the Niger River basin (NRB) and Jebba Hydropower Station (JHS), respectively, as seen in Figure 7. The result shows the annual rainfall variability over NRB and in JHS. However, there was low rainfall from November to February, resulting in a decrease in monthly rainfall variability. In contrast, there was an increase from March for both the NRB and JHS, as shown in Figure 4. Moreover, relatively intensive rainfall was received between July and September, with the maximum mean monthly rainfall record of 170.7 mm received in August over the NRB, while the maximum mean monthly rainfall record of 237.06 mm was received in September in JHS. The lowest rainfall occurred in January, with a rainfall record of 0.5 mm over the NRB, while 0.1mm was recorded in December for JHS, as displayed in Figure 8.

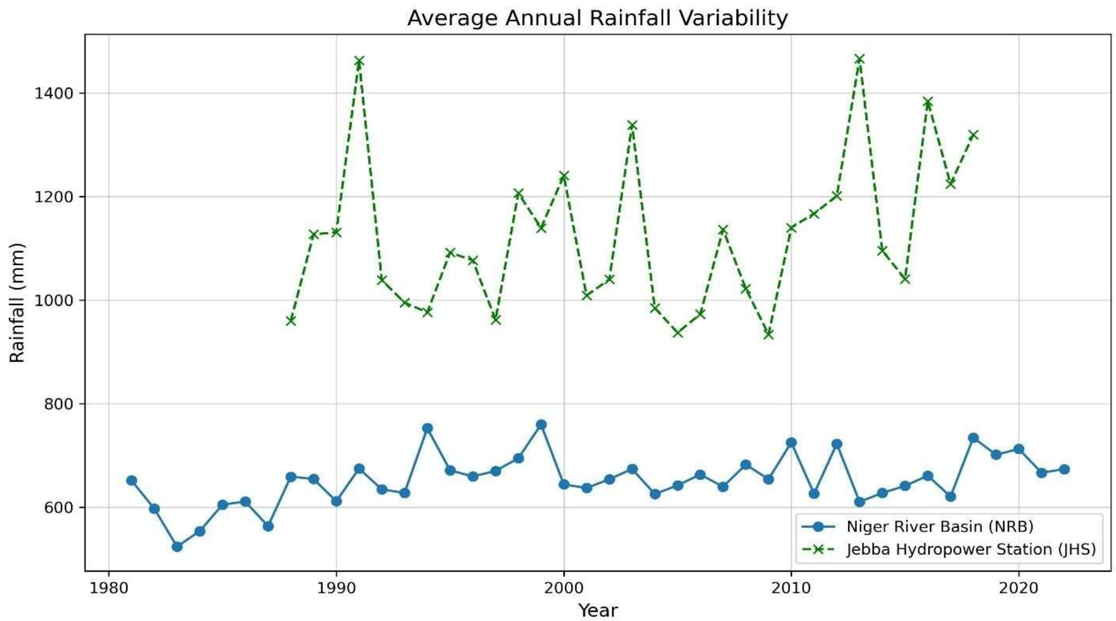


Figure 7**:** The mean annual rainfall (mm) over NRB and JHS

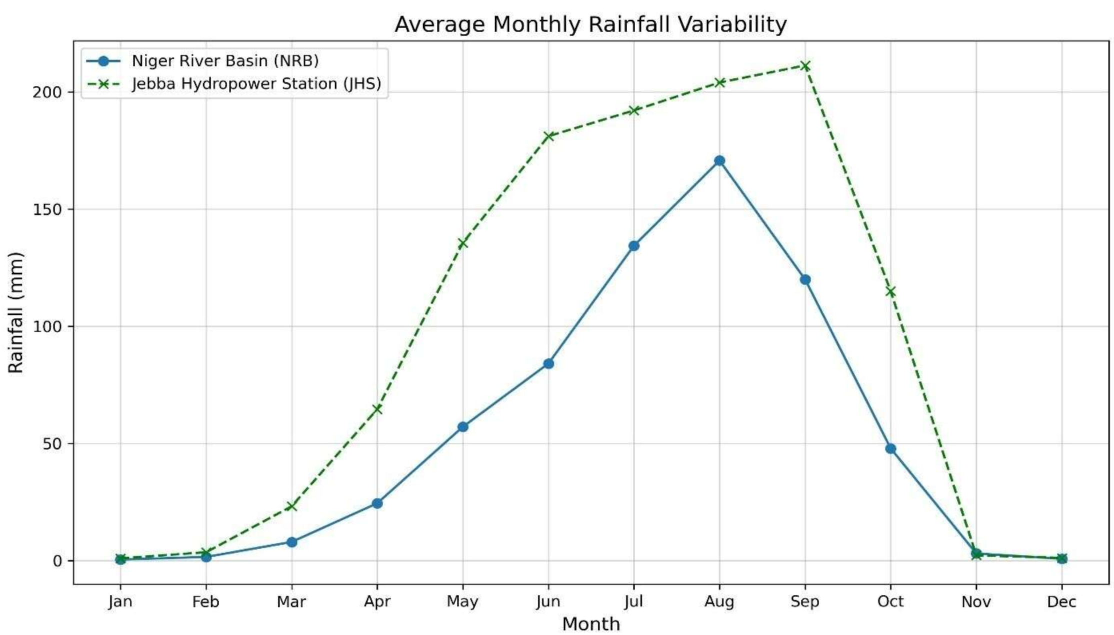
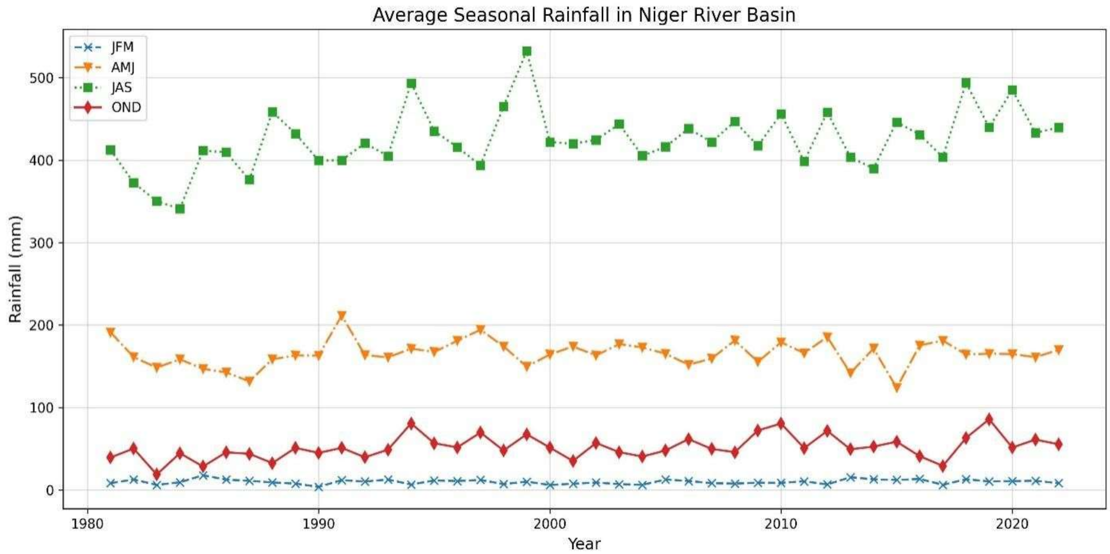


Figure 8: The mean monthly rainfall (mm) over NRB and JHS

4.2 Seasonal Temporal Variability of Rainfall

The inter-annual and seasonal temporal variability was tested to evaluate the detailed rainfall characteristics in the recording period (1981-2022) and (1988-2018) over the NRB and JHS, respectively. The four rainfall seasons selected were January to March (JFM), April to June

(AMJ), July to September (JAS), and October to December (OND). The JAS rainfall showed a similar result as the annual rainfall variability over the NRB and the JHS, as seen in Figure 9



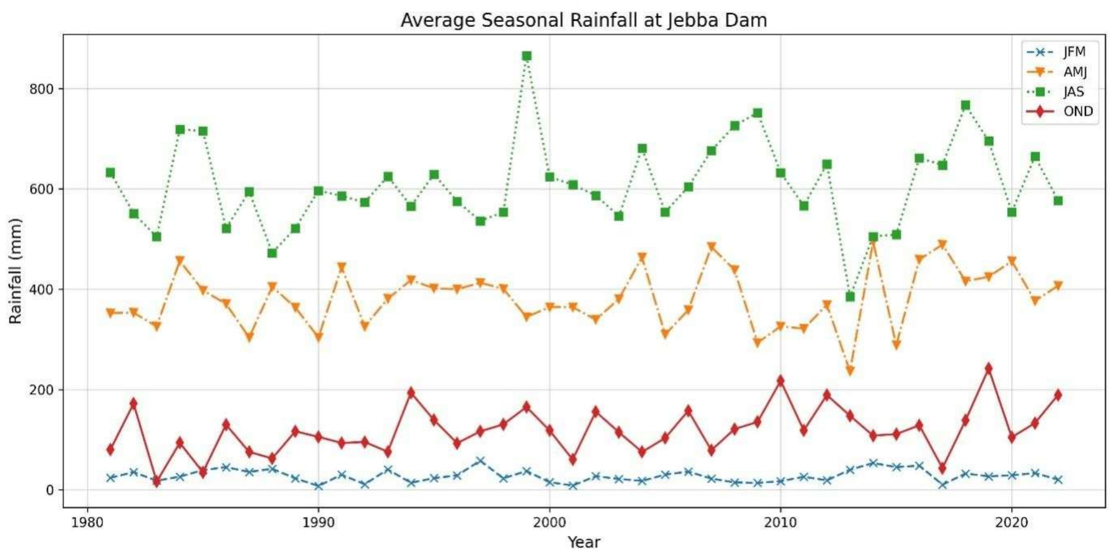


Figure 9**:** Seasonal temporal rainfall variability (mm) over NRB and JHS.

In the Niger River Basin and the Jebba Hydropower Station, the annual mean rainfall and seasonal mean rainfall of AMJ had a CV of < 20, and also JAS for the Niger River Basin, which indicates a normal variability. On the other hand, JFM and OND for the Niger River Basin, and JAS for the Jebba Hydropower Station, had a CV of 20–30%, which indicates moderate variability. Furthermore, Jebba Hydropower Station had a CV >30%, indicating high variability for JFM and OND seasons, as outlined in Table 8**.** In this study, high seasonal rainfall variability was observed only for the Jebba Hydropower Station, whereas moderate variability was detected for the Niger River Basin.

Table 8: Summary of Descriptive Statistics

Region/Station		Annual	JFM	AMJ	JAS	OND
Niger River Basin	Mean	652.68	10.10	165.6	452.2	51.8
	STD	49.14	2.86	16.23	36.95	14.21
	CV%	7.52	28.46	9.80	8.69	27.42
Jebba Hydropower Station	Mean	1123.243	17.90	403.45	612.77	89.12
	STD	150.2136	33.91	112.00	125.14	47.78
	CV%	13.37321	189.48	15.77	20.42	53.62

STD: Standard deviation, **CV:** Coefficient of variation

4.3 Inter-Annual Variability of Rainfall

The inter-annual variability of rainfall using a Standardized Precipitation Index (SPI) for NRB, JHS, and selected rainfall stations neighboring Jebba Hydropower Station (namely Bida, Ilorin, Minna, and Lokoja stations) is shown in Figure 10. The figure shows that the negative anomaly was 47% in the Niger River Basin, 45% at Jebba Station, 40% at Bida Station, 66% at Ilorin Station, 60% at Minna Station, and 46% at Lokoja Station. The Ilorin and Bida Stations recorded the highest and lowest negative anomalies, respectively. The most prolonged dry period was from 1981 to 1989 in the Niger River Basin, followed by 1992 to 1996 at the Ilorin station. Additionally, the driest year was 1983 in the Niger River basin, followed by 1998 at the Bida station. The highest rainfall excess occurred at the Ilorin station in 2016, followed by the Minna rainfall station in 2020.

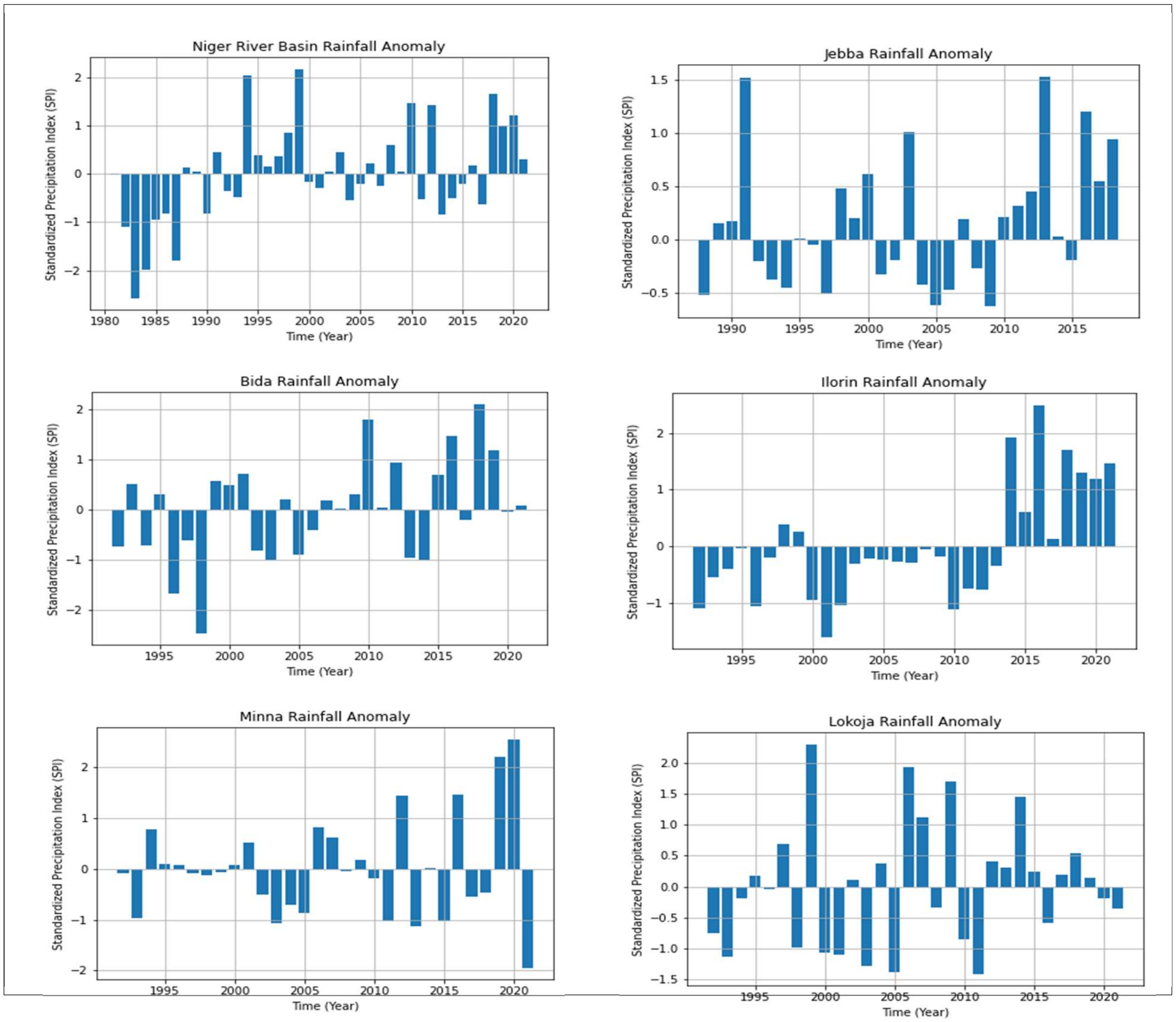


Figure 10**:** Standardized Anomaly Index (SAI) for annual and seasonal rainfall time series for Niger River Basin (NRB) and Jebba Hydropower Station (JHS).

4.4 Modified Man-Kendall and Innovative Trend Analysis

The Modified Man-Kendall (MMK) trend test results of rainfall in the Niger River Basin and Jebba Hydropower Station and its neighboring stations are displayed in Table 9. The results show an increasing trend in rainfall for NRB and Ilorin Station; however, rainfall in Bida, Minna, Lokoja, and Jebba stations exhibits no trend. The Innovative Trend Analysis shows a similar result as displayed in Figure 11 and Figure 12. The rainfall in the NRB, Ilorin Station, has most points falling on the increasing triangle, while annual rainfall in Minna, Lokoja, and Jebba shows no trend. Only Bida station shows a variation showing an increasing trend in ITA but no trend in MMK.

Table 9:Modified Mann-Kendall (at 5% significant level) and Innovative Trend Analysis (D) Statistics for Jebba Hydropower Station and Neighbouring Stations

Region/Station	Hydroclimatic Variable	P-value	Zs	Sen-slope	ITA (D)	Trend
Niger River Basin	Rainfall (mm)	0.0063	2.7310	1.6943	1.0837	+Ve
Ilorin Station	Rainfall (mm)	0.0027	2.9973	29.925	29.4835	+Ve
Bida Station	Rainfall (mm)	0.1007	1.6413	9.6739	13.3128	Non
Minna Station	Rainfall (mm)	1.0000	0.0000	0.1000	3.6800	Non
Lokoja Station	Rainfall (mm)	0.5207	0.6422	3.0706	4.6538	Non
Jebba Station	Rainfall (mm)	0.0891	1.6996	4.6371	0.8491	Non

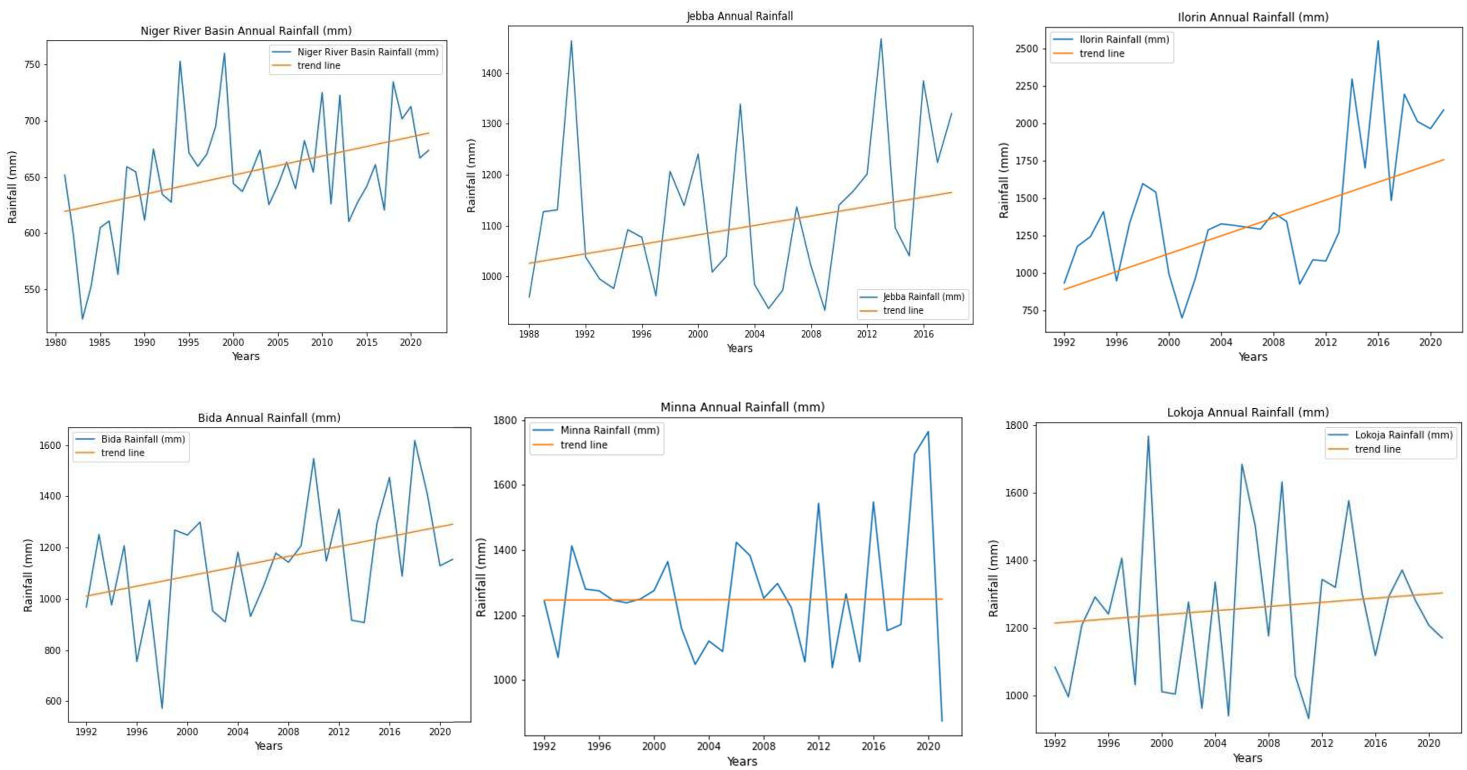


Figure 11: Modified Man-Kendall Trend Test for Rainfall.

