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Impact of Uncertainty in Climate Change Data on Hydropower Generation from Dam Reservoirs in Arid Regions: A Review

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Abstract

Over the past few years, there has been a significant increase in interest in renewable energy, which is essential for reducing greenhouse gas emissions. Hydroelectric power production is directly related to the regional hydrological conditions of a watershed and is sensitive to variations in water availability throughout the year. The impacts of climate change on the hydrologic cycle have received much attention in studies that consider complex, interactive issues. This paper focuses on water resources for power production, which can be estimated based on river basin discharge. There is uncertainty about how climate change will affect hydropower development on various scales, including the global, national, and regional levels. Despite being a global phenomenon, climate change has different effects on hydropower generation at various spatial scales. The different degrees of uncertainty are based on regional geography and local hydrological conditions. This explains the requirement for thoroughly examining how climate change will impact hydropower generation locally or globally. Additionally, it aims to offer a range of strategies for reducing the effects of climate change on hydropower production and guaranteeing the sustainability of the global energy system under climate change to assist decision-makers.

Keywords : Climate Change, Hydropower generation, Uncertainty, Arid and Semi‑Arid regions, Modelling.

تأثير عدم اليقين المناخي على توليد الطاقة الكهرومائية من خزانات السدود في المناطق القاحلة: مراجعة

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الخلاصة

على مدى السنوات القليلة الماضية، كان هناك زيادة كبيرة في الاهتمام بالطاقة المتجددة، والتي تعتبر ضرورية للحد من انبعاثات الغازات المسببة للانحباس الحراري العالمي يرتبط إنتاج الطاقة الكهرومائية بشكل مباشر بالظروف الهيدرولوجية الإقليمية لمستجمعات المياه وهو حساس للاختلافات في توفر المياه -على مدار العام-. لقد حظيت تأثيرات تغير المناخ على الدورة الهيدرولوجية باهتمام كبير في الدراسات التي تنظر في قضايا معقدة وتفاعلية. تركز هذه الورقة على موارد المياه لإنتاج الطاقة، والتي يمكن تقديرها على أساس تصريف أحواض الأنهار. هناك عدم يقين حول كيفية تأثير تغير المناخ على تطوير الطاقة الكهرومائية على مستويات مختلفة، بما في ذلك المستويات العالمية والوطنية والإقليمية. على الرغم من كونه ظاهرة عالمية، فإن تغير المناخ له تأثيرات مختلفة على توليد الطاقة الكهرومائية على مستويات مكانية مختلفة. تستند درجات عدم اليقين المختلفة إلى الجغرافيا الإقليمية والظروف الهيدرولوجية المحلية. وهذا يفسر الحاجة إلى فحص دقيق لكيفية تأثير تغير المناخ على توليد الطاقة الكهرومائية محليا أو عالميا. بالإضافة إلى ذلك، يهدف إلى تقديم مجموعة من الاستراتيجيات للحد من آثار تغير المناخ على إنتاج الطاقة الكهرومائية وضمان استدامة نظام الطاقة العالمي في ظل تغير المناخ لمساعدة صناع القرار.

الكلمات المفتاحية: تغير المناخ، توليد الطاقة الكهرومائية، عدم اليقين، المناطق القاحلة وشبه القاحلة، النمذجة.