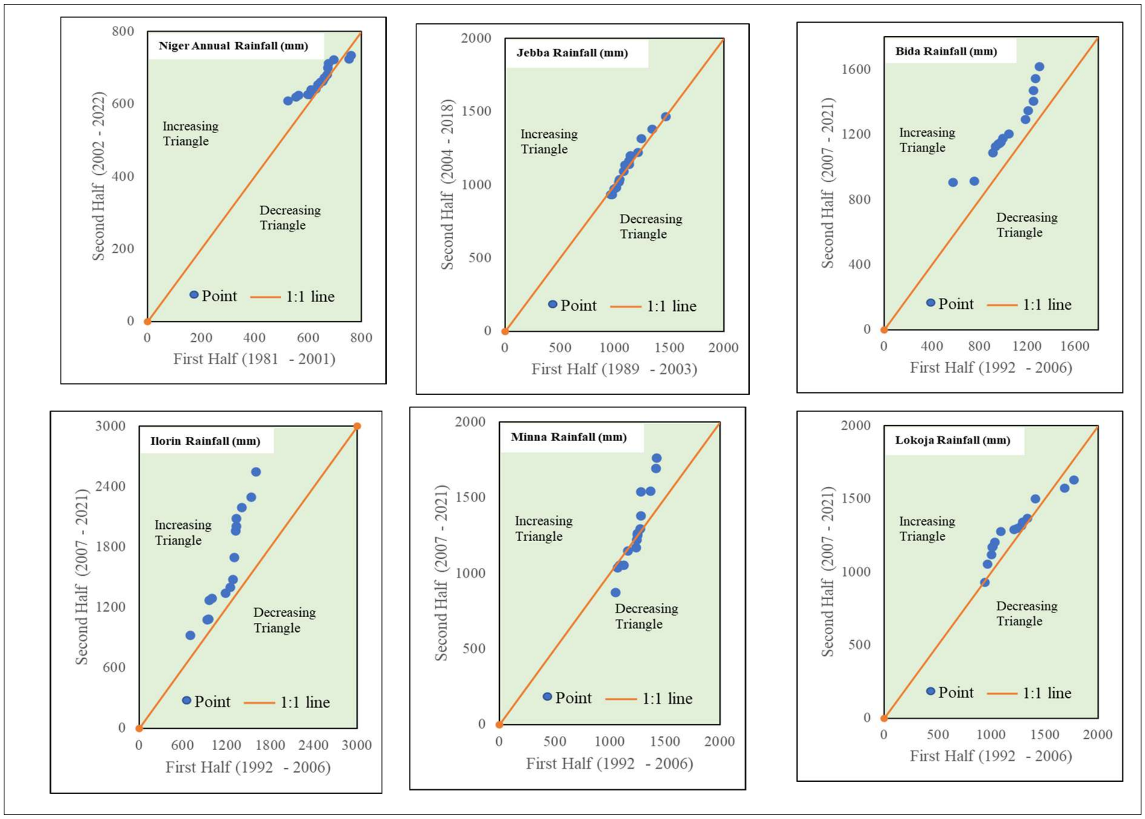


Figure 12**:** Innovative Trend Test for Rainfall

4.5 Homogeneity test and change year detection

The results of the homogeneity tests (Pettit, Standard Normal Homogeneity, Buishand's range) for the rainfall at the Niger River Basin and Jebba hydropower station and its neighboring rainfall stations are displayed in Table 10. The homogeneity test results of the Pettit Test showed that all variables experienced change years except rainfall in Bida and Minna Station. In contrast, the SNHT showed that all variables experienced change years except rainfall in Bida, Minna, Lokoja, and Jebba Station. The Buishand range test also shows a similar result, showing that all variables experienced change years except rainfall in Minna and Lokoja Station. Jointly, all three tests showed no change in the year in rainfall at the Minna Station.

Table 10**:** Change year(t) (Pettitt's, SNHT, and Buishand's range tests), Jebba Hydropower Station, Hydro-climatic variables

Variables	**Pettit test**			**SNHT**			**Buishand's test**		
	Year	p-value	change	Year	p-value	change	Year	p-value	change
NRB Rainfall (mm)	1993	0.0078	True	1987	0.0004	True	1993	0.0028	True
Ilorin Rainfall (mm)	2013	0.0007	True	2013	0.0000	True	2013	0.0003	True
Bida Rainfall (mm)	2006	0.2195	False	2006	0.1631	False	2006	0.0221	True
Minna Rainfall (mm)	2001	0.9908	False	2020	0.3950	False	2015	0.6716	False
Lokoja Rainfall (mm)	2009	0.0433	True	2010	0.1258	False	2009	0.1253	False
JHS Rainfall (mm)	2009	0.0429	True	2010	0.1260	False	2009	0.1276	True

True (P < 0.05), means the variable exhibit a non-homogenous trend

False (P > 0.05), means the variable exhibit a homogenous trend.

4.6 Changes in water balance components under RCP 2.6 and RCP 8.5

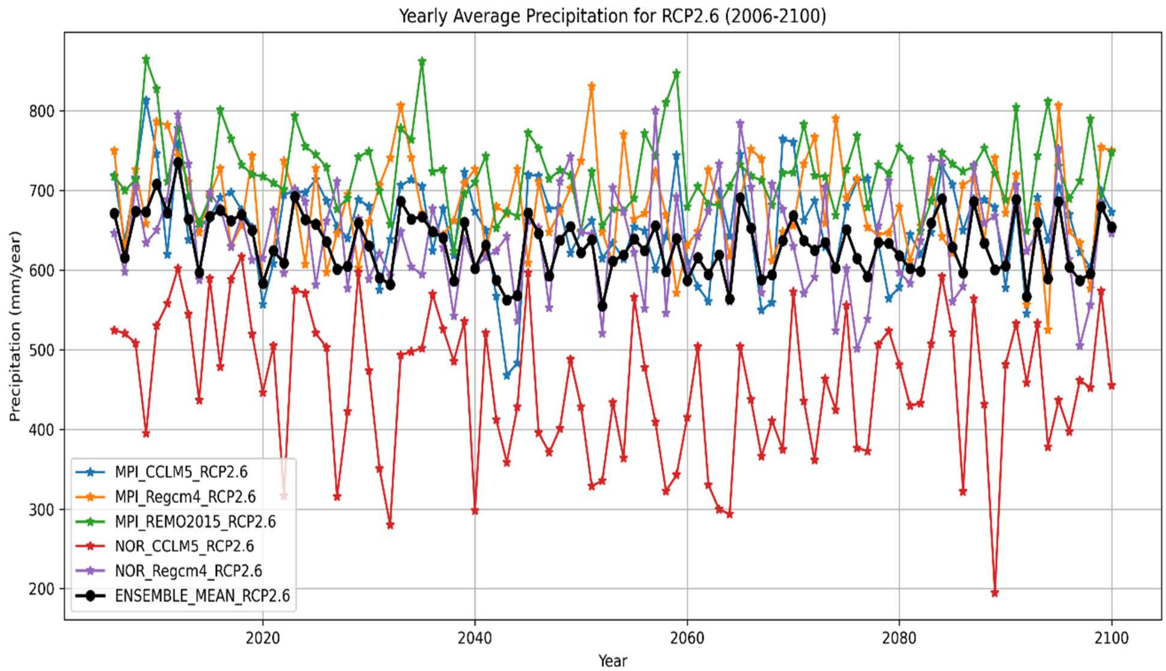
The climate change impacts on the selected water balance components (Precipitation, Surface Runoff, and Evapotranspiration) of the Niger River Basin were analyzed using the land surface model. The annual temporal variability, the projection of the five regional climate models (RCMs), and the ensemble mean under the two scenarios (RCP2.6 and RCP8.5) are displayed in Figure 13 to Figure 15.

4.6.1 Changes in precipitation

Under the RCP2.6 scenario, which represents a low greenhouse emission scenario where aggressive mitigation strategies are implemented, the ensemble mean (the average across five climate models, namely, MPI_CCLM5, MPI_Regcm4, MPI_REMO2015, NOR_CCLM5, and NOR_Regcm4) of the precipitation is projected to vary within a range of 550mm and 750mm, which suggests a relatively stable climate with moderate changes in rainfall pattern. For the high greenhouse gas emission scenario, RCP 8.5, precipitation is projected to gradually decrease around 2060, reaching levels as low as 420mm by the end of the century, as displayed in Figure 13. These changes in precipitation under this scenario indicate a significant decline in rainfall, likely caused by intense global warming and changes in atmospheric circulation patterns.

4.6.2 Changes in surface runoff

In the low-emission scenario RCP 2.6, the ensemble mean (average across the five climate models) of the projected annual surface runoff closely mirrors the variability in the precipitation, as the surface runoff is significantly impacted by the amount of rainfall in the basin. Under this scenario, the surface runoff ranges between 130mm and 180mm, as displayed in Figure 14. Moreover, the similarity between the precipitation and the surface runoff patterns indicates that the water balance in the river basin is relatively stable, with no significant reduction in the runoff, provided emissions are mitigated and global warming is reduced. In contrast, in the high-emission scenario, RCP 8.5, the surface runoff is projected to decline gradually from 2060, eventually reducing to as low as 90mm towards the end of the century. This reduction in runoff is attributed to the decline in precipitation observed under RCP8.5, as rainfall is the primary source of the runoff in the river basin.



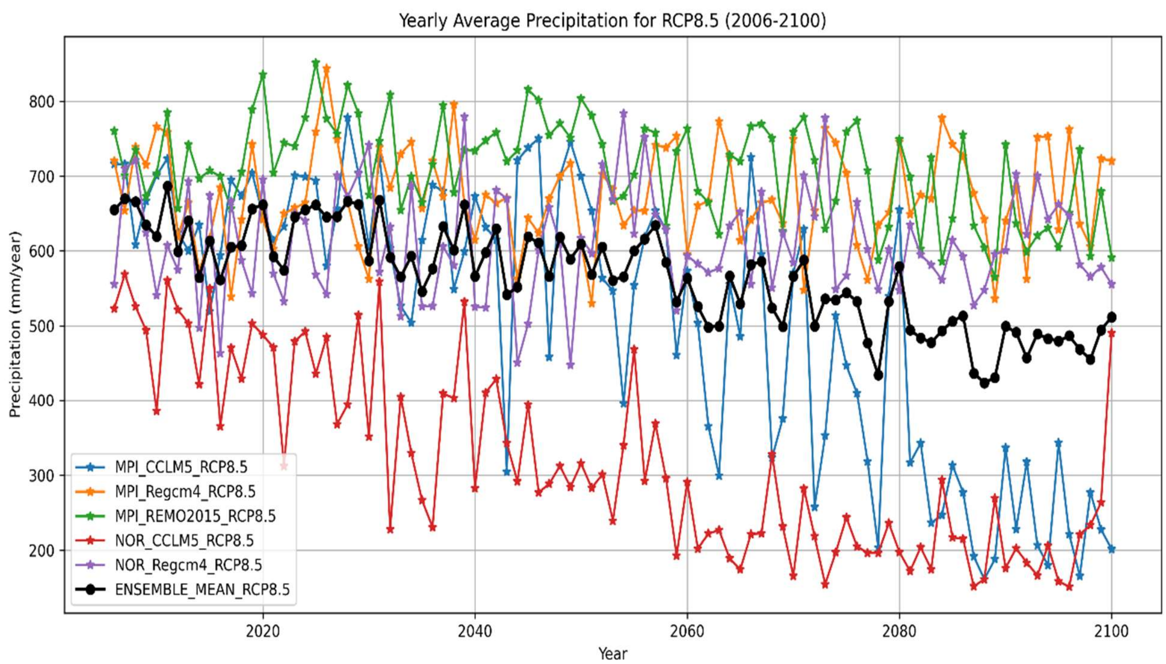
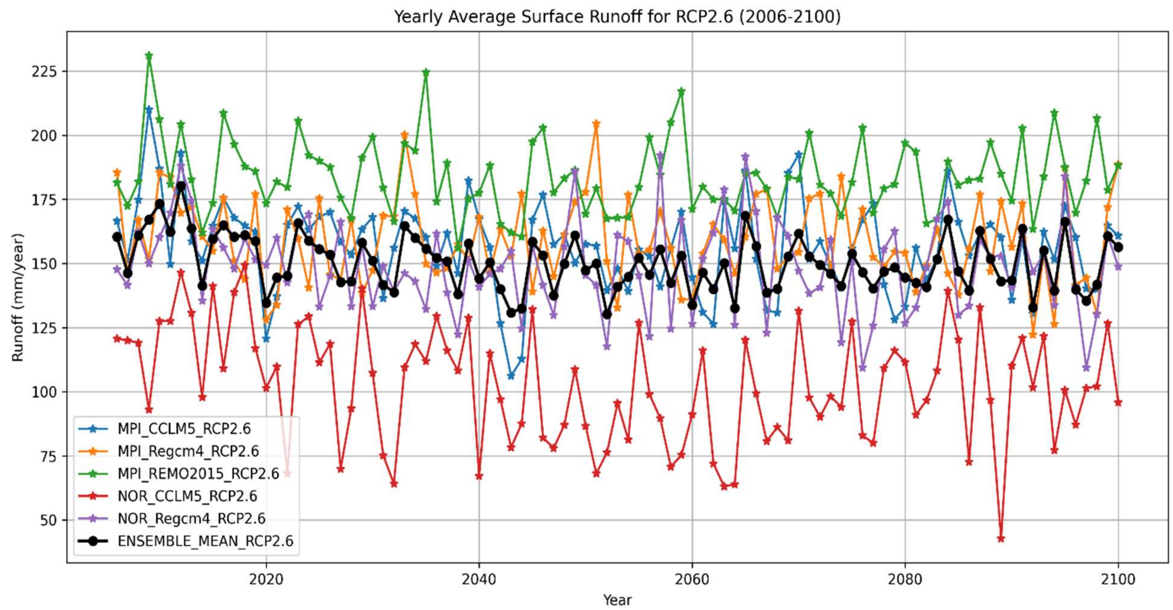


Figure 13: Temporal Variability of Precipitation under RCP 2.6 and RCP 8.5



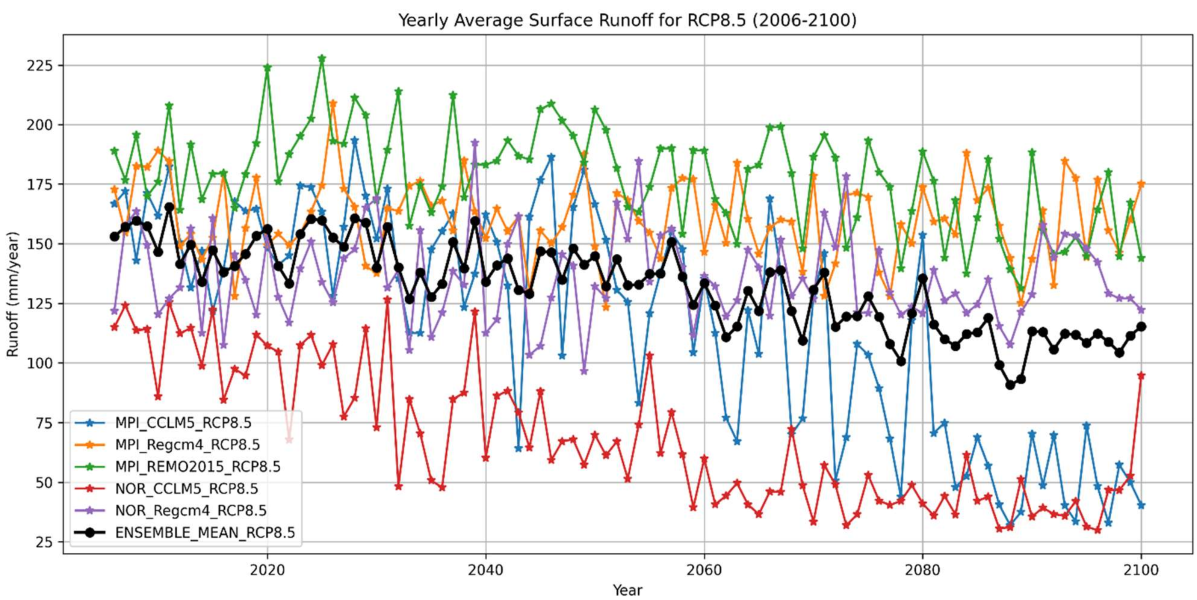


Figure 14: Temporal Variability of Surface Runoff under RCP 2.6 and RCP 8.5

4.6.3 Changes in evapotranspiration

For the low emission scenario, RCP 2.6, the ensemble mean (average across the five climate models) of the evapotranspiration (ET) is projected to range between 380mm and 420mm for the study period, as seen in Figure 15. The relatively narrow range indicates stable water availability and consistent climatic conditions, with sufficient precipitation to sustain soil moisture and vegetation. In contrast, under the high emission scenario, RCP 8.5, the ET is projected to gradually decline from 2060, decreasing to as low as 300mm. This decline mirrors the reduction in precipitation (420mm) and runoff (90mm) as less available water limits evaporation and plant transpiration.

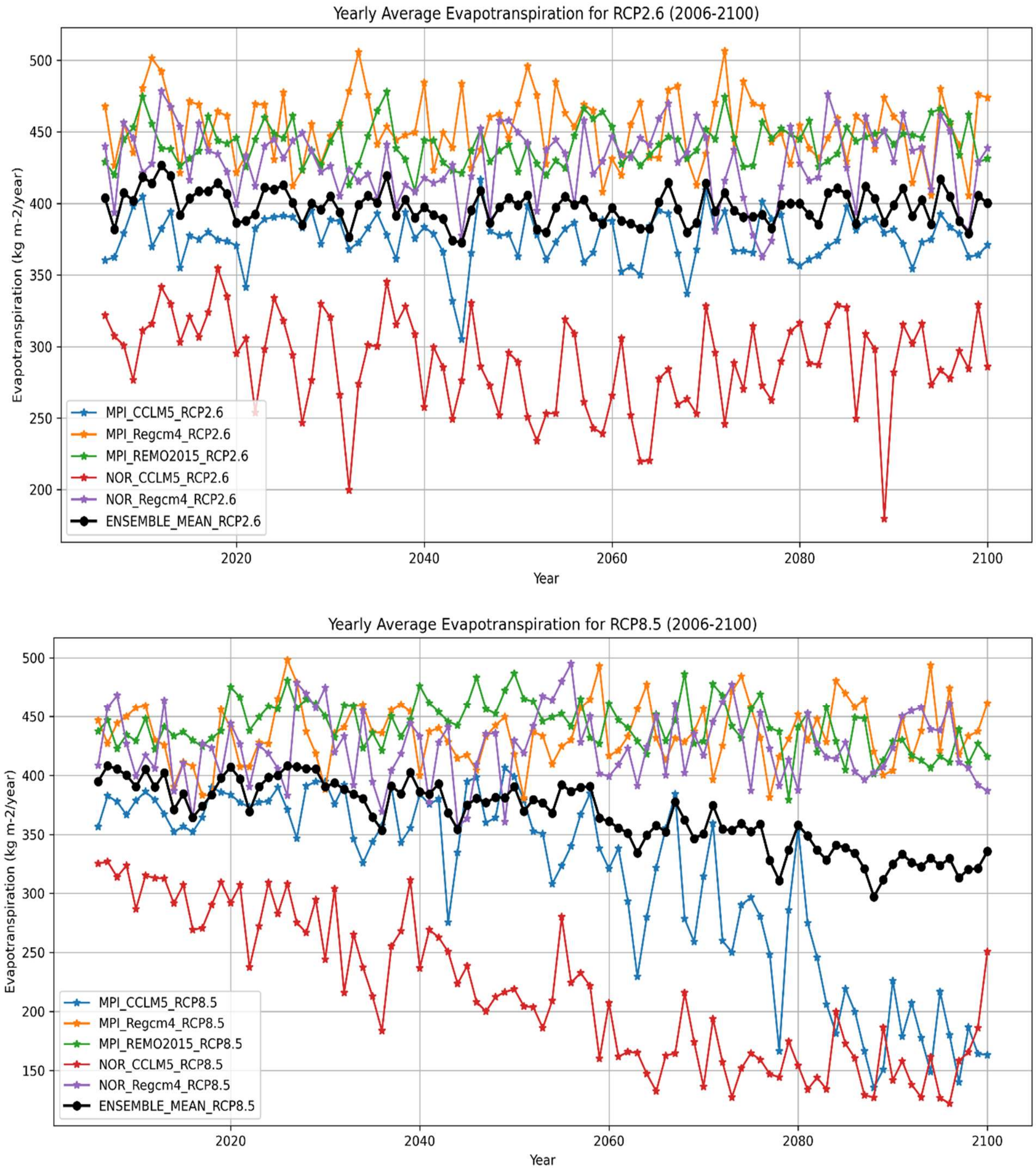


Figure 15: Temporal Variability of Evapotranspiration under RCP 2.6 and RCP 8.5

4.7 Spatial variability of the water balance components

The spatial variability of the water balance components using the ensemble mean of the five climate models for the two scenarios (RCP2.6 and RCP 8.5) is displayed in Figure 16 to Figure 19.

4.7.1 Spatial variability of precipitation,

The spatial variability of precipitation reflects the differences in the changes in rainfall distribution across the Niger River Basin. Under the two scenarios, RCP 2.6 and RCP 8.5, the low and the high emission scenario, the variability demonstrates a significant divergence, with the RCP2.6 showing a range from moderately wet to relatively dry conditions as seen in Figure 16**.** In contrast, the RCP 8.5 reflects a much drier climate, with precipitation levels ranging as low as 0-200mm/year in certain areas, especially the Sahara region. This could affect the region's water availability, as RCP 8.5 shows a more likely decline in water availability due to reduced rainfall.

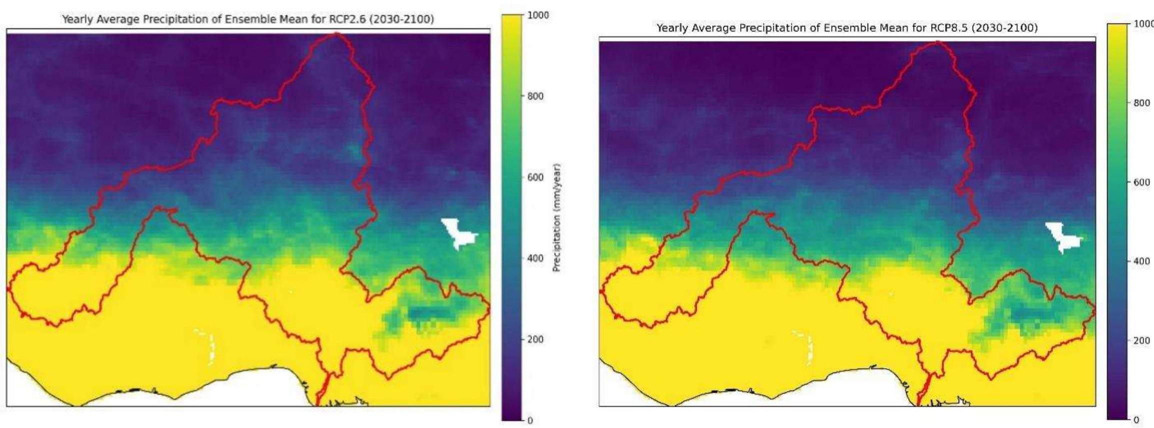


Figure 16: Spatial Variability of Precipitation under RCP 2.6 and RCP 8.5

4.7.2 Spatial variability of surface runoff

The spatial variability of the ensemble mean of the annual surface runoff shows regional differences, with some areas experiencing either an increase or a decrease in runoff in RCP 2.6 and RCP 8.5, depending on the local climatic and geographical conditions in the river basin. The projected decline in runoff reduced to as low as 0-100mm/year in some regions, as seen in Figure 17. The interconnected nature of rainfall and runoff in the hydrological process shows that the decline in runoff is more pronounced under the high emission scenario, RCP8.5, which is attributable to the reduced precipitation and increased evaporation driven by higher global temperatures, especially in the arid and semi-arid regions, which are particularly vulnerable to minimal rainfall and higher temperatures.

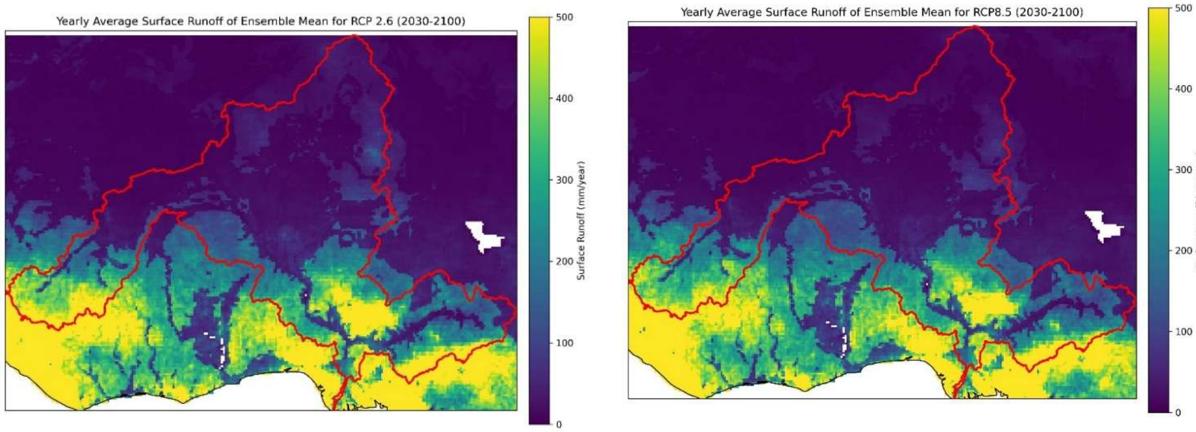


Figure 17: Spatial Variability of Surface Runoff under RCP 2.6 and RCP 8.5.

4.7.3 Spatial variability of evapotranspiration

The spatial variability of the ensemble mean of the evapotranspiration (ET) shows a variation between an increase and a decrease in the amount of evapotranspiration under both scenarios, RCP 2.6 and RCP 8.5, at various regions, as seen in Figure 18. Some regions experienced lower ET values, especially under the RCP 2.6 scenario, likely due to soil moisture availability and changes in vegetation. In contrast, some regions experienced higher ET values as high as 1000mm, especially under the RCP 8.5 scenario, driven by increased temperatures and higher atmospheric water demand. The increased temperature contributes to the acceleration in evaporation and plant transpiration in the high-emission scenario, RCP 8.5.

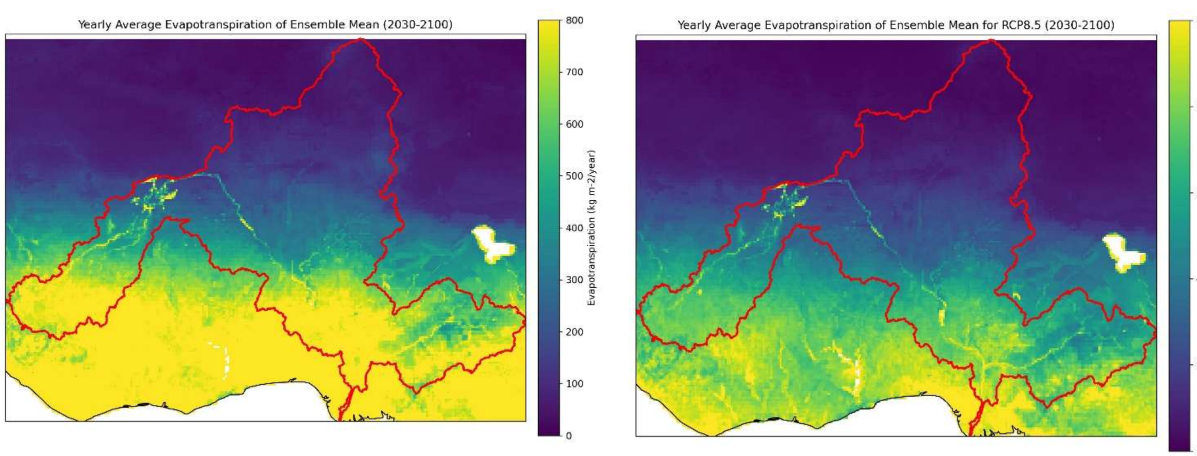


Figure 18: Spatial Variability of Evapotranspiration under RCP 2.6 and RCP 8.5

4.8 Discussion of Results

In this chapter, the variability of annual and monthly rainfall over the Niger River Basin (NRB) and Jebba Hydropower Station (JHS) has been analyzed and characterized. The lowest recorded rainfall in the study occurred in 1983 (523.7 mm for NRB) and 2009 (933.7 mm for JHS), while the highest was in 1999 (759.7 mm) and 1991 (1,462.8 8 mm), in NRB and JHS, respectively. Rainfall remained low from November to February but increased from March, peaking between July and September. The highest mean monthly rainfall was observed in August for NRB (170.7 mm) and in September for JHS (237.06 mm). The Standardized Precipitation Index revealed negative anomalies across all stations, with the highest anomaly recorded in Ilorin (66%) and the lowest in Bida (40%). The longest drought occurred from 1981 to 1989 across the NRB, with 1983 being the driest year. Excess rainfall was observed in 2016 at Ilorin and in 2020 at Minna. Trend analysis using Mann-Kendall (MMK) and Innovative Trend Analysis (ITA) showed increasing rainfall trends at NRB and Ilorin. However, other stations, Bida, Minna, Lokoja, and Jebba, showed no consistent trends, except for Bida, which displayed a rising trend only in ITA. Change point detection using Pettitt, SNHT, and Buishand tests revealed that most stations experienced shifts in rainfall patterns, except Minna, where all tests confirmed no significant change. The other stations showed mixed results, with some tests indicating changes while others did not, especially for Lokoja and Jebba. Future projections of precipitation, surface runoff, and evapotranspiration were assessed using five Regional Climate Models (RCMs) under RCP 2.6 and RCP 8.5. Under RCP 2.6, annual precipitation is projected to remain relatively stable (550–750mm), with surface runoff ranging from 130–180mm and evapotranspiration between 380–420mm. However, under RCP 8.5, a significant decline is projected after 2060. By 2100, precipitation could reduce to 420mm, surface runoff to 90mm, and evapotranspiration to 300mm. These declines are directly tied to reduced rainfall and could indicate increasing water stress in the river basin. Overall, the evidence from observations and projections points to a future change in the NRB toward more variable and perhaps drier climate conditions, which could have significant implications for hydropower operations and water resource planning in the river basin.

4.9 Partial Conclusion

This study presents a detailed assessment of hydroclimatic variability in the Niger River Basin (NRB), with emphasis on the Jebba Hydropower Station. Through the use of robust statistical tools, including the Standardized Precipitation Index (SPI), Modified Mann-Kendall (MMK), Innovative Trend Analysis (ITA), and homogeneity tests, key patterns in rainfall variability, trends, and change points have been identified across several rainfall stations in the basin. While some stations, particularly Ilorin and Bida, exhibited statistically significant trends, others showed no major directional change, indicating spatial heterogeneity in rainfall behaviour. The influence of rainfall variability on hydropower generation is evident. Inflow into the Jebba reservoir, and thus its electricity generation potential, is tightly linked to upstream rainfall patterns. Decreased rainfall not only affects reservoir storage levels but also impacts turbine operations, leading to reductions in energy output. This finding reinforces the importance of rainfall as a key driver of hydropower reliability and efficiency in the region. Projected changes in climate under different Representative Concentration Pathways (RCPs) further emphasize the urgency of planning for hydrological shifts. Under the low-emission RCP 2.6 scenario, the basin is likely to maintain relatively stable hydrological conditions. This scenario supports water resource sustainability, ecosystem health, and consistent hydropower output. Conversely, under the high-emission RCP 8.5 scenario, a marked decline in precipitation, surface runoff, and evapotranspiration is anticipated, potentially leading to water stress, reduced agricultural productivity, and compromised energy production. In light of these findings, it is critical to include flexible and proactive methods in basin-wide water and energy management plans. To maintain hydropower production and ensure livelihoods, it will be crucial to invest in integrated water resource management, promote climate-resilient infrastructure, and improve early warning systems. In addition, transitioning to low-carbon development pathways and reducing greenhouse gas emissions remain critical to minimizing long-term climate risks.

In summary, this study underscores the vulnerability of the Niger River Basin and its hydropower infrastructure to climate-induced changes. By recognizing and preparing for these challenges, policymakers and stakeholders can strengthen regional resilience, enhance sustainable development outcomes, and ensure energy security. The next chapter builds on these insights by exploring the impacts of hydroclimatic trends on hydropower generation for green hydrogen production in the study area.

CHAPTER 5: EFFECT OF HYDROCLIMATIC TREND ON HYDROPOWER GENERATION FOR GREEN HYDROGEN PRODUCTION

Chapter 5 presents trends in hydroclimatic variables, hydropower generation, and the potential for green hydrogen production. Section 5.1 presents the results of the seasonality of hydropower generation in the study area. Section 5.2 features the estimated green hydrogen production and re-electrification potential. Section 5.3 presents the results of the estimated petrol (or gasoline) replacement and the amount of greenhouse gas emissions prevented. This chapter examines the influence of hydroclimatic trends and variability on hydropower generation and the potential for green hydrogen production. The major results of this chapter have been summarized in a paper publication and are now available in the Journal of Water and Climate Change (https://doi.org/10.1007/978-3-031-68330-5_11).

5.1 Hydropower in Nigeria has strong seasonality

The statistical evaluation provides a reference for understanding the inter-annual fluctuations and seasonal patterns of hydropower, which is essential for assessing how hydrogen production may be affected by climate variability. The outcomes of the trend analysis, conducted using the Modified Mann-Kendall (MMK) test, are presented in Table 11. Results reveal increasing patterns in reservoir inflow, outflow, turbine release, and electricity production, while evaporation losses demonstrate a downward trend. No notable trend was observed in maximum temperature or rainfall. The inter-annual variability and seasonal behaviour of hydropower generation are illustrated in Figure 19. The inter-annual analysis reveals considerable fluctuations in hydropower output, with a minimum of 2065 MWh recorded in 1993 and a maximum of 4150 MWh in 2016, representing a 50.2% increase. Seasonal variation also reflects this pattern, as the peak generation of 2412 MWh occurred during the 2007 dry season, while the lowest value of 684.7 MWh was observed in the 1988 wet season. Overall, the findings reveal a rising trend in energy production at both annual and seasonal scales, likely driven by the positive trends in reservoir inflow and turbine discharge, which strongly determine hydropower output. Seasonal analysis indicates that hydropower production is greater during the dry season (October–April) compared to the wet season (May–September). This difference may be linked to flooding events in the wet season and the relatively stable inflows observed in the dry season. Further information on flooding at the dam is provided in the study by Olukanni et al. (2016). Excess energy produced during the dry season can serve as an alternative pathway for green hydrogen production; nevertheless, this study adopts an approach that relies on a defined proportion of hydropower output.

Table 11: MMK trend analysis statistics (with the P-value at 0.05 significant level) and Zs (normalized test statistics) show the trend, either increasing (+Ve), decreasing (-Ve), or no trend (Non) for all variables.

Jebba dam variables	**P-value**	**Zs**	**Trend**
Rainfall (mm/yr)	0.0891	1.6996	Non
Max. Temperature (ºC)	0.2960	1.0449	Non
Reservoir Inflow (m^3/s)	0.0000	5.3603	+Ve
Reservoir Outflow (m^3/s)	0.0005	3.4672	+Ve
Evaporation loss (m^3/s)	0.0005	-3.4633	-Ve
Turbine discharge (m^3/s)	0.0000	4.7610	+Ve
Energy Generation (MWh)	0.0001	3.8071	+Ve

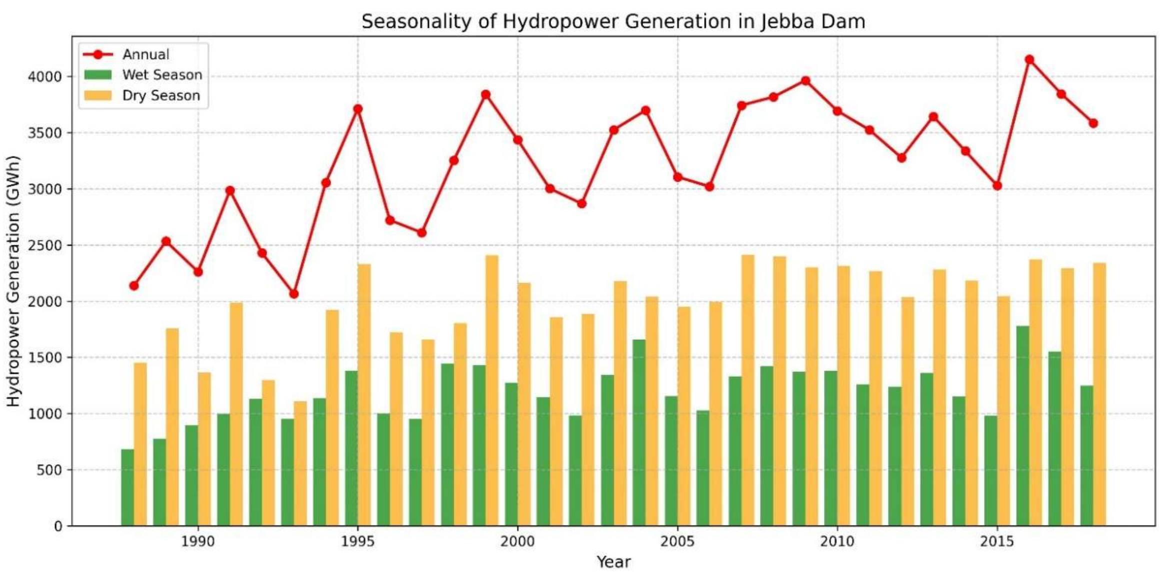


Figure 19: Inter-annual variability and seasonality of annual hydropower generation in the wet (green) and dry (orange) seasons at Jebba hydropower Station.

To examine the relationship between energy generation and selected hydrological and climate variables (rainfall, maximum temperature, reservoir inflow, outflow, evaporation loss, and turbine discharge), a correlation matrix was developed using a 95% confidence level. As shown in Figure 20a, the correlation matrix for the Jebba hydropower plant reveals that energy generation is highly and significantly correlated with reservoir inflow, outflow, and turbine discharge, with correlation coefficients of 0.9, 0.9, and 0.99, respectively. In contrast, maximum temperature and rainfall exhibit weaker correlations of 0.42 and 0.15, while evaporation loss shows an almost negligible negative correlation (–0.013). Additionally, turbine discharge demonstrates a strong relationship with both inflow and outflow, reflected by a coefficient of 0.92. Likewise, the sensitivity analysis result is presented in Figure 20b, the analysis shows that turbine discharge contributes most strongly to energy generation, with a mean decrease accuracy of 0.59. Reservoir inflow and outflow follow with values of 0.23 and 0.17, while rainfall has only a minor effect at 0.04. By comparison, temperature (0.02) and evaporation loss (0.01) exert negligible influence on power generation at the hydropower station.