1. Introduction

Hydropower, an environmentally friendly and sustainable energy source, utilizes the force of water from higher reservoirs to create electricity. It serves a crucial role in fulfilling current and future energy needs. As of 2019, hydropower accounted for 16% of worldwide electricity production (Killingtveit., 2019), dominating renewable energy sources by 78% (Sun, 2020). Additionally, it significantly aids in reducing greenhouse gas emissions and addressing the issue of global warming. Conversely, hydropower generation faces significant vulnerability to climate change, especially in arid and semi-arid regions. It heavily depends on water resources, making it susceptible to fluctuations in precipitation patterns, snowmelt, streamflow, and the timing of water flow. As per the Intergovernmental Panel on Climate Change (IPCC, 2021), these factors can exhibit substantial year-to-year variability, indicating potentially severe impacts of climate change on hydropower generation. The report projects adverse effects on hydropower generation potential, suggesting a potential decrease of up to 6% due to climate change. This decline in hydropower capacity is linked to shifts in hydrological patterns and water availability resulting from temperature and precipitation changes. Climate change is anticipated to alter the patterns and spatial distribution of water resources, influenced by shifts in precipitation and temperature. These changes could lead to varying flow patterns, affecting consistency and seasonal variations. Despite advancements in climate research, a comprehensive understanding of specific regions within the Euphrates basin, notably the Haditha Watershed, still needs to be completed. The existing climate scenarios for these areas often need more precision, potentially failing to capture crucial nuances in the basin's climate, thereby contributing to climate-related uncertainties. Lately, arid regions have undergone discernible climate fluctuations, leaning towards hotter and drier conditions over the past few decades (Huang et al., 2016; Corwin., 2021). The uncertainties and shifts in climate can substantially modify the hydrological dynamics of the Euphrates River basin, impacting both regional and local scales can influence variables such as discharge volumes and the timing of surface flow (Sharafati ,et, al., 2020; Muratoglu ,et ,al., 2022). Projections on a global scale suggest that low- and mid-latitude areas might encounter water scarcity problems because of reduced water availability. Conversely, higher-latitude regions could experience increased surface flow volumes (Mankin, et, al., 2019). There are crucial gaps in research that demand more specific insights into the effects, vulnerabilities, and resilience of hydropower reservoir basins concerning climate change and its variability. Utilizing ensemble scenarios and the outcomes from (GCMs) becomes essential to bridging these gaps. The primary challenge to hydropower generation from reservoirs hinges on the volume and timing of streamflow, both of which are intricately linked to precipitation patterns. This interdependence makes hydropower reservoir generation exceptionally susceptible to fluctuations brought about by changing climate conditions.

2. Effect of Climate Change

2.1. Effect of Climate Change in Arid Regions

Arid and semi-arid regions globally require increased water resources, particularly for irrigation, to support food production (Golla., 2021; Mirdashtvan ,et .al., 2021). The strain on the water supply in these areas is intensified by population pressure, compounded by the effects of climate change, such as rising temperatures and an abundance of high solar radiation (Lange., 2019; Ismail & Go., 2021). Considering greenhouse gas (GHG) emissions presents a challenge that the physical environment may struggle to address. This issue is spurred by three distinct geographical factors and the atmospheric layer responsible for regulating spatial and temporal variations in climate and weather patterns (Wang & Gu., 2021, Zittis ,,et, al., 2022). Arid and semi-arid regions confront water scarcity challenges exacerbated by the effects of climate change. The sparse vegetation, particularly under prolonged exposure to intense solar radiation, rising temperatures, and heightened evaporation rates, further contributes to the strain on water resources in these areas (Nikolaou ,et, al., 2020; Morante-Carballo ,et, al., 2022). Reports from the Intergovernmental Panel on Climate Change (IPCC) in 2021, addressing the adaptation and mitigation strategies for arid and semi-arid regions concerning water resources, emphasize the importance of considering temperature and precipitation variations over a minimum of 30 to 50 years (Singh., & Chudasama., 2021, El-Rawy ,et ,al., 2023). This extended timeframe is crucial for assessing hydrological effects through Global Climate Models (GCMs) (Hargrove ,et ,al., 2023; Dias, et ,al., 2023). The basin within arid regions is projected to undergo a reduction in annual runoff and a decrease in the volume of water stored in reservoirs due to the impacts of climate change. These changes significantly affect regional hydrological processes and the development of local ecosystems (Şen., 2021; Raulino ,et ,al., 2021). Consequently, there will likely be an increase in evapotranspiration (ET) and a decrease in soil moisture (SM) and streamflow (SF). These effects will manifest under different scenarios of global climate change and alterations in land use or cover (Huang et al., 2022; Verma et al., 2023).