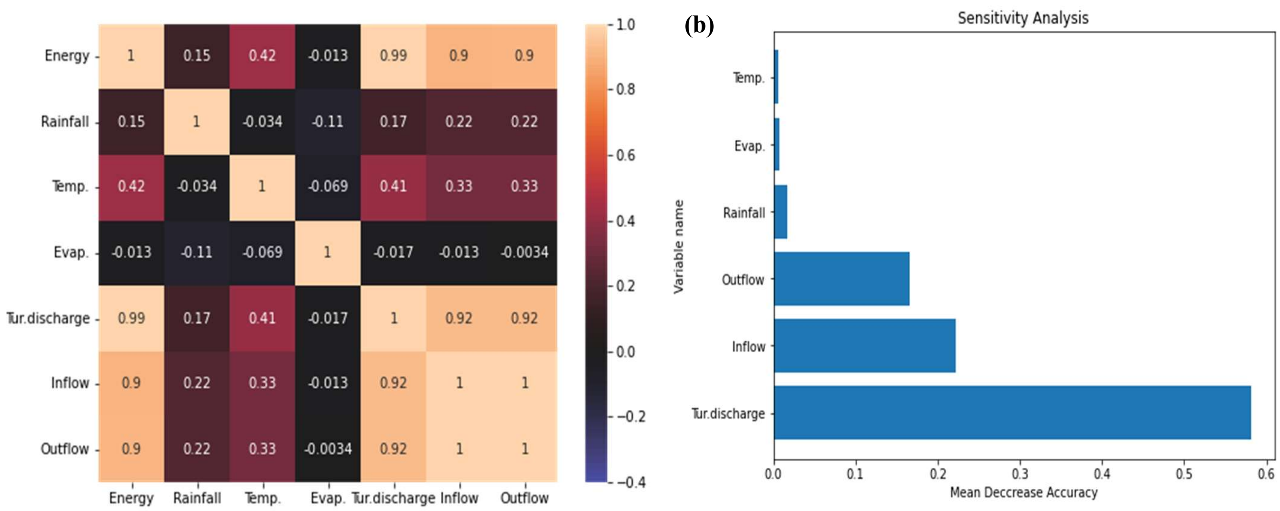


Figure 20: **(a)** Pearson correlation coefficient for energy generation and other hydroclimatic variables **(b)** Sensitivity analysis of energy generation to other hydroclimatic variables

5.2 Estimation of green hydrogen production and re-electrification potential.

The hydropower resources corresponding to the five considered scenarios were analyzed, and the findings on annual and quarterly green hydrogen production potential are presented in Figures 21a and 21b. Meanwhile, the annual and quarterly potential for re-electrification through hydrogen-fueled cells is illustrated in Figures 21c and 21d, respectively. In the first scenario, which assumed 100% reliance on hydropower, the maximum and minimum annual hydrogen production potentials were 59,111 tons and 40,125 tons, respectively, corresponding to re-electrification potentials of 1,182 GWh and 803 GWh in 2021 and 2002. The highest quarterly output was observed in the fourth quarter of 2021, with 18,744 tons of hydrogen and 374 GWh of re-electrification potential. Overall, the findings indicate that hydrogen production and re-electrification capacity across the five modelled scenarios exhibit a strong linear relationship with hydropower generation. This implies that hydrogen can provide a stable and consistent production profile, making it a viable option for energy storage and rural re-electrification in communities lacking access to electricity.

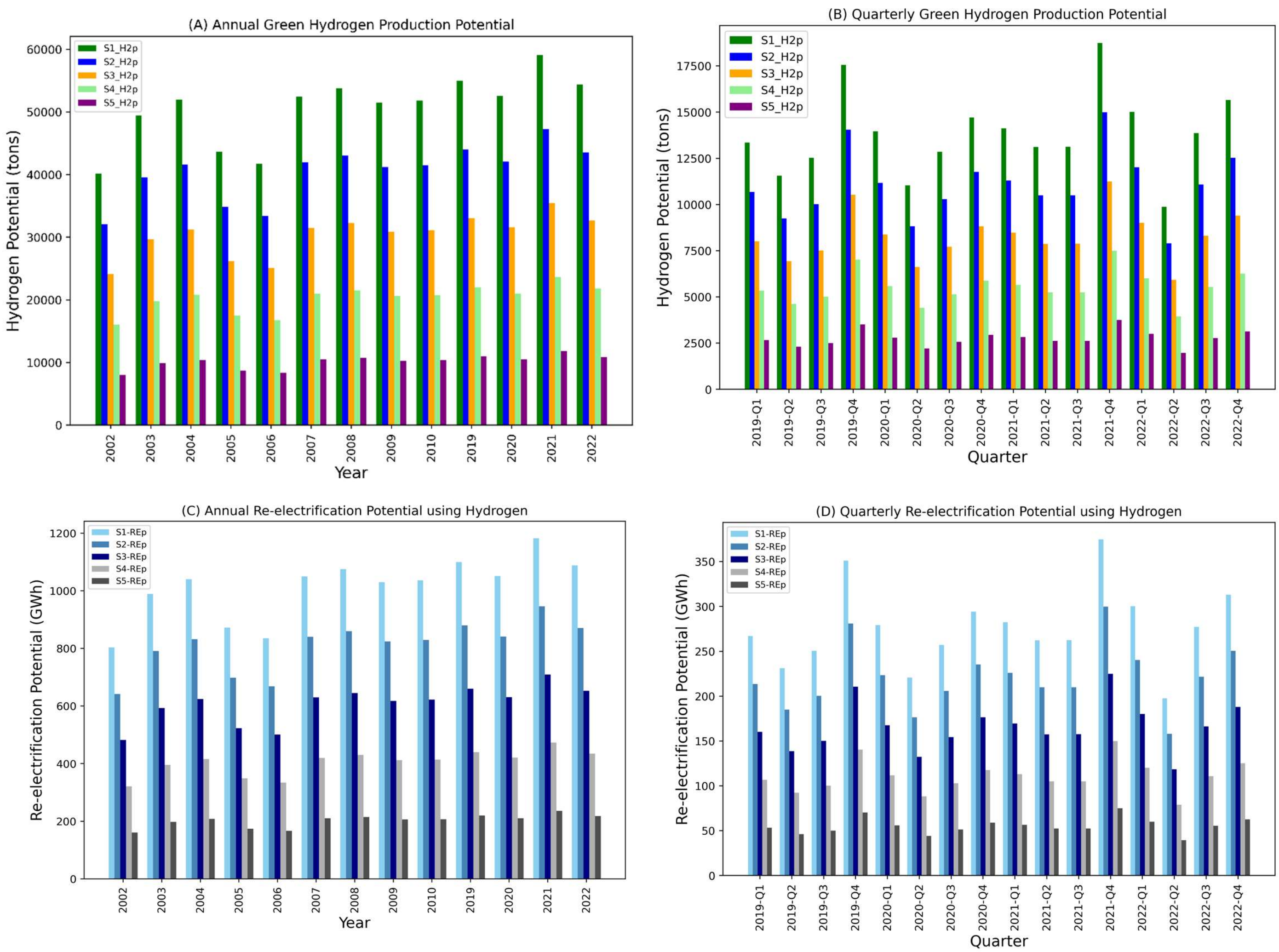


Figure 21**:** Scenario 1 (S1) to Scenario 5 (S5) estimated **(a)** Annual green hydrogen production potential **(**H2p**), (b)** Quarterly green hydrogen production potential **(**H2p**), (c)** Annual re-electrification potential (REp), and **(d)** Quarterly re-electrification potential (REp) at Jebba Hydropower Station.

5.3 Estimation of petrol (or gasoline) replacement and the amount of greenhouse gas emissions prevented.

The estimated annual and quarterly quantities of petrol replacement by hydrogen across the five hypothetical scenarios are presented in Figure 22 (a and b), the annual and quarterly amounts of CO_2 emissions that could be mitigated are presented in Figure 22 (c and d) while the annual and quarterly volumes of CO emissions that could be avoided are presented in Figure

22 (e and f). In the first scenario, where hydrogen was generated entirely from hydropower, the maximum and minimum petrol replacement potentials were 0.224 million liters and 0.152 million liters, corresponding to the use of 59,111 tons and 40,125 tons of hydrogen in 2021 and 2002, respectively. These substitutions would avert 0.52 million kg of CO_2 and 0.92 thousand kg of CO in 2021, as well as 0.35 million kg of CO_2 and 0.63 thousand kg of CO in 2002. On a quarterly scale, hydrogen production from the same scenario in 2021-Q4 could replace 0.0709 million liters of petrol using 18,744 tons of hydrogen, thereby preventing 0.163 million kg of CO_2 and 0.293 thousand kg of CO. Such fuel substitution demonstrates the potential of hydrogen deployment for reducing greenhouse gas (CO_2 and CO) emissions while supporting the re-electrification of rural communities in Nigeria lacking reliable energy access. Based on the country's estimated electricity consumption as reported in the study by (Olaniyan et al., 2018), considering an average household electricity demand of 90–135 kWh per month for five members, or 18–27 kWh per capita per month, the hydrogen production of 59,111 tons equivalent to a re-electrification potential of 1,182,000 kWh (1,182 GWh) in 2021, could supply electricity to approximately 730–1,094 households, representing 3,648–5,472 individuals in rural areas. Such an intervention could also lower the country's annual CO_2 emissions, which are predominantly attributed to fossil fuel combustion, as noted by Climate Watch (2020). Across all sectors, such gradual emission reductions would strengthen the nation's climate change mitigation strategies and support progress toward carbon neutrality.

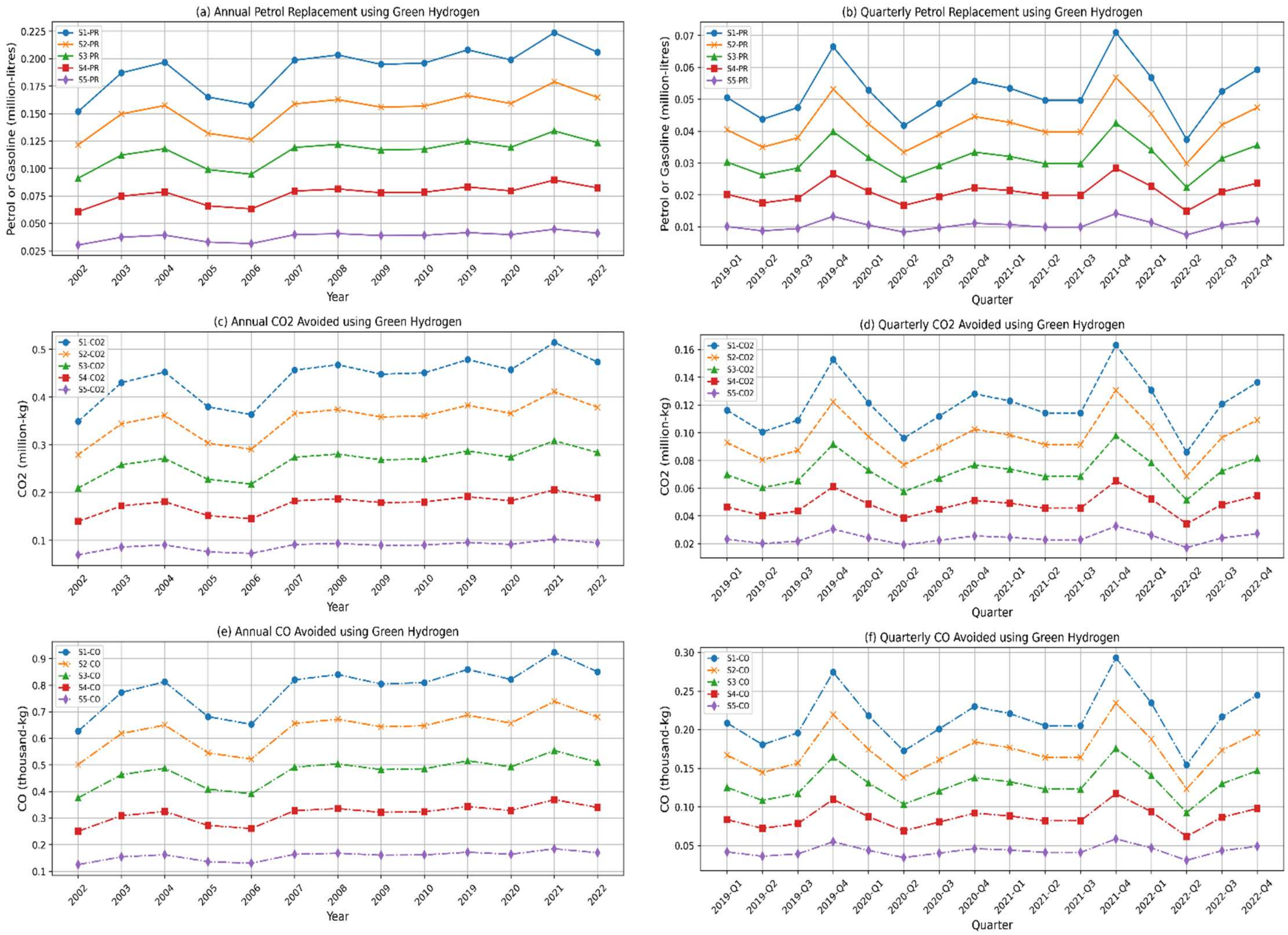


Figure 22: Scenario 1 (S1) to Scenario 5 (S5) estimated (a-b) Annual and quarterly petrol replacement (PR), (c-d) Annual and quarterly CO_2 emissions avoided, (e-f) Annual and quarterly CO emissions avoided using green hydrogen for re-electrification.

5.4 Discussion of Results

This study highlights the influence of hydroclimatic variability on hydropower generation and its implications for the efficiency and reliability of green hydrogen production in Nigeria, both for re-electrification and as a substitute for fossil fuels. Trend analysis indicates a marked increase in energy output between 1988 and 2018, primarily driven by rising reservoir inflows, outflows, and turbine discharges, which are identified as key determinants of hydropower generation. Sensitivity analysis further reveals that turbine discharge exerts the strongest influence on energy output among these variables, underscoring its critical role in determining the station's electricity production. The hydroclimatic trends identified at the station align with the findings of Salami et al., (2010), who reported similar impacts of climate change on reservoir water resources. Their study observed significant upward trends in inflow, outflow, and turbine discharge, alongside a slight but declining trend in evaporation loss. Additionally, the present analysis reveals that turbine discharge, reservoir inflow, and outflow exhibit stronger correlations with energy generation compared to other factors, such as rainfall, temperature, and evaporation loss. These results are consistent with the observations of Liman et al. (2021), who found that inflow and outflow exhibit stronger correlations with energy generation compared to temperature and evaporation losses. Similarly, their study reported that hydropower production is more pronounced during the dry season than in the wet season. The observed increase in the hydropower production is directly reflected in the potential for green hydrogen generation, emphasizing the critical role of water resource availability in supporting both hydropower and hydrogen production. Greater hydropower output translates into increased hydrogen yields, which can be harnessed for energy storage during periods of surplus electricity and as a substitute for fossil fuel consumption. Replacing fossil fuels, such as petrol, with hydrogen offers a pathway to reducing greenhouse gas emissions and advancing climate change mitigation. Moreover, strengthening investment in green hydrogen technologies and hydropower infrastructure is essential for meeting Nigeria's 2050 hydrogen capacity targets. Such development would enhance energy security by providing reliable and versatile storage solutions applicable to diverse sectors, including electricity generation, transportation, and industry, while reducing dependence on imported fossil fuels. Ultimately, this transition supports energy diversification, builds resilience against supply disruptions, and contributes to achieving net-zero carbon emissions by eliminating fossil fuel–based generators by 2050.

Furthermore, the study demonstrates that coupling hydropower generation with green hydrogen production for re-electrification, alongside replacing fossil fuel generators with hydrogen fuel cell systems, offers environmental advantages through reduced CO_2 and CO emissions. In the context of ongoing global and national discussions on energy transition, this assessment recommends strategically integrating green energy into the national energy mix by designating portions of hydropower output—across five proposed scenarios, including surplus generation for hydrogen production. Such an approach represents a viable pathway toward achieving national energy transition targets and mitigating future increases in greenhouse gas emissions. It should be noted, however, that the scope of this study is limited to a single hydropower facility at the Jebba Dam, due to data availability and the focus on site-specific analysis, despite Nigeria's broader estimated untapped hydropower potential of 14,750 MW (ECN & UNDP, 2005), which can be developed to serve as an integrated system for hydroelectricity generation and green hydrogen production. This integration supports Nigeria's carbon neutrality and net-zero targets by 2060 (Climate Action Tracker, 2023), while offering economic advantages through green hydrogen export revenues and job creation within the energy sector. It also contributes to the achievement of the United Nations Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), which underscore the role of sustainable energy solutions in advancing broader development objectives. Moreover, this evaluation of Jebba hydropower for green hydrogen production is expected to stimulate future research on hydro-to-hydrogen pathways in Nigeria.

The findings of this study highlight the complex interconnections among hydroclimatic variability, hydropower generation, and green hydrogen production potential. They further demonstrate the role hydrogen can play in climate change mitigation by serving as a cleaner substitute for fossil fuels. Although this analysis focused on a single hydropower reservoir, the methodology is scalable to other sites across the country, enabling the development of integrated hydropower systems for hydrogen production, fossil fuel displacement, and broader decarbonization efforts. Continued investigation of these dynamics remains critical in light of climate change and the evolving global energy landscape.

5.5 Partial Conclusion

This section outlines the chapter's partial conclusion, policy relevance, and recommendations. The study examined the impact of hydroclimatic variability on hydropower generation and its implications for green hydrogen production in Nigeria. At Jebba Dam, hydropower output increased significantly from 1988 to 2018, largely due to increased reservoir inflow and turbine discharge. This increase directly enhanced the seasonal and annual potential for green hydrogen production, including re-electrification potential, fossil fuel replacement, and associated emissions reductions. Hydrogen produced from surplus hydropower can serve as a clean energy carrier, supporting Nigeria's decarbonization goals. With energy sector emissions rising from 142,678 Gg CO_2-eq in 2000 to 245,918 Gg CO_2-eq in 2017 in Nigeria, according to (Federal Republic of Nigeria (2021), hydrogen offers a pathway to mitigate emissions, especially from fuel combustion, which accounts for over 60% of total emissions. Fuel cells powered by green hydrogen could supply electricity to thousands of off-grid households, improving energy access and reducing dependence on fossil fuel generators. For instance, 59,111 tons of hydrogen could yield 1,182 GWh of electricity, benefiting approximately 3,600–5,500 people. Due to aging infrastructure, initial hydropower utilization for hydrogen production is expected to start modestly at around 20%, with future scale-up dependent on investments in dam upgrades and the development of untapped sites. The country's estimated 12,220 MW of unexploited hydropower capacity offers a significant opportunity for expanding green hydrogen production, strengthening energy security, and potentially generating export revenue. To realize this potential, targeted policy interventions are needed. These should include incentives for hydropower-hydrogen integration, investments in infrastructure, and coordinated assessments of environmental and socio-economic impacts. Such efforts will be key to aligning hydrogen development with Nigeria's net-zero target by 2060.

Following the assessment of the effect of hydroclimatic trends on hydropower generation for green hydrogen production, the next chapter discusses the projected future changes in reservoir inflow, hydropower potential, and the green hydrogen potential under evolving climatic change.

CHAPTER 6: FUTURE CHANGES IN GREEN HYDROGEN PRODUCTION POTENTIAL FROM HYDROPOWER GENERATION

This chapter assesses the potential changes in future reservoir inflow, hydroelectric energy generation, and green hydrogen production at the Jebba hydropower station, considering the cascaded dam. Section 6.1 shows the Jebba Dam catchment delineation. Section 6.2 presents the calibration and validation of the hydrology model. Section 6.3 presents the projected changes in reservoir inflow; Section 6.4 illustrates the changes in hydropower generation. Section 6.5 reveals the changes in the potential for future green hydrogen production and its application in replacing fossil fuels.

6.1 Catchment Delineation of Jebba Catchment

The catchment delineation of the Jebba catchment was done using the delineation tool of the Global Watersheds web app, as shown in Figure 23 at https://mghydro.com/watersheds/

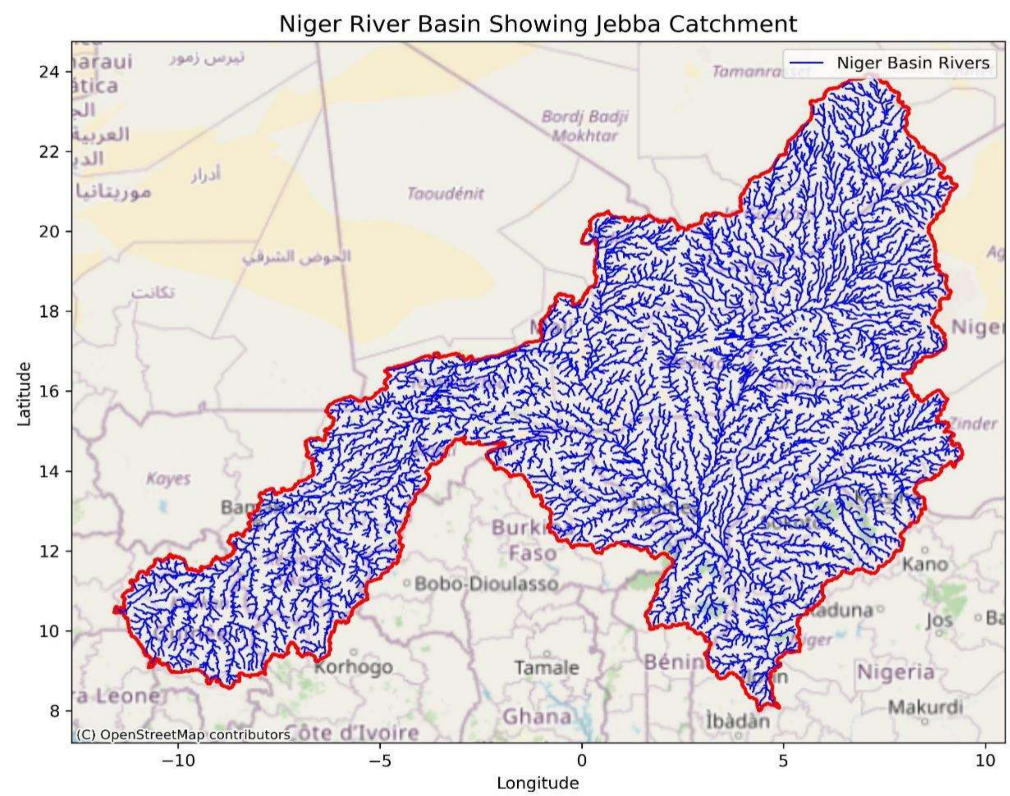


Figure 23: Jebba Catchment delineation

6.2 Calibration and Validation

The models were calibrated from 1984 to 1996, as seen in Figure 24a and validated from 1997 to 2004, as seen in Figure 24b. The best optimum inflow model parameters were deduced from automatic calibration between simulated and observed reservoir inflow. This resulted in moderate calibration correlation efficiency values of 0.68 (KGE) and a relative bias of 0.95, and the validation also had similar efficiency values of 0.69 (KGE) and a relative bias of 1.02, as seen in Figure 25 of the performance error metrics. The hydropower Python model was calibrated using the reservoir operation rule of the Kainji Dam upstream of Jebba Dam. Figure 26a and b display the simulated and observed reservoir inflow and hydropower generation of Jebba Dam, respectively, showing a high correlation.

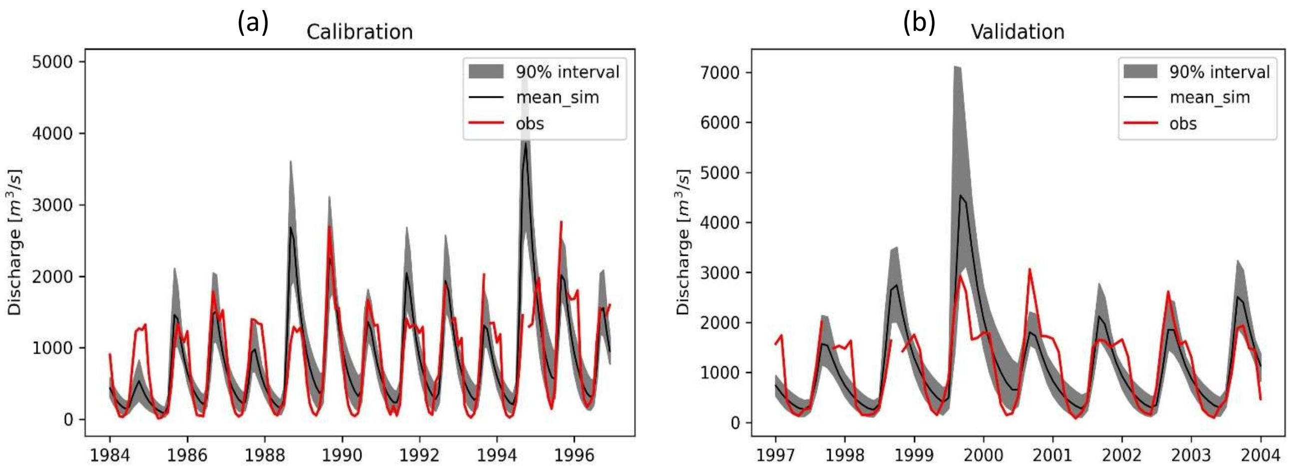


Figure 24: Calibration and validation of the hydrological model.

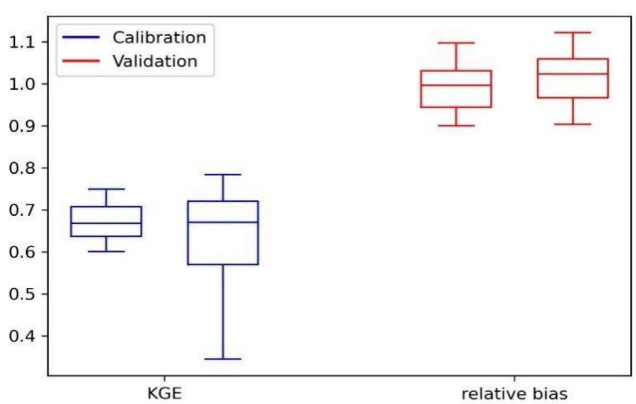


Figure 25: Performance error metrics of the hydrologic model.

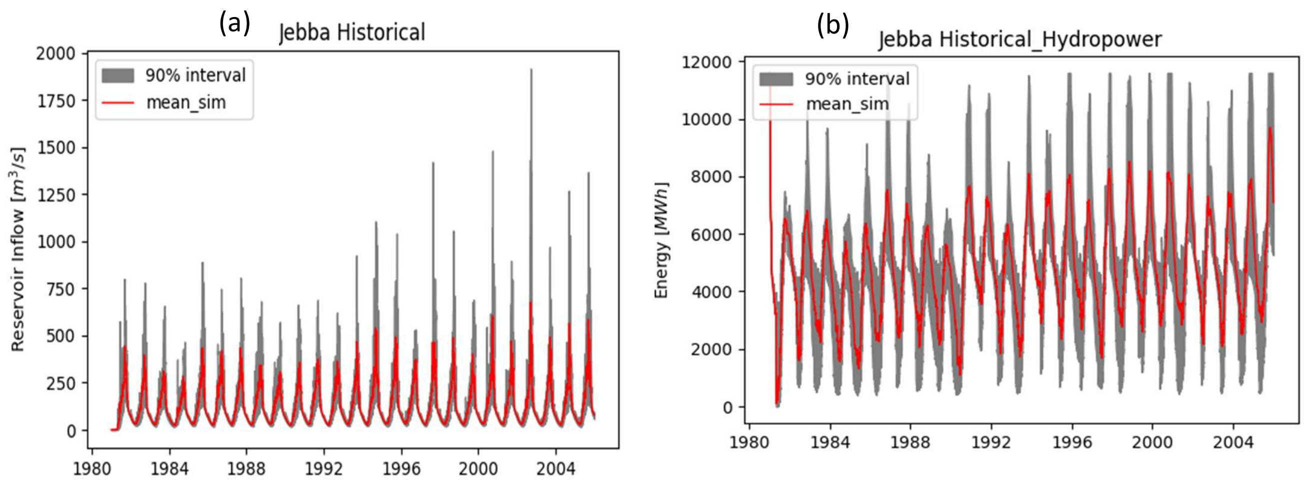


Figure 26: Historical simulation of reservoir inflow and hydropower generation in Jebba Dam.

6.3 Reservoir Inflow

The projected climate change impacts on the reservoir inflow of Jebba Dam using daily climatic data of the selected eight (8) Global Climate Models (GCMs) for SSP245 and SSP585 are displayed in Figure 27. The ensemble mean (average across the 8 GCMs) was also calculated. Under SSP245, which represents an intermediate emissions scenario where carbon emissions increase moderately, the reservoir inflow initially increased from 2025 to 2065, reaching a high of 5000 m^3/s, with the highest peak recorded in 2050 due to peak rainfall and reservoir inflow. Similarly, under SSP585, which represents a high-emission scenario with a strong focus on economic growth driven by fossil fuels, leading to a rapid increase in carbon emissions, the reservoir inflow initially increased to values ranging between 0 and 5000 m^3/s before gradually declining from 2065 to 2100. There was a slight difference between the two scenarios, with SSP 245 having a higher reservoir inflow while SSP 585 had a lower reservoir inflow.

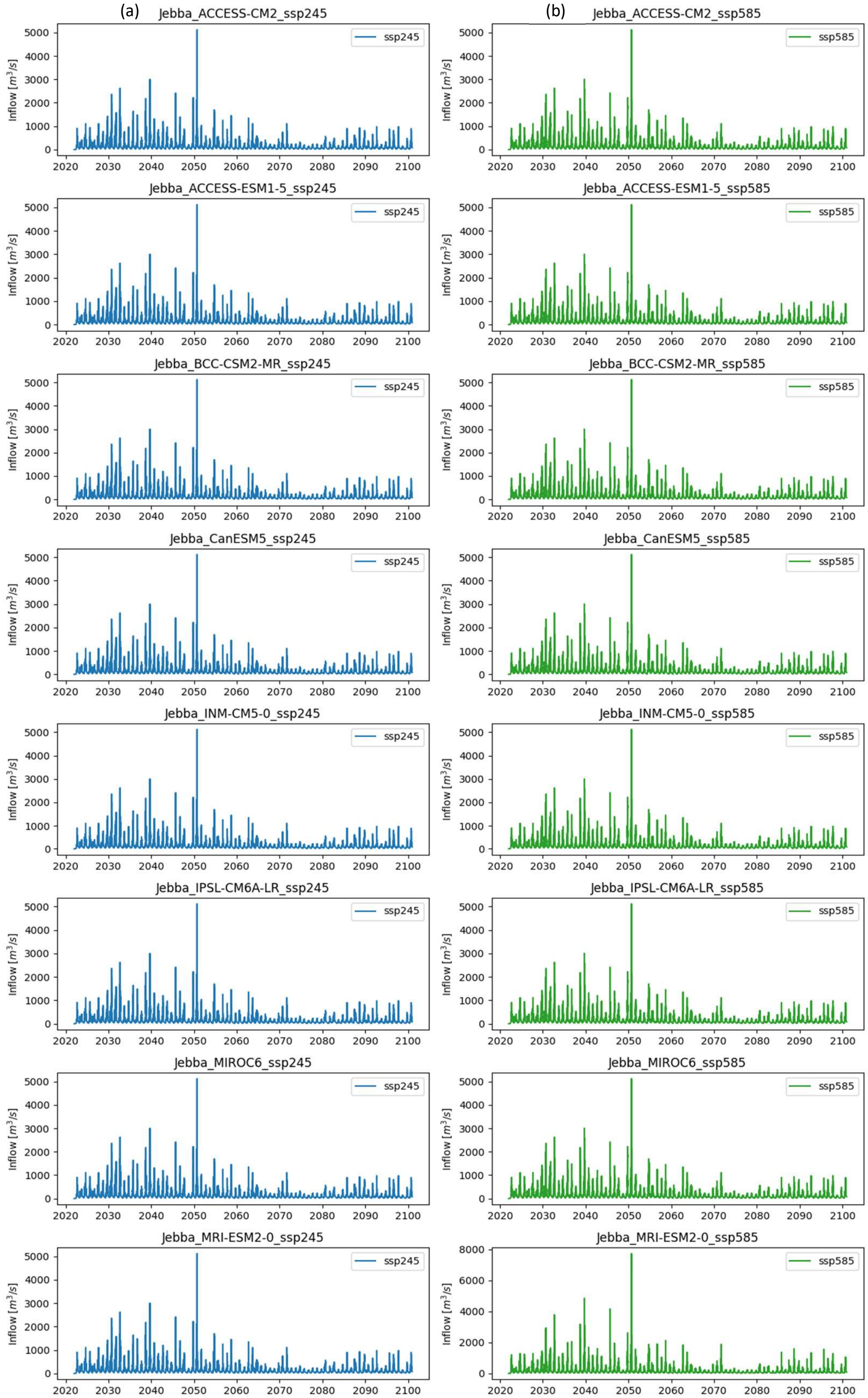


Figure 27: Jebba Reservoir Inflow Projection for all 8GCMs (a) SSP245 and (b) SSP585.

6.4 Hydropower Production

The projected climate change impacts on the hydropower generation of Jebba Dam using daily climatic data of the eight (8) selected GCMs for SSP245 and SSP585 are displayed in Figure

28. The ensemble mean (average across the 8GCMs) was also obtained. Changes in the hydropower generation followed a similar pattern to the reservoir inflow, as the amount of reservoir inflow available mainly influences the hydropower generation. The hydropower generation initially increased from 2025 to 2065, reaching a high of 12000 MWh in Jebba dam under SSP245; however, there was a gradual decline in the amount of hydropower generation beginning in 2060 under both SSP245 and SSP585 scenarios. Notably, this decline was more pronounced under the SSP585 high-emission scenario due to the corresponding reduction in the reservoir inflow.

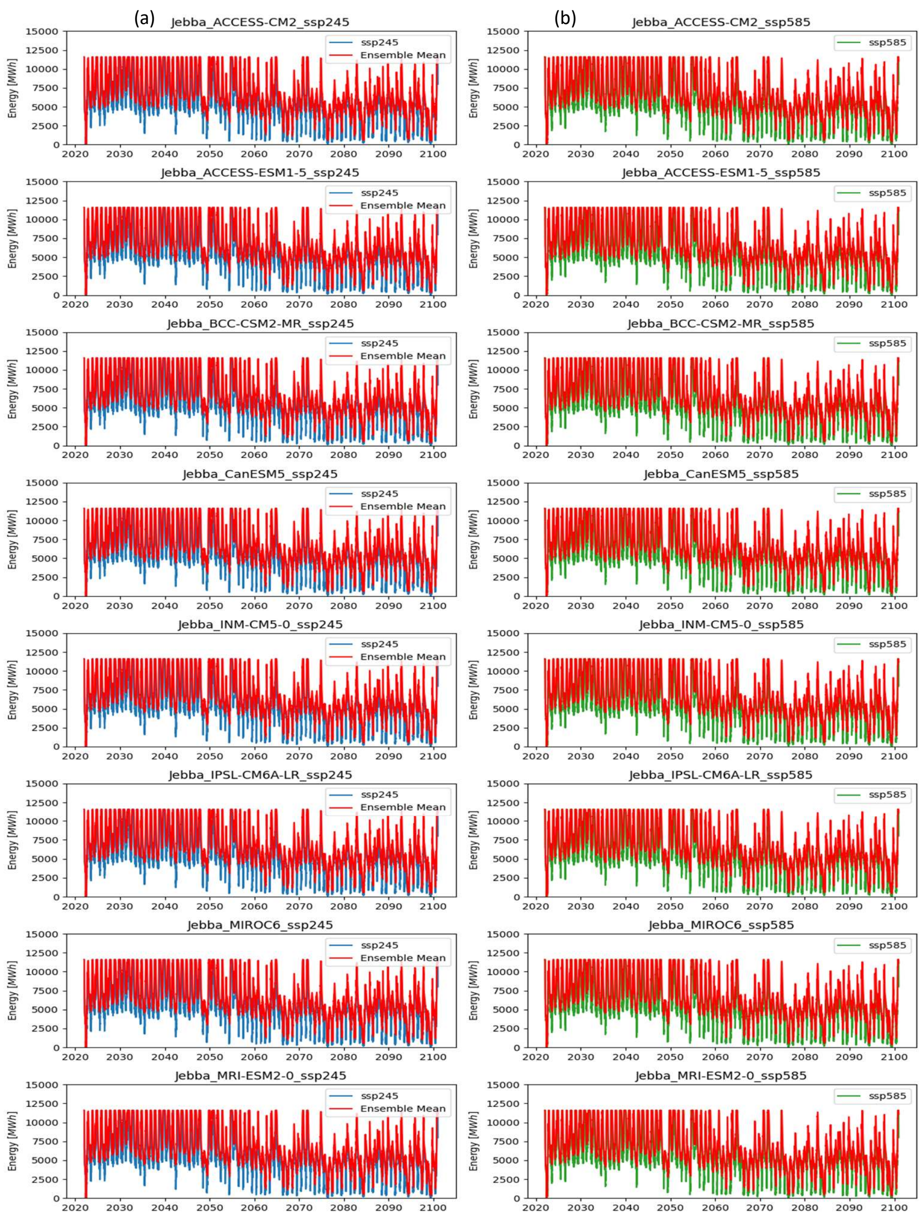


Figure 28: Jebba Hydropower Projection for all 8GCMs (a) SSP245 and (b) SSP585.

6.4.1 Changes in annual and monthly average hydropower projection in Jebba Dam

The projected changes in the annual under SSP245 and SSP585 are presented in Figure 29a and b, respectively, while the monthly average hydropower generation in Jebba Dam under SSP245 and SSP585 is presented in Figure 29c and d, respectively**.** The ensemble mean (average across the eight GCMSs) indicates that hydropower generation initially increased from 2025 to 2055, reaching a peak of 4 TWh under the SSP245 and SSP585 scenarios; however, a gradual decline began in 2056. Furthermore, changes in the monthly average indicate that hydropower generation gradually declined from approximately 250 GW to about 150 GW from January to June. However, there was a gradual increase from approximately 152 GW in July to a peak of 300 GW in November. This is attributable to a decline in reservoir inflow at the beginning of January, followed by a gradual increase in July, which could be due to the increase in rainfall during the region's rainy season.