2.2. Emission Scenarios: Shared Socioeconomic Pathways

Indeed, the IPCC introduced a new set of climate scenarios known as Shared Socioeconomic Pathways (SSPs) in their AR_6 report (Meinshausen ,et ,al., 2020, Siabi ,et ,al., 2023). The IPCC and other researchers have developed past scenarios such as SA90, IS92, SRES, and RCPs to explore different climate futures. However, none of these previous scenarios comprehensively cover the entire range of potential climate futures (Stammer et al., 2021). The Shared Socioeconomic Pathways (SSPs) build upon the Representative Concentration Pathways (RCPs) introduced in the IPCC's AR_5. The RCPs (Gütschow ,et ,al., 2021(categorized four potential pathways based solely on their radiative forcing in the year 2100, ranging from RCP 2.6 to RCP 8.5, indicating a projected radiative forcing of 2.6 to 8.5 W/m^2, respectively, without considering socioeconomic factors. In contrast, the SSPs, classified according to the AR6 report by IPCC in 2021, encompass five scenarios (SSP 1.9, SSP 1–2.6, SSP 2–4.5, SSP 3–7.0, and SSP5–8.5) which integrate various socioeconomic factors such as population trends, economic growth, education, and other societal aspects into their projections (Siabi ,et, al., 2023). Figure(1) illustrates the trajectories of SSPs and the broader patterns of change in weather trends. The solid lines denote the CMIP6 ensemble mean, while the shaded areas encompass the range of CMIP6 results projected for 2100. Conversely, RCP scenarios are represented by dashed lines, indicating the CMIP5 ensemble mean. This depiction is derived from the research conducted by Tebaldi et al. in 2020.