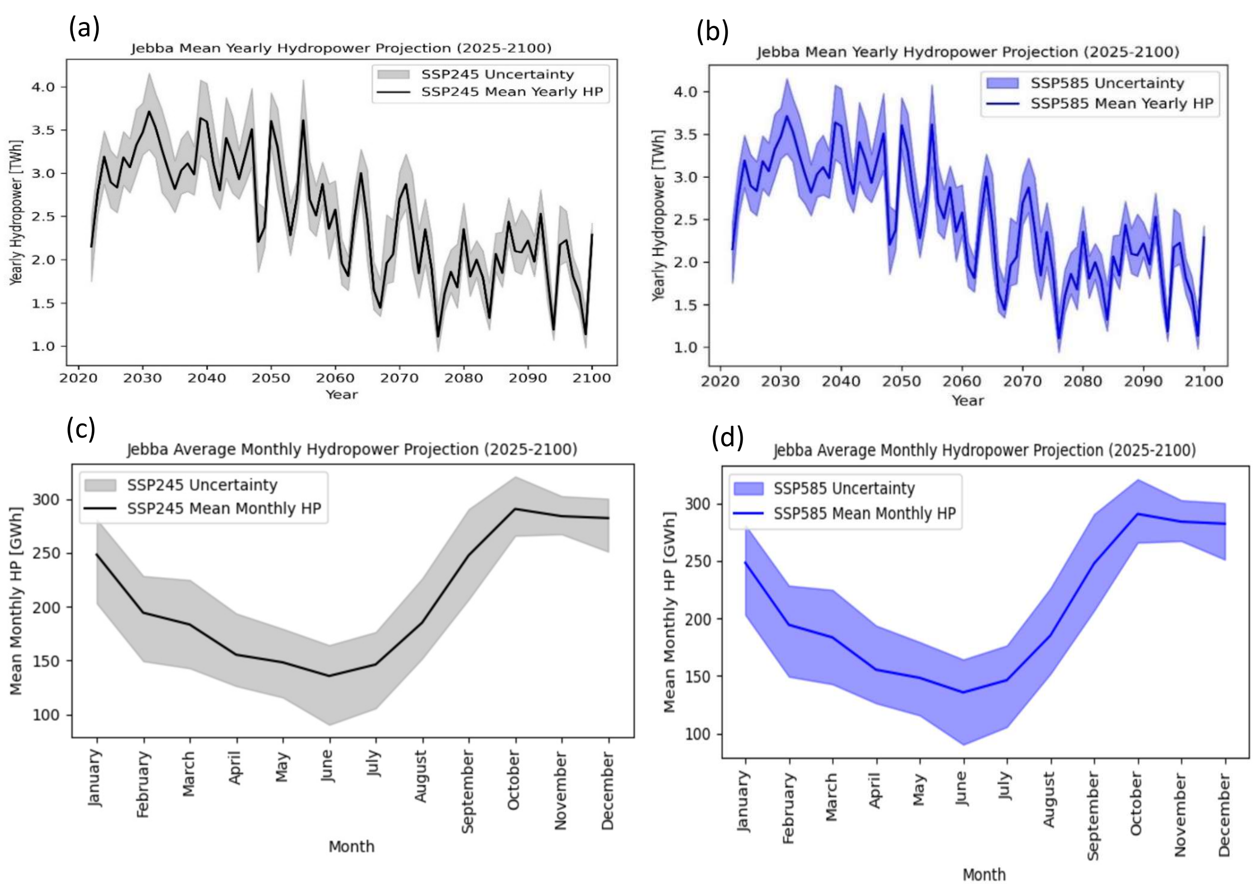


Figure 29: Projected changes in annual monthly hydropower generation in Jebba dam under SSP245 and SSP585.

6.5 Changes in Green Hydrogen Production Potential

The projected changes in green hydrogen production potential from hydropower generation in Jebba Dam under SSP245 and SSP585 are presented in Figure 30a and b, respectively. The ensemble mean (average across the eight GCMs), shows that the green hydrogen production potential from hydropower generation had an initial increase in production potential from 2025 to 2055; the green hydrogen production potential ranged from 12,000 tonnes to 5,000 tonnes of hydrogen in the first scenario (S1), the scenario of high hydropower demand and low renewable supply, while it ranged from about 32,000 tonnes to 10,000 tonnes of hydrogen in the second scenario (S2), the scenario of low hydropower demand and high renewable supply as seen in Figure 30a, this shows that the maximum amount of green hydrogen that can be produced from the first scenario (S1) is about 12,000 tonnes of hydrogen using about 700GWh of hydro-electric energy, why the maximum amount for the second scenario is 32,000 tonnes of hydrogen using about 1450 GWh of hydro-electric energy under SSP245, the difference in the green hydrogen potential under SSP585 was relatively small, however, SSP245 has more green hydrogen potential compared to SSP 585.

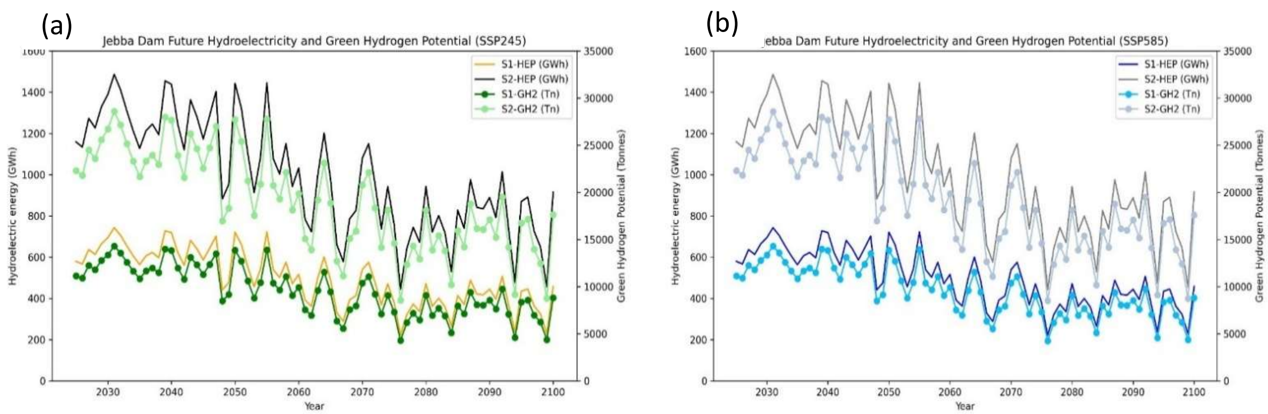


Figure 30: Projected changes in green hydrogen production potential from hydropower generation in Jebba Dam under (a)SSP245 (b) SSP585

6.6 Changes in re-electrification, petrol replacement, and CO_2 emission prevention

The projected changes in re-electrification, petrol replacement, and CO_2 emission prevention using green hydrogen produced from future hydropower generation under SSP245 and SSP585 are presented in Figure 31a and b, respectively. The ensemble means (average across the eight GCMs) shows that re-electrification, petrol replacement, and CO_2 emission prevention increased or decreased based on the amount of green hydrogen produced from the projected hydroelectric energy. The estimated re-electrification, petrol replacement, and CO_2 emission prevention amount initially increased from 2025 to 2055. This period (2025 to 2055), which reveals an initial increase, shows that under the first scenario (S1) for SSP245, the estimated petrol replacement using hydrogen fuel cells for re-electrification ranged from between 42 x 10^6 litres to 53 x 10^6 litres, with an electricity generation of about 224GWh to 275GWh which could prevent about 98 to 120 tonnes of CO_2 emission. Likewise, under the second scenario (S2) for SSP245, the estimated petrol replacement using hydrogen fuel cells for re-electrification ranged from 80 × 10^6 litres to 10 × 10^6 litres, with an electricity generation of about 448 to 550 GWh, which could prevent approximately 195 to 245 tonnes of CO2 emissions. The two scenarios under SSP585 exhibited similar patterns, although in terms of re-electrification, petrol replacement, and CO2 emission prevention, SSP245 had a higher quantity of petrol replacement using hydrogen fuel cells for re-electrification and the prevention of CO2 emissions.

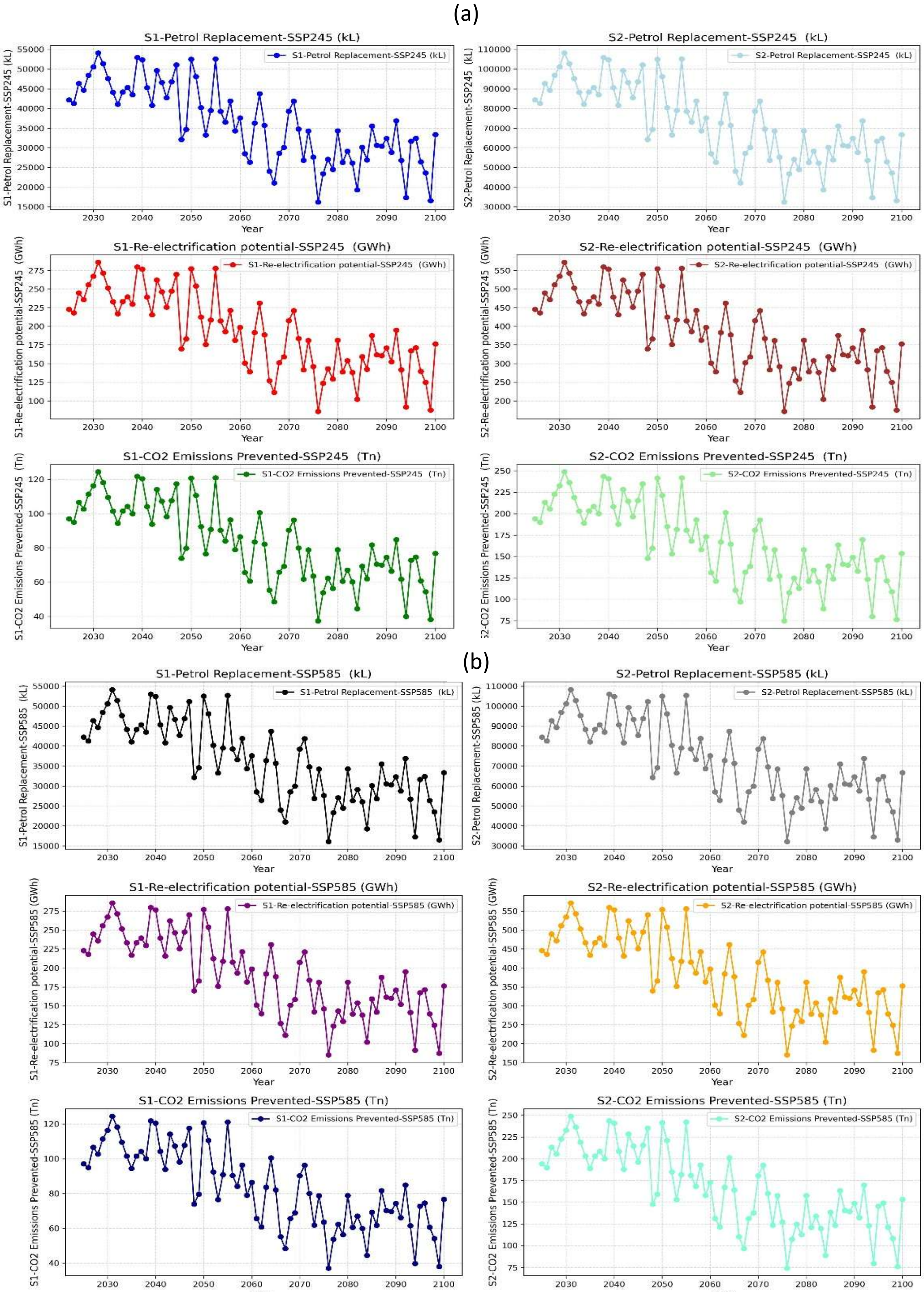


Figure 31: Re-electrification, Petrol Replacement, and CO2 emission Prevention using hydrogen under (a) SSP245 (b) SSP585

6.7 Discussion of Results

The projection of reservoir inflow at Jebba Dam under SSP245 and SSP585 scenarios reveals a clear climate-driven trend. The ensemble median from the eight Global Climate Models (GCMs) used in the study indicates that the inflow rises until around 2055, peaking at approximately 5,000 m^3/s before gradually declining through 2100. This pattern is primarily attributed to an initial increase in precipitation and runoff, followed by long-term reductions driven by rising temperatures and evapotranspiration under intensified greenhouse gas emissions. Hydropower generation mirrors this inflow trend. Between 2025 and 2055, Jebba Dam's daily electricity output is projected to increase to about 12,000 MWh, supporting substantial green hydrogen production. For example, under SSP245-S1, hydrogen production ranges from 5,000 to 12,000 tonnes using ~700 GWh, while SSP245-S2 yields up to 32,000 tonnes using ~1,450 GWh. This has strong environmental co-benefits, potentially replacing 42–105 million litres of petrol and preventing 98–245 tonnes of CO_2 emissions, depending on the scenario. These findings align with Khanal et al., (2024), who found that the projected increases in precipitation and temperature in Nepal's Chameliya Basin under SSP245 and SSP585 would enhance wet-season hydropower output but cause winter reductions. This seasonal imbalance underscores the importance of adaptive hydrogen storage and hybrid energy systems in ensuring consistent production. Comparatively, Oyerinde et al., (2016) modelled the Kainji Dam, upstream of Jebba, and also projected rising inflow and hydropower generation under RCP4.5 and RCP8.5. Their simulations indicated inflow increases of 200–500 m^3/s, with energy production rising by 50–100 MW by the end of the century. Notably, the RCP8.5 pathway showed a more pronounced impact due to greater warming and rainfall. Similar to this study, hydropower output was found to be highly sensitive to upstream precipitation trends, highlighting the strong dependency of reservoir-based energy systems on climate dynamics. While the Kainji study emphasized the long-term hydropower expansion potential under high-emission futures, our results highlight the trade-offs: although higher emissions may temporarily boost hydropower capacity through elevated inflows, this is followed by a decline, posing risks to the stability of hydrogen generation. Hence, the low-emission SSP245 pathway appears more sustainable for long-term water-energy security in Nigeria. Together, these findings underscore the importance of integrating climate-smart planning into hydropower and green hydrogen development strategies. Investments in forecasting, flexible infrastructure, and water-efficient operations will be critical to sustaining output under variable future climates.

6.8 Partial Conclusion

The results highlight a significant temporal shift in the reservoir inflow and hydropower production patterns of Jebba Dam, attributed to climate change. Between 2025 and 2055, a window of increased water availability and energy output appears to be present. This period can be utilized to enhance hydropower and green hydrogen production, thereby meeting the growing energy needs. It can also play a key role in supporting the government's plan to reduce carbon emissions by replacing fossil fuel generators with hydrogen fuel cell units, aiding efforts to prevent CO_2 emissions and combat climate change. However, the decline in inflow and hydropower generation after 2055 emphasizes the urgent need for adaptive management strategies. The expected reduction in reservoir inflow and energy production toward the end of the century presents serious challenges for both energy security and water resource management. Strategic planning will be crucial to address the impacts of lower water availability at the dam. This might involve investing in alternative energy sources, such as floating photovoltaic (FPV) systems, which could also help decrease evaporation, improve water conservation, and develop more effective water storage infrastructure. These projections highlight the importance of incorporating climate change scenarios into long-term water and energy planning. By understanding and preparing for these changes, stakeholders can develop more resilient systems that adapt to future climate conditions. Following this assessment, the next chapter presents the general conclusion and perspectives from this study.

CHAPTER 7: GENERAL CONCLUSION AND PERSPECTIVES

7.1. Conclusions

This study presents a comprehensive evaluation of the potential for green hydrogen production from the Jebba hydropower dam in the Niger River Basin as a strategy for mitigating climate change. The findings highlight the observed trends in hydroclimatic variables, the influence of climate change on water balance components (precipitation, runoff, and evapotranspiration), and the role of hydroclimatic variability in shaping hydrogen production from hydropower. In addition, the analysis examines projected changes in reservoir inflow, hydropower generation, and green hydrogen production, highlighting their implications for substituting fossil fuels, rural electrification, and reducing CO_2 emissions under future climate conditions. These findings, conclusions, and recommendations could support the policy and regulatory framework, enhancing the country's energy transition and climate change mitigation efforts. In conclusion;

Firstly, the annual mean rainfall variability in the Niger River Basin and the Jebba hydropower station shows that the region has been undergoing normal variability. For the hydropower station and the river basin, seasonal variations were found to be high, moderate, and normal. The Ilorin and Bida rainfall stations have the most significant and lowest negative anomalies, respectively, according to the Standardized Precipitation Index (SPI), indicating they are more susceptible to protracted dry periods. The study highlights the significance of rainfall variability in determining hydropower generation capacity and how climate-related factors, such as drought, may affect energy output. It concludes that variability in rainfall affects water availability at the hydropower station, contributing to the increasing trend in reservoir inflow, turbine discharge, and energy generation. A decrease in rainfall in the river basin and the hydropower station could result in drought, affecting the quantity of reservoir inflow and negatively impacting energy generation at the station. In light of these conclusions, it is imperative to practice resilience-building and adaptive water management techniques to guarantee water security and sustainable energy production in the face of climate change and unpredictability.

Secondly, the projected changes in precipitation, surface runoff, and evapotranspiration under different RCP scenarios indicate significant potential impacts on the water balance of the Niger River Basin. Under the low-emission scenario (RCP 2.6), the region may experience relatively stable hydrological conditions; for example, the precipitation variability remains within a manageable range, with areas experiencing moderate wet and dry conditions. This supports long-term regional sustainability and reduces the risk of water scarcity and drought. Likewise, the surface runoff variability suggests that adhering to low-emission pathways can sustain the river basin hydrology, supporting water resource management and ecosystem health. Furthermore, stable ET levels under the low-emission scenario ensure healthy vegetation growth and ecosystem functioning, maintaining agricultural productivity and water resource availability. In contrast, the high-emission scenario (RCP 8.5) suggests a shift towards drier conditions with reduced water availability, which could have profound implications for agriculture, water supply, and overall ecosystem health in the region. For example, lower runoff implies less water flowing through the river basin, which can potentially reduce water availability and increase competition for limited water resources. Thirdly, hydropower generation at the dam has increased substantially due to hydroclimatic variability, particularly the rising trends in reservoir inflow and turbine discharge. This increase in energy output has produced a parallel upward trend in the estimated green hydrogen potential, re-electrification capacity, the volume of fossil fuel (petrol) that can be substituted, and the CO_2 and CO emissions that can be prevented through hydrogen adoption. Hydrogen production and utilization thus present a viable pathway for reducing emissions from Nigeria's energy sector, which, according to the First National Inventory Report (Federal Republic of Nigeria, 2021), rose from 142,678 Gg CO_2-eq in 2000 to 245,918 Gg CO_2-eq in 2017. With hydrogen fuel cells, an average household of five members could be provided with electricity of 18–27 kWh per capita per month, equivalent to the national consumption rate of 90–135 kWh per household per month. For instance, 59,111 tons of hydrogen, with a re-electrification potential of 1,182 GWh, could supply electricity to an estimated 730–1,094 households or 3,648–5,472 people currently without access to the grid. Nevertheless, considering the aging state of Nigeria's hydropower plants, the most feasible starting point is to utilize the minimum allocation of 20% of hydroelectric output for hydrogen production. This gradual approach could guide the country toward the large-scale adoption of green hydrogen while investments in upgrading existing plants and developing untapped hydropower sites are pursued.

Although the country's energy landscape could be significantly altered and its carbon neutrality goal could be enhanced by integrating hydrogen into hydropower systems, several policy interventions and recommendations are essential to support its development and deployment. Energy planners should consider the 12,220 MW of untapped hydropower potential that could contribute to a surplus energy output, which could be converted into hydrogen to create a robust hydrogen economy. This, in turn, would help the nation reach its 2060 carbon neutrality target and increase its revenue as an export commodity. Finally, the climate change impact assessment highlights a critical temporal shift in the reservoir inflow and hydropower production dynamics of Jebba Dam.

The period between 2025 and 2055 seems to offer a window of increased water availability and energy production, which could be used to meet rising energy demands and maximize hydropower output and green hydrogen production. This would support the government's decarbonization plan to replace gasoline generators with hydrogen fuel cell generators, thereby phasing out fossil fuel generators and contributing to the nation's efforts to mitigate climate change and reduce CO_2 emissions. However, the subsequent decline in inflow and hydropower generation after 2055 highlights the urgent need for adaptive management strategies. The projected decrease in reservoir inflow and hydropower production towards the end of the century poses significant challenges for energy security and water resource management. To lessen the effects of the hydropower station's decreased reservoir inflow, strategic planning is crucial. This might involve investing in alternative energy sources, such as floating photovoltaic (FPV), which could enhance water conservation techniques, reduce the dam's evaporation rate, and facilitate the development of infrastructure for more effective water management and storage. These forecasts underscore the importance of incorporating climate change scenarios into long-term energy production and water resource planning. By comprehending and anticipating these changes, stakeholders can create more resilient systems that adapt to changing climate conditions.

7.2. Perspectives

This study lays a critical foundation for expanding the scope of research on green hydrogen production using hydropower resources in Nigeria. It provides insights that can inform policy development, investment decisions, and the adoption of cleaner energy solutions. Focusing on a specific hydropower dam, Jebba Dam, the study provides a detailed framework and preliminary insights that can be applied to other hydropower dams across the country. Scaling up this approach will enable a comprehensive evaluation of Nigeria’s hydropower potential for green hydrogen production, supporting the transition to a clean and renewable energy system.