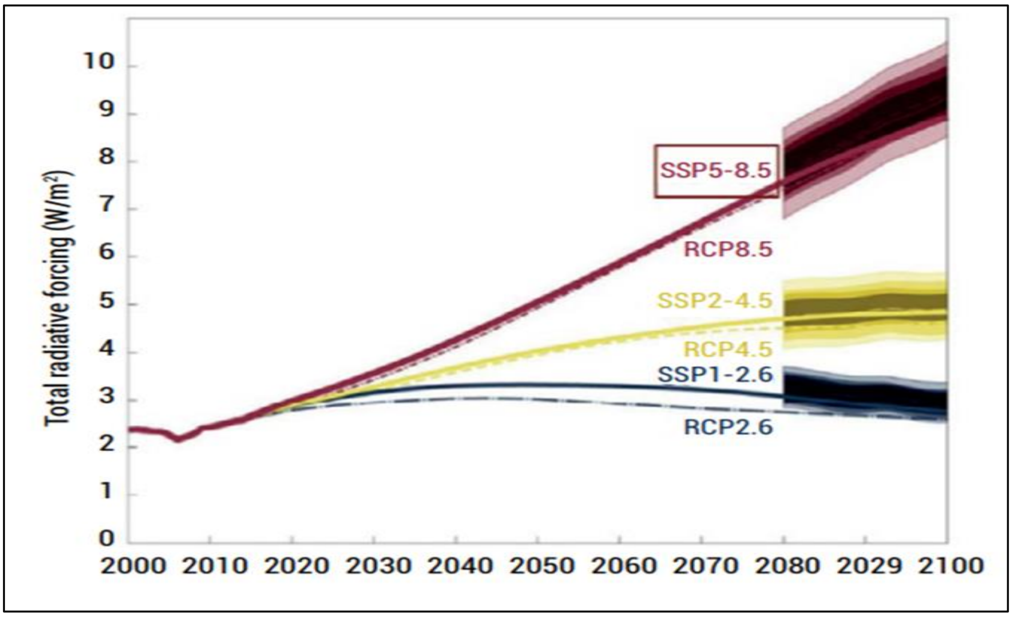


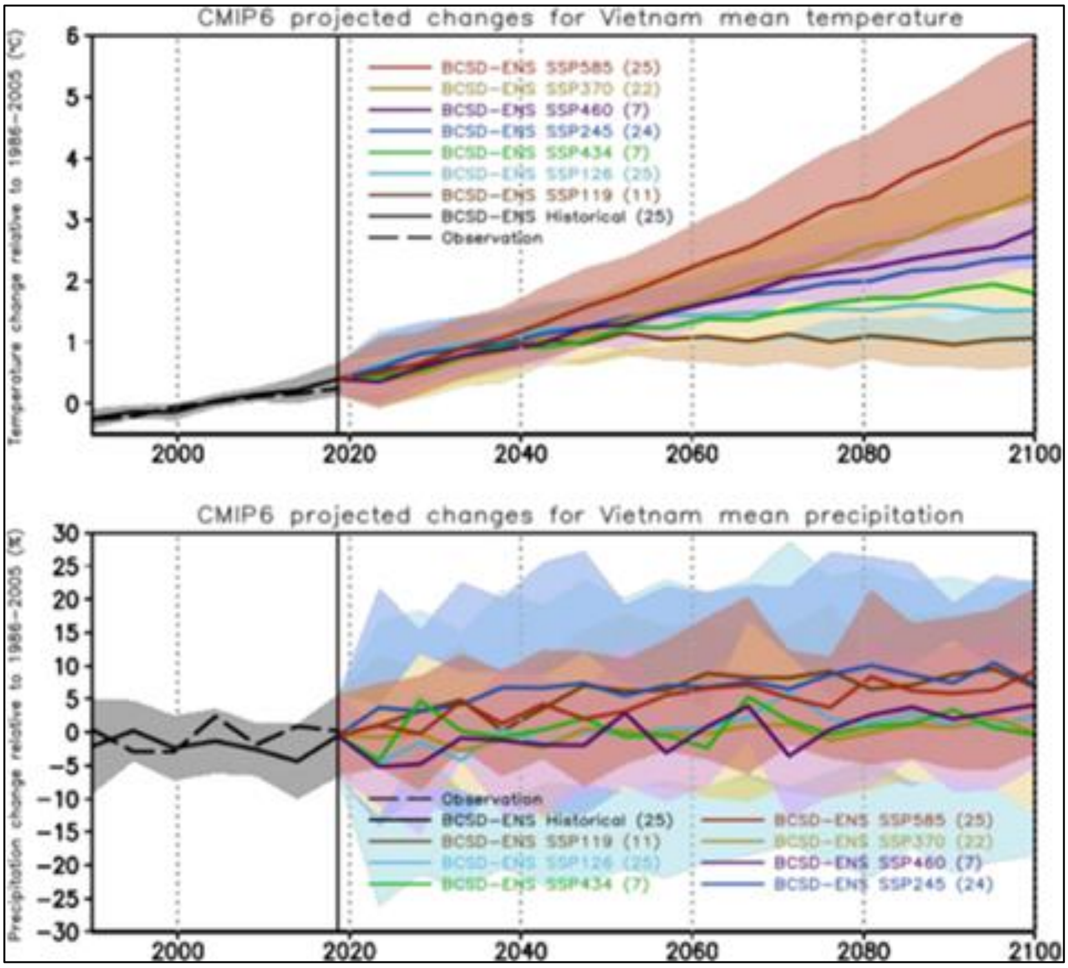
Figure (1): Present the climate projections derived from the Model Intercomparison Project (MIP) scenario within the framework of CMIP6. (Tebaldi, et ,al., 2020).

2.3. Modelling of Hydrological Systems under Climate Change

Employing diverse empirical models and specialized techniques within hydrological programs is vital for simulating watersheds, explicitly focusing on managing water quality. This approach aims to address the challenges posed by both the quantity and quality of water management within the complexities of the water cycle (Pandi et al., 2021). Water resource and watershed analyses have emerged as critical components of hydrological modelling sciences in the 21st century (Sun et al., 2023). They play a pivotal role in contemporary research objectives, particularly in directly studying the effects of climate change on global resources. This involves analyzing reduced rainfall patterns and the repercussions of natural floods and erosion on water resources. Hydrological modelling is increasingly pivotal for risk analysis and assessment (Li et al., 2019, Swain et al., 2020, Tayyeh & Mohammed., 2023). It has become a strategic tool benefiting the scientific community and decision-makers, aiding in informed decision-making processes. Cutting-edge technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), and other advanced tools are integral to hydrological modelling. Their integration enhances these models' precision, scope, and efficacy, allowing for a more comprehensive understanding of water-related dynamics and their implications. Digital spatial data of a hydrological system is employed to extract topographic, topological, and hydrological information for delineating purposes in hydrologic modelling (Wu ,et ,al., 2019, Castro ,et ,al., 2020). Spatial datasets and hydrologic models, often derived from digital elevation models, facilitate topological analysis (Ibrahim ,et ,al., 2020, Liu, et ,al., 2021). This process aids in determining crucial hydrological parameters related to streams, rivers, and watersheds. These parameters include curve number, area, lag-time for watersheds, and the routing model and duration for specific stream segments (Cotugno ,et ,al., 2021, Bhusal ,et ,al., 2022). The Assessment of Science Integrating Point and Nonpoint Sources (BASINS) system, created by the US Environmental Protection Agency, was designed to amalgamate Geographic Information Systems (GIS), watershed tools, and various models like SWAT, MIKE SHE, and HMS. These models were utilized to quantify and assess the impacts of land-use alterations on a catchment's peak flow patterns (Yuan et al., 2020, Srinivas, et ,al., 2020, Liu ,,et al., 2021). Stream runoff and hydropower generation characteristics in arid regions vary across different climate types, from hot and dry to moderate or humid to warm conditions (Yang ,et ,al., 2020, Annys ,et ,al., 2020). River discharge capacities play a significant role in influencing the output of hydropower, particularly under the impact of climate change (Maran ,et ,al., 2014, Qin ,et ,al., 2020).

2.4. Uncertainty from Global Climate Models with Emission Scenario

The uncertainties within (GCMs) primarily stem from inaccuracies in depicting climate processes (model physics) and flawed model structures. These issues hinder the models' ability to accurately capture short-term (interannual) and longer-term (decadal) variability in climate patterns (Alizadeh., 2022, Omid., 2022). Another significant source of uncertainty in all climate models arises from the challenge of accurately representing the complex interactions among different subsystems, including the atmosphere, hydrosphere, and lithosphere. These interconnections add layers of complexity and uncertainty to climate modelling efforts (Slingo & Palmer., 2011, Srikrishnan ,et, al., 2022). In several recent studies, there has been a notable emphasis on the differences in predicted climate changes among different Global Climate Models (GCMs). These variations are apparent in the expected alterations' scale and frequency, as delineated in the IPCC's 2021 report. Multiple studies have compared earlier iterations (CMIP3/CM1P2) of climate projections and more recent versions (CMIP4/CMIP5). These analyses have unveiled noteworthy discrepancies between the two sets of projections (Lutz ,et ,al., 2013, Alves et al., 2016, Carvalho ,et ,al., 2022). Even with advancements in enhancing model construction, the extent of uncertainties has shown minimal change, as noted in reports from the IPCC in 2014 and 2021. Although Global Climate Models inherently contain uncertainties, numerous techniques have been devised to measure and address them, all to generate reliable future projections. This principle is highlighted in studies conducted by (McSweeney ,et, al., 2015, Raju & Kumar., 2020). For instance, recognizing the limitations of individual models in accurately simulating regional climatic processes, a pragmatic strategy involves combining projections from multiple (GCMs). This amalgamation produces an ensemble mean representing the most probable future climate scenario. Figure (2) demonstrates that uncertainty is also associated with the selection of parameterization used to depict specific processes in model construction, as discussed by (Tran ,et ,al., 2023).



Figure(2) : CM1P6 model-based time series of temperature and precipitation (historical and projections) from 2020 to 2100 relative to the 1980-2000 baseline for the SSPs scenarios. The shaded area represents the range of changes projected by the 20 models for each year. (Tran et al, 2023).