Future research could explore forecasting hydropower demand under various scenarios, taking into account factors such as population growth, industrial development, and climate change. These projections would help understand how hydropower generation could meet electricity and green hydrogen production needs. Furthermore, by incorporating optimization tools, such as techno-economic-environmental analysis, the prospects for feasible and sustainable green hydrogen production can be substantially strengthened. This approach would strike a balance between economic efficiency and environmental sustainability by minimizing costs and emissions while maximizing energy output. By integrating these advanced methodologies, future studies could provide actionable strategies to scale up green hydrogen production cost-effectively and environmentally responsibly, contributing to Nigeria's renewable energy goals and global commitments to carbon neutrality.

References

Abbas, N., Wasimi, S. A., Al-Ansari, N., & Sultana, N. (2018). Water Resources Problems of Iraq: Climate Change Adaptation And Mitigation. *Journal of the International Association for Environmental Hydrology*, *26*.

Abdoulaye, A. O., Lu, H., Zhu, Y., & Hamoud, Y. A. (2021). Future irrigation water requirements of the main crops cultivated in the Niger River Basin. *Atmosphere*, *12*(4). https://doi.org/10.3390/atmos12040439

Abera, W., Getaneh, Y., Balcha, Y., Assefa, T., Mulatu, C. A., Ebrahim, G. Y., Tesfaye, M., Dawit, M., Abebe, W. B., & Taye, M. T. (2024). Framing water–energy–food–ecosystem (WEFE) nexus interactions in the Tana-Beles Sub-basin of Ethiopia. *Sustainability Nexus Forum*, *32*(1). https://doi.org/10.1007/s00550-024-00540-2

Abhinav C, & Emanuele T. (2021). *What is green hydrogen and why do we need it? An expert explains*. weforum.org/agenda/2021/12/what-is-green-hydrogen-expert-explains-benefits/

Abungba, J. A., Khare, D., Pingale, S. M., Adjei, K. A., Gyamfi, C., & Odai, S. N. (2020). Assessment of Hydro-climatic Trends and Variability over the Black Volta Basin in Ghana. *Earth Systems and Environment*, *4*(4), 739–755. https://doi.org/10.1007/s41748-020-00171-9

Adeoti, O., Ayelegun, T. A., & Osho, S. O. (2014). Nigeria biogas potential from livestock manure and its estimated climate value. In *Renewable and Sustainable Energy Reviews* (Vol. 37, pp. 243–248). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.05.005

Adonadaga, M. G. (2014). Climate Change Effects and Implications for Wastewater Treatment Options in Ghana. *Journal of Environment and Earth Science*, *4*(8), 2225–0948.

Afolabi, M. (2025). Long-term streamflow discharge from the Niger River Basin into the delta region. *Hydrological Sciences Journal*. https://doi.org/10.1080/02626667.2025.2478137

Aich, V., Liersch, S., Vetter, T., Fournet, S., Andersson, J. C. M., Calmanti, S., van Weert, F. H. A., Hattermann, F. F., & Paton, E. N. (2016). Flood projections within the Niger River Basin under future land use and climate change. *Science of the Total Environment*, *562*, 666–677. https://doi.org/10.1016/j.scitotenv.2016.04.021

Ale, B. B., & Bade Shrestha, S. O. (2008). Hydrogen energy potential of Nepal. *International Journal of Hydrogen Energy*, *33*(15), 4030–4039. https://doi.org/10.1016/j.ijhydene.2008.04.056

Alizadeh, M. R., Adamowski, J., & Inam, A. (2022). Integrated assessment of localized SSP–RCP narratives for climate change adaptation in coupled human-water systems. *Science of The Total Environment*, *823*, 153660. https://doi.org/10.1016/j.scitotenv.2022.153660

Andersen, I., & Golitzen, K. G. (2005). *The Niger River Basin: A Vision for Sustainable Management - Google Books* (5th Edition). World Bank. https://books.google.com.ng/books?hl=en&lr=&id=DQj7Zpv-IwkC&oi=fnd&pg=PR5&dq=The+Niger+River+Basin+A+Vision+for+Sustainable+Management&ots=VG__agViE8&sig=VZgUycYt3rMHcKSd0dy4MwOogv4&redir_esc=y#v=onepage&q=The%20Niger%20River%20Basin%20A%20Vision%20for%20Sustainable%20Management&f=false

Animashaun, I. M., Oguntunde, P. G., Akinwumiju, A. S., & Olubanjo, O. O. (2020). Rainfall Analysis over the Niger Central Hydrological Area, Nigeria: Variability, Trend, and Change point detection. *Scientific African*, *8*. https://doi.org/10.1016/j.sciaf.2020.e00419

Aryal, A., Shrestha, S., & Babel, M. S. (2018). Quantifying the sources of uncertainty in an ensemble of hydrological climate-impact projections. *Theoretical and Applied Climatology*, *135*, 193–209. https://doi.org/10.1007/s00704-017-2359-3

Asfaw, A., Simane, B., Hassen, A., & Bantider, A. (2018). Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *Weather and Climate Extremes*, *19*, 29–41. https://doi.org/10.1016/j.wace.2017.12.002

Aulia, A., Jeong, D., Saaid, I. M., Kania, D., Shuker, M. T., & El-Khatib, N. A. (2019). A Random Forests-based sensitivity analysis framework for assisted history matching. *Journal of Petroleum Science and Engineering*, *181*. https://doi.org/10.1016/j.petrol.2019.106237

Ayodele R, Alao M, Ogunjuyigbe A, &, & Munda J. (2019). Electricity generation prospective of hydrogen derived from biogas using food waste in south-western Nigeria. *Biomass and Bioenergy*, *127*. https://doi.org/10.1016/j.biombioe.2019.105291

Ayodele T, & Ogunjuyigbe A. (2015). Increasing household solar energy penetration through load partitioning based on quality of life: The case study of Nigeria. *Sustainable Cities and Society*, *18*, 21–31. https://doi.org/10.1016/j.scs.2015.05.005

Aziz, F., & Obuobie, E. (2017). Trend analysis in observed and projected precipitation and mean temperature over the Black Volta Basin, West Africa. In *1400| International Journal of Current Engineering and Technology* (Vol. 7, Issue 4). http://inpressco.com/category/ijcet

Babalola, T. E., Oguntunde, P. G., Ajayi, A. E., & Akinluyi, F. O. (2021). *Future Climate Change Impacts on River Discharge Seasonality for Selected West African River Basins*. www.intechopen.com

Ballo, A., Valentin, K. K., Korgo, B., Ogunjobi, K. O., Agbo, S. N., Kone, D., & Savadogo, M. (2022). Law and Policy Review on Green Hydrogen Potential in ECOWAS Countries. In *Energies* (Vol. 15, Issue 7). MDPI. https://doi.org/10.3390/en15072304

Bangar, V., Goyal, R., & Pandey, R. (2020). Climate Change Responses and Sustainable Development: Integration of Mitigation and Adaptation. *Sustainable Development Goals Series*, 203–214. https://doi.org/10.1007/978-3-030-42488-6_13

Bari S., Rahman M, Hoque M, &, & Hussain M. (2016). Analysis of seasonal and annual rainfall trends in the northern region of Bangladesh. *Atmospheric Research*, *176*.

Basu, S. K., Mukherjee, S. S., Magbalot-Fernandez, A., Cetzal-Ix, W., & Zandi, P. (2025). Assessment of global environmental health through the lens of climate change. *International Journal on Environmental Sciences*, *16*(1), 27–38. https://doi.org/10.53390/ijes.2025.16104

Bates B, Kundzewicz Z, Wu S, &, & Palutikof J. (2008). Climate Change and Water. *Technical Paper for Intergovernmental Panel on Climate Change, Geneva, Switzerland*.

Bekele, D., Alamirew, T., Kebede, A., Zeleke, G., & Melese, A. M. (2017). Analysis of rainfall trend and variability for agricultural water management in Awash River Basin, Ethiopia. *Journal of Water and Climate Change*, *8*(1), 127–141. https://doi.org/10.2166/wcc.2016.044

Benestad, R. (2016). Downscaling Climate Information. *Oxford Research Encyclopedia of Climate Science*. https://doi.org/10.1093/acrefore/9780190228620.013.27

Bergström, S. (1992). *THE HBVMODEL-its structure and applications*.

Bewket, W., & Conway, D. (2007). A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia. In *International Journal of Climatology* (Vol. 27, Issue 11, pp. 1467–1477). https://doi.org/10.1002/joc.1481

Bhatt, R. P. (2017). Hydropower Development in Nepal - Climate Change, Impacts and Implications. In *Renewable Hydropower Technologies*. InTech. https://doi.org/10.5772/66253

Biggs, E. M. (2009). *Changes in Hydrological Extremes and Climate Variability in the Severn Uplands*.

Boko, B. A., Konaté, M., Yalo, N., Berg, S. J., Erler, A. R., Bazié, P., Hwang, H. T., Seidou, O., Niandou, A. S., Schimmel, K., & Sudicky, E. A. (2020). High-resolution, integrated hydrological modeling of climate change impacts on a semi-arid urban watershed in Niamey, Niger. *Water (Switzerland)*, *12*(2). https://doi.org/10.3390/w12020364

Buishand. (1982). *Some Methods for Testing The Homogeneity of Rainfall Records*.

Burgess, M. G., Becker, S. L., Langendorf, R. E., Fredston, A., & Brooks, C. M. (2023). Climate change scenarios in fisheries and aquatic conservation research. *ICES Journal of Marine Science*, *80*(5), 1163–1178. https://doi.org/10.1093/icesjms/fsad045

Chand, S. (2021). Climate Change a Repercussion of Human Induced Systems. *International Journal of Advanced Research*, *9*(9), 449–452. https://doi.org/10.21474/ijar01/13431

Chris C., Pete J., Martin F., Diego H., James P., James D., Bo E., Gregory J., Joel C., & Andrew P. (2014). Quasi-Global Precipitation Time Series for Drought Monitoring. *U.S. Geological Survey*. https://doi.org/10.3133/ds832

Climate Action Tracker. (2023). *Nigeria; Net zero target Average*. https://climateactiontracker.org/countries/nigeria/#:~:text=At%20COP26%2C%20former%20President%20Buhari,the%202060%20net%20zero%20target.

Climate Watch. (2020, January 29). *Nigeria GHG Emissions*. https://www.climatewatchdata.org/countries/NGA?end_year=2020&start_year=1990#ghg-emissions

Costa, A. C., & Soares, A. (2009). Homogenization of climate data: Review and new perspectives using geostatistics. In *Mathematical Geosciences* (Vol. 41, Issue 3, pp. 291–305). https://doi.org/10.1007/s11004-008-9203-3

Cox, D. R. , & S. A. (1955). Some quick sign tests for trend in location and dispersion. . *Biometrika*, *42*((1/2)), 80–95.

Cui, L., Wang, L., Lai, Z., Tian, Q., Liu, W., & Li, J. (2017). Innovative trend analysis of annual and seasonal air temperature and rainfall in the Yangtze River Basin, China during 1960–2015. *Journal of Atmospheric and Solar-Terrestrial Physics*, *164*, 48–59. https://doi.org/10.1016/j.jastp.2017.08.001

Dai, A., & Trenberth, K. E. (2002). *Estimates of Freshwater Discharge from Continents: Latitudinal and Seasonal Variations*. www.R-ArcticNET.sr.unh.edu

David L., Rosie F., Charles K., Keith O., Sean S., & Mariana V. (2019). *CLM5 Documentation*.

Driga, A. M., & Drigas, A. S. (2019). Climate Change 101: How Everyday Activities Contribute to the Ever-Growing Issue. *International Journal of Recent Contributions from Engineering, Science & IT (IJES)*, *7*(1), 22. https://doi.org/10.3991/ijes.v7i1.10031

East, J. D., Monier, E., & Garcia-Menendez, F. (2022). Characterizing and quantifying uncertainty in projections of climate change impacts on air quality. *Environmental Research Letters*, *17*(9), 94042. https://doi.org/10.1088/1748-9326/ac8d17

ECN, & UNDP. (2005). *Renewable Energy Master Plan (REMP): Final Draft Report*. https://www.iceednigeria.org/resources/nov.-2005.pdf

Elsherif, S. M., & Taha, A. F. (2025). *Climate Science and Control Engineering: Insights, Parallels, and Connections*. https://doi.org/10.48550/ARXIV.2504.21153

Emmanuel, L. A., M'Po, Y. N. , Biaou, C. A. , Komi, K. , Hounguè, R. , Yao, K. B. , & Afouda, A. A. (2018). Mid-Century daily discharge scenarios based on climate and land use change in Ouémé River Basin at Bétérou Outlet. *Hydrology*, *5*(4). https://doi.org/10.3390/hydrology5040069

Federal Republic of Nigeria. (2021). *National GHG Inventory Report (NIR1)*.

Fotedar, A. (2025). Climate Change: Mitigation Strategies and Need for Adaptation. *Premier Journal of Environmental Science*, *2*. https://doi.org/10.70389/pjes.100011

Gain, A. K., Giupponi, C., & Renaud, F. G. (2012). Climate change adaptation and vulnerability assessment of water resources systems in developing countries: A generalized framework and a feasibility study in Bangladesh. *Water (Switzerland)*, *4*(2), 345–366. https://doi.org/10.3390/w4020345

Georgopoulou, E., Mirasgedis, S., Sarafidis, Y., Giannakopoulos, C., Varotsos, K. V, & Gakis, N. (2024). Climate Change Impacts on the Energy System of a Climate-Vulnerable Mediterranean Country (Greece). *Atmosphere*, *15*(3), 286. https://doi.org/10.3390/atmos15030286

Ghosh, S., Sharma, A., Gupta, J., Subramanian, A., & Shekhar, S. (2024). *Towards Kriging-informed Conditional Diffusion for Regional Sea-Level Data Downscaling*. https://doi.org/10.48550/ARXIV.2410.15628

Glassman, D., Wucker, M., Isaacman, T., & Champilou, C. (2011). *The Water-Energy Nexus Adding Water to the Energy Agenda*. www.worldpolicy.org

H2Atlas-Africa. (2021). *H2 ATLAS-AFRICA FLIER*. www.h2atlas.de/africa

Hamed, A. A., Sayed, M. E., & Meshari, L. A.-H. (2020). Assessment of future water, energy, and food nexus by using Weap and Leap models in the state of Kuwait. *Journal of Environmental Science*, *49*(9), 495–526. https://doi.org/10.21608/JES.2020.206395

Hamed, K. H. , & Rao, A. R. (1998a). A modified Mann–Kendall trend test for autocorrelated data. *Journal of Hydrology*, *204*.

Hamed, K. H. , & Rao, A. R. (1998b). A modified Mann-Kendall trend test for autocorrelated data. In *Journal of Hydrology* (Vol. 204).

Harry, S., & Morad, M. (2013). Sustainable development and climate change: Beyond mitigation and adaptation. *Local Economy: The Journal of the Local Economy Policy Unit*, *28*(4), 358–368. https://doi.org/10.1177/0269094213476663

Hirsch R, Slack J, &, & Smith R. (1982). Techniques of trend analysis for monthly water quality data. *Water Resources Research*, *18*(1), 107–201.

Hussain, Md., & Mahmud, I. (2019). pyMannKendall: a python package for non parametric Mann Kendall family of trend tests. *Journal of Open Source Software*, *4*(39), 1556. https://doi.org/10.21105/joss.01556

IEA. (2019). *The Future of Hydrogen*.

IEA. (2020). *SDG7: Data and Projections,* . IEA, Paris . https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity

IPCC. (2007). An Assessment of the Intergovernmental Panel on Climate Change. . *Climate Change* .

IPCC. (2013). *IPCC: the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

IPCC. (2022). *IPCC AR6 WGII Summary For Policymakers 2022*.

JICA. (2014). *Federal Republic of Nigeria Federal Ministry of Water Resources (FMWR) The Project for Review and Update of Nigeria National Water Resources Master Plan Volume 2 Summary Report*.

Jung, S., Bae, Y., Kim, J., Joo, H., Kim, H., & Jung, J. (2021). Analysis of small hydropower generation potential: estimation of the potential in ungauged basins. *Energies*, *14*(11). https://doi.org/10.3390/en14112977

Karaki, K. (2017). *Understanding ECOWAS Energy Policy From national interests to regional markets and wider energy access?* http://allafrica.com/stories/201311191358.html.

Kendall, M. (1975a). Rank correlation measures. . *Charles Griffin,* , *202*(15).

Kendall, M. (1975b). Rank Correlation Methods,. *Charles Griffin & Company Ltd. London UK.*

Khan, S. A., Al Rashid, A., & Koç, M. (2023). Adaptive response for climate change challenges for small and vulnerable coastal area (SVCA) countries: Qatar perspective. *International Journal of Disaster Risk Reduction*, *96*, 103969. https://doi.org/10.1016/j.ijdrr.2023.103969

Khanal, A., Kafle, M., Khanal, A., & Neupane, P. (2024). Hydro-energy generation in Chameliya River Basin amid climate change. *Journal of Applied Water Engineering and Research*, *13*(1), 1–14. https://doi.org/10.1080/23249676.2024.2392597

Khetrapal, N. (2018). Human Activities and Climate Change. *Encyclopedia of the Anthropocene*, 401–408. https://doi.org/10.1016/b978-0-12-809665-9.10510-5

Kim, J., Cho, H.-R., & Cho, Y.-S. (2014). Projection of Climate Change with Uncertainties: 1. GCM and RCP Uncertainties. *Journal of Korean Society of Hazard Mitigation*, *14*(5), 317–327. https://doi.org/10.9798/kosham.2014.14.5.317

Koo, H., Chen, M., Jakeman, A. J., & Zhang, F. (2020). A global sensitivity analysis approach for identifying critical sources of uncertainty in non-identifiable, spatially distributed environmental models: A holistic analysis applied to SWAT for input datasets and model parameters. *Environmental Modelling & Software*, *127*, 104676. https://doi.org/10.1016/j.envsoft.2020.104676

Lawin, A. E., Hounguè, N. R., Biaou, C. A., & Badou, D. F. (2019). Statistical analysis of recent and future rainfall and temperature variability in the Mono River watershed (Benin, Togo). *Climate*, *7*(1). https://doi.org/10.3390/cli7010008

Lee Hannah. (2022). The Climate System and Climate Change,. In Lee Hannah (Ed.), *Climate Change Biology* (Third, pp. 13–50). Academic Press.

Liman, H. M., Nwaerema, P., & Yisa, J. (2021). Impact of Climate Variability on Reservoir Based Hydro-Power Generation in Jebba Dam, Niger State, Nigeria. *Hydro Science & Marine Engineering*, *3*(1). https://doi.org/10.30564/hsme.v3i1.2795

Liman, H. M., Nwaerema, P., & Yisa, J. (2023). Citation: Characterization of Climatic Parameters and River Flow Capacity on Electricity Generation in Jebba Dam. *British Journal of Multidisciplinary and Advanced Studies: Engineering and Technology*, *4*(3), 21–30. https://doi.org/10.37745/bjmas.2022.0204

Liu, H., Xiong, W., Pequeño, D. N. L., Hernández-Ochoa, I. M., Krupnik, T. J., Burgueño, J., & Xu, Y. (2022). Exploring the uncertainty in projected wheat phenology, growth and yield under climate change in China. *Agricultural and Forest Meteorology*, *326*, 109187. https://doi.org/10.1016/j.agrformet.2022.109187

Lopez, A., Fung, F., New, M., Watts, G., Weston, A., & Wilby, R. L. (2009). From climate model ensembles to climate change impacts and adaptation: A case study of water resource management in the southwest of England. *Water Resources Research*, *45*(8). https://doi.org/10.1029/2008WR007499

Mahmood, S., Khan, A. U., Babur, M., Ghanim, A. A. J., Al-Areeq, A. M., Khan, D., Najeh, T., & Gamil, Y. (2024). Divergent path: isolating land use and climate change impact on river runoff. *Frontiers in Environmental Science*, *12*. https://doi.org/10.3389/fenvs.2024.1338512

Maka, A. O. M., & Mehmood, M. (2024). Green hydrogen energy production: current status and potential. *Clean Energy*, *8*(2), 1–7. https://doi.org/10.1093/ce/zkae012

Mann, H. B. (1945). *Nonparametric Tests Against Trend* (Vol. 13, Issue 3).

Meza, E. (2021). *Germany Eager to Partner with West African Countries on Green Hydrogen.* . Journalism for Energy Transition. .

Muhammad, M. M. (2024). The causes of climate change, its effects on Human Health and Biodiversity, and Mitigation Measures. *Journal of Advances in Science and Technology*, *21*(1), 197–204. https://doi.org/10.29070/0emk8j33

Nigeria Hydrological Services Agency. (2020, September 5). *Low flow discharge measurement exercise*. NIHSA Website. https://nihsa.gov.ng/2020/11/05/low-flow-discharge-measurement-exercise/

Niu, G. Y., Yang, Z. L., Dickinson, R. E., & Gulden, L. E. (2005). A simple TOPMODEL-based runoff parameterization (SIMTOP) for use in global climate models. *Journal of Geophysical Research Atmospheres*, *110*(21), 1–15. https://doi.org/10.1029/2005JD006111

Nonki, R. M., Lenouo, A., Lennard, C. J., & Tchawoua, C. (2019). Assessing climate change impacts on water resources in the Benue River Basin, Northern Cameroon. *Environmental Earth Sciences*, *78*(20). https://doi.org/10.1007/s12665-019-8614-4

Obahoundje, S., Diedhiou, A., Kouassi, K. L., Ta, M. Y., Mortey, E. M., Roudier, P., & Kouame, D. G. M. (2022). Analysis of hydroclimatic trends and variability and their impacts on hydropower generation in two river basins in Côte d'Ivoire (West Africa) during 1981-2017. *Environmental Research Communications*, *4*(6). https://doi.org/10.1088/2515-7620/ac71fa

Ogilvie, A., Mahé, G., Ward, J., Serpantié, G., Lemoalle, J., Morand, P., Barbier, B., Diop, A. T., Caron, A., Namarra, R., Kaczan, D., Lukasiewicz, A., Paturel, J. E., Liénou, G., & Clanet, J. C. (2010). Water, agriculture and poverty in the niger river basin. *Water International*, *35*(5), 594–622. https://doi.org/10.1080/02508060.2010.515545

Oguntunde, P. G., & Abiodun, B. J. (2013). The impact of climate change on the Niger River Basin hydroclimatology, West Africa. *Climate Dynamics*, *40*(1–2), 81–94. https://doi.org/10.1007/s00382-012-1498-6

Oguntunde, P. G., Lischeid, G., & Abiodun, B. J. (2018). Impacts of climate variability and change on drought characteristics in the Niger River Basin, West Africa. *Stochastic Environmental Research and Risk Assessment*, *32*(4), 1017–1034. https://doi.org/10.1007/s00477-017-1484-y

Okedina, I. M., Chidinma, E. E., Olatunde, Y. O., & Chdinma, E. E. (2018). *Energy and climate change: impact of food, water, and energy nexus on economic growth in Nigeria*.

Okkan, U., Fistikoglu, O., Ersoy, Z. B., & Noori, A. T. (2023). Investigating adaptive hedging policies for reservoir operation under climate change impacts. *Journal of Hydrology*, *619*, 129286. https://doi.org/10.1016/j.jhydrol.2023.129286

Olaniyan, K., McLellan, B. C., Ogata, S., & Tezuka, T. (2018). Estimating residential electricity consumption in Nigeria to support energy transitions. *Sustainability (Switzerland)*, *10*(5). https://doi.org/10.3390/su10051440

Olaoye, T., Ajilore, T., Akinluwade, K., Omole, F., & Adetunji, A. (2016). Energy Crisis in Nigeria: Need for Renewable Energy Mix. *American Journal of Electrical and Electronic Engineering*, *4*(1), 1–8. https://doi.org/10.12691/ajeee-4-1-1

Olatunji, S., & Abdulfatai, S. (2022). Investigation of seepage paths from dam embankments using magnetic methods: case study of Jebba earth dam, Nigeria. *Sustainable Water Resources Management*, *8*(3). https://doi.org/10.1007/s40899-022-00657-6

Olukanni, D. O., Adejumo, T. A., Adedeji, A. A., & Salami, A. W. (2016). *Assessment of Jebba hydropower dam operation for improved energy production and flood management*. *11*(13). www.arpnjournals.com

Olukanni, D. O., & Salami, A. W. (2012). Assessment of Impact of Hydropower Dams Reservoir Outflow on the Downstream River Flood Regime – Nigeria's Experience. *Hydropower - Practice and Application*. https://doi.org/10.5772/33180

Oyerinde, G. T., Wisser, D., Hountondji, F. C. C., Odofin, A. J., Lawin, A. E., Afouda, A., & Diekkrüger, B. (2016). Quantifying uncertainties in modeling climate change impacts on hydropower production. *Climate*, *4*(3). https://doi.org/10.3390/cli4030034

Padilha, J., Trindade, L., Souza, R., & Miguel, M. (2009). An evaluation of the potential of the use of wasted hydroelectric capacity to produce hydrogen to be used in fuel cells in order to decrease CO2 emissions in Brazil. *International Jounal of Hydrogen Energy* , *34*(19).

Pan, H., Tang, J.-P., Cheng, L., & Li, M.-C. (2024). Ensemble projections of climate and streamflow in a typical basin of semi-arid steppes in Mongolian Plateau of 2021–2100. *Advances in Climate Change Research*, *15*(2), 230–243. https://doi.org/10.1016/j.accre.2024.02.004

Parker, E. R., Mo, J., & Goodman, R. S. (2022). The dermatological manifestations of extreme weather events: A comprehensive review of skin disease and vulnerability. In *Journal of Climate Change and Health* (Vol. 8). Elsevier Masson s.r.l. https://doi.org/10.1016/j.joclim.2022.100162

Pathak, P. K., Yadav, A. K., & Kamwa, I. (2025). Green hydrogen: a strategic energy vector for achieving net-zero emissions by 2050. *Sustainable Energy & Fuels*, *9*(19), 5218–5226. https://doi.org/10.1039/d5se00902b

Pettitt, A. N. (1979). A Non-Parametric Approach to the Change-Point Problem. In *Source: Journal of the Royal Statistical Society. Series C (Applied Statistics)* (Vol. 28, Issue 2).

Pingale, S. M., Khare, D., Jat, M. K., & Adamowski, J. (2016). Trend analysis of climatic variables in an arid and semi-arid region of the Ajmer District, Rajasthan, India. *Journal of Water and Land Development*, *28*(1), 3–18. https://doi.org/10.1515/jwld-2016-0001

Polewko-Klim, A., Lesiński, W., Golińska, A. K., Mnich, K., Siwek, M., & Rudnicki, W. R. (2020). Sensitivity analysis based on the random forest machine learning algorithm identifies candidate genes for regulation of innate and adaptive immune response of chicken. *Poultry Science*, *99*(12), 6341–6354. https://doi.org/10.1016/j.psj.2020.08.059

Posso, F., Espinoza, J. L., Sánchez, J., & Zalamea, J. (2015). Hydrogen from hydropower in Ecuador: Use and impacts in the transport sector. *International Journal of Hydrogen Energy*, *40*(45), 15432–15447. https://doi.org/10.1016/j.ijhydene.2015.08.109

Posso, F., & Zambrano, J. (2014). Estimation of electrolytic hydrogen production potential in Venezuela from renewable energies. *International Journal of Hydrogen Energy*, *39*(23), 11846–11853. https://doi.org/10.1016/j.ijhydene.2014.06.033

Raghavendra, P. (2024). Are We the Reason for Climate Change? *International Journal for Research in Applied Science and Engineering Technology*, *12*(5), 1517–1521. https://doi.org/10.22214/ijraset.2024.61848

Rahman, M. H. ur, Ahmad, A., Wang, X., Wajid, A., Nasim, W., Hussain, M., Ahmad, B., Ahmad, I., Ali, Z., Ishaque, W., Awais, M., Shelia, V., Ahmad, S., Fahd, S., Alam, M., Ullah, H., & Hoogenboom, G. (2018). Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. *Agricultural and Forest Meteorology*, 94–113. https://doi.org/10.1016/j.agrformet.2018.02.008

Sadik-Zada, E. R. (2021). Political economy of green hydrogen rollout: A global perspective. *Sustainability (Switzerland)*, *13*(23). https://doi.org/10.3390/su132313464

Salami, A. W., Raji, M. O., Sule, B. F., Abdulkareem, Y. A., & Bilewu, S. O. (2010). Impacts of climate change on the water resources of Jebba hydropower reservoir. *Proceedings of 2nd International Conference on Sustainable Urban Water Supply in Developing Countries,* 298–312.

Scafetta, N. (2023). CMIP6 GCM Validation Based on ECS and TCR Ranking for 21st Century Temperature Projections and Risk Assessment. *Atmosphere*, *14*(2), 345. https://doi.org/10.3390/atmos14020345

Şen, Z. (2012). Innovative Trend Analysis Methodology. *Journal of Hydrologic Engineering*, *17*(9), 1042–1046. https://doi.org/10.1061/(asce)he.1943-5584.0000556

Şen, Z. (2014). Trend Identification Simulation and Application. *Journal of Hydrologic Engineering*, *19*(3), 635–642. https://doi.org/10.1061/(asce)he.1943-5584.0000811

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Robinson, A., Hare, W., Schaeffer, M., Perrette, M., & Reinhardt, J. (2016). Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change 2016 17:6*, *17*(6), 1585–1600. https://doi.org/10.1007/S10113-015-0910-2

Sharma, B., Kumar, J., Collier, N., Ganguly, A. R., & Hoffman, F. M. (2025). *Land Cover Changes Cause Increased Losses during Photosynthetic Extremes*.

Soriano, M. A., & Herath, S. (2020). Climate change and traditional upland paddy farming: a Philippine case study. *Paddy and Water Environment*, *18*(2), 317–330. https://doi.org/10.1007/s10333-019-00784-5

Sun, L., Pan, B., Gu, A., Lu, H., & Wang, W. (2018). Energy–water nexus analysis in the Beijing–Tianjin–Hebei region: Case of electricity sector. *Renewable and Sustainable Energy Reviews*, *93*, 27–34. https://doi.org/10.1016/j.rser.2018.04.111

Svoboda, M., Hayes, M., & Wood, D. (2012). *Standardized Precipitation Index User Guide*. Hydrology Commons, Other Earth Sciences Commons. https://digitalcommons.unl.edu/droughtfacpub

Tadese, M. T., Kumar, L., Koech, R., & Zemadim, B. (2019a). Hydro-climatic variability: A characterisation and trend study of the Awash River Basin, Ethiopia. *Hydrology*, *6*(2). https://doi.org/10.3390/hydrology6020035

Tadese, M. T., Kumar, L., Koech, R., & Zemadim, B. (2019b). Hydro-climatic variability: A characterisation and trend study of the Awash River Basin, Ethiopia. *Hydrology*, *6*(2). https://doi.org/10.3390/hydrology6020035

Tao, F., Rötter, R. P., Palosuo, T., Gregorio Hernández Díaz-Ambrona, C., Mínguez, M. I., Semenov, M. A., Kersebaum, K. C., Nendel, C., Specka, X., Hoffmann, H., Ewert, F., Dambreville, A., Martre, P., Rodríguez, L., Ruiz-Ramos, M., Gaiser, T., Höhn, J. G., Salo, T., Ferrise, R., … Schulman, A. H. (2018). Contribution of crop model structure, parameters and climate projections to uncertainty in climate change impact assessments. *Global Change Biology*, *24*(3), 1291–1307. https://doi.org/10.1111/gcb.14019

Taxak, A. K., Murumkar, A. R., & Arya, D. S. (2014). Long term spatial and temporal rainfall trends and homogeneity analysis in Wainganga basin, Central India. *Weather and Climate Extremes*, *4*, 50–61. https://doi.org/10.1016/j.wace.2014.04.005

Thapa, B. S., Neupane, B., Yang, H. seong, & Lee, Y. H. (2021a). Green hydrogen potentials from surplus hydro energy in Nepal. *International Journal of Hydrogen Energy*, *46*(43), 22256–22267. https://doi.org/10.1016/j.ijhydene.2021.04.096

Thapa, B. S., Neupane, B., Yang, H. seong, & Lee, Y. H. (2021b). Green hydrogen potentials from surplus hydro energy in Nepal. *International Journal of Hydrogen Energy*, *46*(43), 22256–22267. https://doi.org/10.1016/j.ijhydene.2021.04.096

Thota, V. (2025). The Role of Human Activity In Climate Change. *Open Access Journal of Multidisciplinary Research*, *1*(2), 1–17. https://doi.org/10.47760/oajmr.2025.v01i02.001

Ugbor, O. N., Omoigberale, M. O., Amoutchi, A. I., Affian, K., & Mehner, T. (2023). Environmental and spatial determinants of fish community structure in an Afro-tropical river ecosystem. *Ecology of Freshwater Fish*, *32*(4), 852–863. https://doi.org/10.1111/eff.12726

United States Department of Energy. (2008). *Hydrogen Data*. www.hydrogen.energy.gov

UN-Water. (2013). *What is Water Security? Infographic. UN-Water, Geneva, Switzerland.* . Retrieved from: www.unwater.org/publications/water-security-infographic

Vukialau-Taoi, M., Lili, L., & Bolatolu, W. (2023). Differential Effects of Precipitation and Temperature on Seed Phenology and Seed Production in Agathis Macrophylla in Fiji. *Journal of Tropical Forest Science*, *35*(2), 157–167. https://doi.org/10.26525/jtfs2023.35.2.157

Wang, H., Sun, F., Feng, Y., Wang, T., & Liu, W. (2025). Intensification of hourly and small watershed flooding with rising temperatures. *Journal of Hydrology*, *649*, 132444. https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.132444

Wu, H., & Qian, H. (2017). Innovative trend analysis of annual and seasonal rainfall and extreme values in Shaanxi, China, since the 1950s. *International Journal of Climatology*, *37*(5), 2582–2592. https://doi.org/10.1002/joc.4866

Yang, S., Gao, Y., Torben, K., Keenlyside, N., & Counillon, F. (2020). The Climate Model: An ARCPATH Tool to Understand and Predict Climate Change. *Springer Polar Sciences*, 157–180. https://doi.org/10.1007/978-3-030-52324-4_8

Yangouliba, G. I., Koch, H., Liersch, S., Sintondji, L. O., Sidibé, M., Larbi, I., Limantol, A. M., Yira, Y., Dipama, J. M., & Kwawuvi, D. (2022). Impacts of hydro-climatic trends and upstream water management on hydropower generation at the Bagré dam. *Journal of Water and Climate Change*, *13*(6), 2399–2413. https://doi.org/10.2166/wcc.2022.452

Yue, H., Gebremichael, M., & Nourani, V. (2022). Performance of the Global Forecast System's medium-range precipitation forecasts in the Niger river basin using multiple satellite-based products. *Hydrology and Earth System Sciences*, *26*(1), 167–181. https://doi.org/10.5194/hess-26-167-2022

Zhang, H., Wang, B., Lan, T., Shi, J., & Lu, S. (2016). Change-point detection and variation assessment of the hydrologic regime of the Wenyu River. *Toxicological and Environmental Chemistry*, *98*(3–4), 358–375. https://doi.org/10.1080/02772248.2015.1123480

Zhou, A., Zhou, W., & Manandhar, P. (2020). *A Study on the Prospect of Hydropower to Hydrogen in Nepal*.

ANNEX

Annex 1: List of published papers

Aremu, E.O., Lawin, A.E., Olukanni, D., Franssen, H.J.H. (2024). Estimation of Green Hydrogen Production Potentials from Exploitable Hydropower Resources for Re-electrification and Climate Change Mitigation in Nigeria. In: Narra, MM., Narra, S. (eds) Innovations in Circular Economy and Renewable Energy in Africa. World Sustainability Series. Springer, Cham. https://doi.org/10.1007/978-3-031-68330-5_11

Aremu, E. O., Lawin, A. E., Olukanni, D. O., Franssen, H. J. H., & Voisin, N. (2025). Exploring green hydrogen production from the Jebba Hydropower Station for Nigeria's clean energy transition. Journal of Water and Climate Change, 16(7), 2209-2225. https://doi.org/10.2166/wcc.2025.175

- **Article submitted**

Aremu, E.O., Lawin, A.E., Olukanni, D. Comparative trend analysis of hydroclimatic Variables for sustainable water resource management in Jebba Dam in the Niger River Basin. International Conference on Advancement of Engineering Innovation for Sustainable Development ***(Under Review)***

Emmanuel Olorunyomi Aremu was born in Omu-Aran, Kwara State, Nigeria in the year, 1993. He had his primary school education at Concordia Faith International Nursery and Primary School, Omu-Aran, from 1999-2004. He proceeded to secondary school education at Federal Government College, Ikole-Ekiti, Nigeria, from 2004 to 2010, where he was appointed as senior prefect. He had his bachelor's degree in Civil engineering at the Federal University of Technology, Minna, Niger State in the year 2015. He obtained a Master of Engineering in Water Resources and Environmental Engineering from the University of Benin, Benin City, Edo State, in 2021. After he received his master's degree, he was awarded a full doctoral scholarship by the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) to study Climate change and water resources. His research interests include hydropower, hydrology, and clean energy, especially green hydrogen, and floating photovoltaic systems. He is happily married to his beloved wife, Lydia Aremu, and has a son, Zoe.

Abstract: Nigeria faces a growing energy crisis driven by population growth and expanding industrial demands, exacerbated by the impacts of climate change. As global efforts shift toward low-carbon energy solutions, green hydrogen, produced from renewable sources like hydropower, presents a viable strategy for meeting Nigeria's future energy needs while contributing to climate change mitigation. This study assesses the impacts of climate variability on hydropower generation and explores the green hydrogen production potential of the Jebba Hydropower Station within the Niger River Basin (NRB). The research is guided by three main objectives: (i) evaluating the impacts of climate change on water balance components; precipitation, surface runoff, and evapotranspiration, in the NRB; (ii) analyzing historical trends in hydroclimatic variables, hydropower output, and hydrogen potential at the Jebba station; and (iii) projecting future hydropower generation and green hydrogen production potential under two climate scenarios (SSP245 and SSP585) for the period 2025–2100, using 1984–2009 as the baseline. Multiple datasets, including historical climate records, streamflow data, turbine discharge, and energy generation, were used alongside satellite rainfall and climate model outputs. Statistical and trend analyses (including Modified Mann-Kendall and homogeneity tests) were applied to detect variability, trends, and change points in hydroclimatic variables. A land surface modeling approach, using Community Land Model 5, was used to assess water balance dynamics, and hydropower simulation was conducted to estimate future hydropower and green hydrogen output. Re-electrification potential, petrol replacement, and CO_2 emission avoidance were also quantified. Results reveal significant historical rainfall variability, with Ilorin and Bida stations recording the highest and lowest negative anomalies, respectively. Rainfall trends are increasing in parts of the NRB, particularly at Ilorin station, while most stations show evidence of hydroclimatic change. Under RCP 2.6, the basin is projected to maintain relatively stable hydrological conditions, whereas RCP 8.5 suggests a shift toward reduced water availability by the end of the century. Hydropower generation at Jebba Dam increased significantly between 1988 and 2018, driven by rising reservoir inflow and turbine discharge. This, in turn, enhanced green hydrogen potential, enabling significant energy output, fossil fuel substitution, and emissions reduction. Future projections indicate that the period from 2025 to 2065 will offer optimal conditions for hydrogen production, with reservoir inflow and energy generation peaking before gradually declining due to climate change impacts. Notably, under SSP245, hydrogen production potential ranged up to 32,000 tonnes, capable of replacing over 100 million litres of petrol and preventing up to 245 tonnes of CO_2 emissions. This study underscores the need for climate-resilient energy planning and highlights the potential of hydropower-based green hydrogen as a sustainable energy solution for Nigeria's low-carbon future.

Keywords: hydro-climatic variability, hydropower, climate change, mitigation, green hydrogen, Jebba dam

PhD

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ASSESSMENT OF GREEN HYDROGEN PRODUCTION POTENTIAL FROM JEBBA HYDROPOWER RESERVOIR IN THE NIGER RIVER BASIN AS AN OPTION FOR CLIMATE CHANGE MITIGATION

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