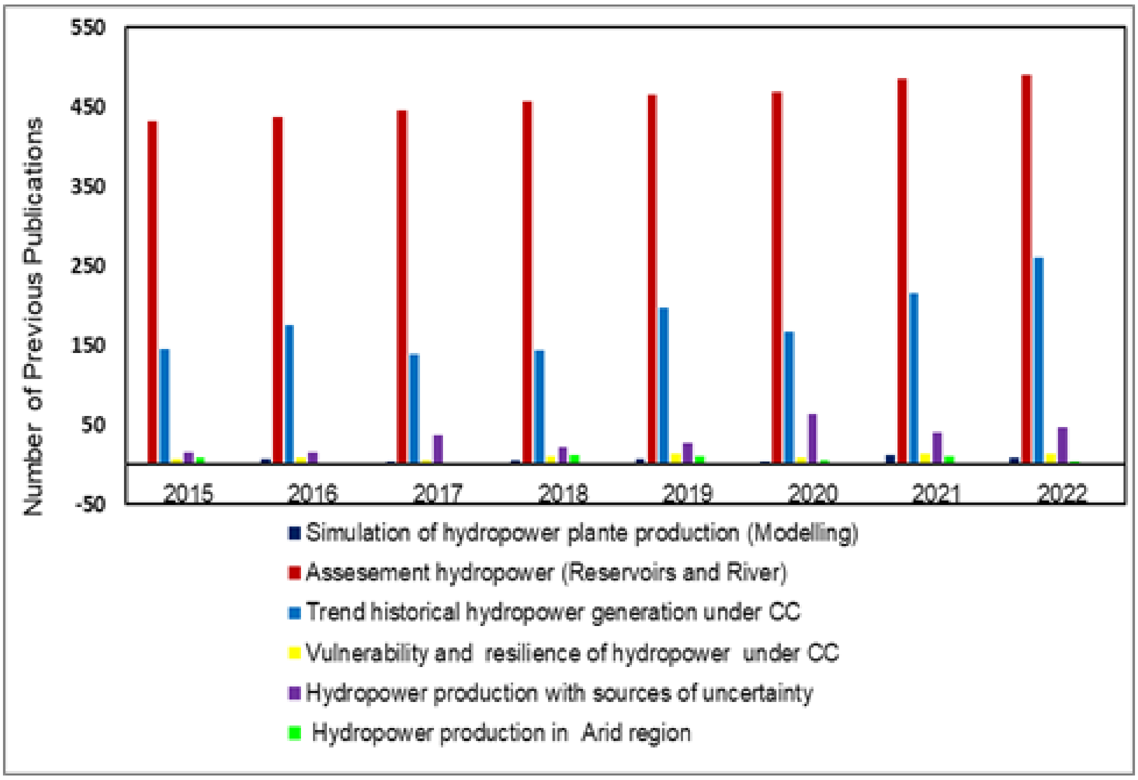
The second significant source of uncertainty in emission scenario studies and simulations stems from predicting future environmental policies and the magnitude of greenhouse gas (GHG) emissions (Maier ,et, al., 2016, Aguiar ,et ,al., 2016, Ho ,et ,al., 2019).

2.5. Power Generation under Climate Change

The effects of global warming on water resources entail changes in the hydrological cycle and variations in water availability, affecting both river flows and the storage capacity of reservoirs (Chaturvedi ,et ,al., 2021, Kahaduwa & Rajapakse., 2022). Hydropower plants are susceptible to these alterations in water availability and the hydrological cycle (Falchetta ,et, al., 2019, Mtilatila et al., 2020, Almeida ,et ,al., 2021). The efficiency of reservoir operations is a fundamental requirement for effective hydropower production (Riggins., 2022). Climate change has led to significant shifts in temperature, precipitation, and streamflow patterns, exerting a considerable influence on hydropower projects. These alterations affect the design considerations for dams and reservoirs, as well as impacting their operational lifespans (Lu ,et ,al., 2020, Qin et al., 2020, Tariku et al., 2021). Reservoirs play a pivotal role in alleviating water scarcity within the system, ensuring a sustainable supply for hydropower generation (Brunner et al., 2019, Rafique et al., 2020). Moreover, reservoir operating rules serve as commonly used guidelines for regulating basin releases, aiming to maximize the advantages a reservoir offers while upholding predetermined inflow and storage levels (Tegegne & Kim, 2020, Wang et al., 2020, Munir et al., 2022). As per the Working Group II Contribution to the IPCC AR6, the findings indicate anticipated risks in the near-term, mid-term, and long-term across various global warming scenarios. These risks encompass pathways that surpass a sustained 1.5°C global warming level, posing challenges under these conditions.

2.6. Performance of Hydropower Generation

Historically, the assessment of reservoir performance amidst climate change and uncertainty has primarily focused on evaluating the reliability of inflow volume and timing (Chadwick ,et, al., 2020, Ren ,et ,al., 2020, Mortezaeipooya ,et ,al., 2022). Apart from the conventional criteria, some researchers have introduced two additional metrics—resilience and vulnerability—to gauge diverse aspects and evaluate the performance of reservoirs (Thushara ,et ,al., 2019, Ren ,et .al., 2020, Nguyen ,et ,al., 2020). Performance indices are computed using fundamental data tied to reservoir hydropower generation, encompassing metrics like the volume of water required and provided across all periods, the frequency of failures, and the magnitude of these failures concerning their duration and severity. Studies often employ monthly or yearly periods for these evaluations. Resilience and vulnerability serve as two critical criteria for assessing reservoir performance. Resilience measures the system's capacity for swift recovery, while vulnerability evaluates the potential severity of consequences in the event of failure. Indeed, there is a scarcity of global studies dedicated to crafting indicators for assessing reservoirs, and those available often emphasize the monotonic trends related to the reliability and vulnerability linked to reservoir inflows (Nguyen et al., 2020, Bozorg et al., 2022, Tayyeh & Mohammed., 2024). Statistical indices have often been limited to a narrow scope, and they have yet to be extensively employed to investigate the performance behaviour of a hydropower, including aspects like resilience, and vulnerability, for evaluation and their correlation with the sources of uncertainty. According to an exhaustive review and the most up-to-date information available from ScienceDirect Figure (3) highlights a substantial body of research in power generation. However, it is noteworthy that these studies have yet to delve into modelling hydroelectric energy production from reservoirs within arid regions. This modelling approach considers all crucial factors, such as storage capacity, water levels, turbine count, and generation efficiency. It seeks to factor in the potential impacts of climate change on these reservoirs. Furthermore, this research intends to quantify generation efficiency using statistical metrics related to vulnerability and resilience while accounting for all sources of uncertainty from climate and hydrological modelling to provide a comprehensive and detailed understanding of this intricate phenomenon.



Figure(3): Previous studies based upon ScienceDirect data.

3. Conclusions

Global greenhouse gas emissions substantially impact hydroelectric power, both in the short and long term, regardless of whether it is applied on a large or small scale. Hence, comprehending strategies to sustain, minimize vulnerability, and optimize hydropower production amid the adverse impacts of climate change becomes crucial. Despite published successes in enhancing approaches to mitigate the adverse effects of climate change on water resources and hydropower, considerable uncertainties persist in hydrological processes due to climate change, subsequently influencing hydroelectric power generation.

Indeed, enhancing methods for forecasting and predicting alterations in the hydrological regime resulting from climate-induced extreme events is crucial for better and more precise evaluations of hydropower development potential in adverse climate conditions. However, none of the large-scale studies mentioned in this research encompassed the essential hydrographic conditions necessary for such assessments. Establishing general measures to mitigate the impacts of climate change proves challenging due to the diversity and distinctiveness of each hydropower station.

Ultimately, it is crucial to intensify and regulate technological initiatives for hydropower management to safeguard the environment, ecosystems, and socio-economic sectors. This includes optimizing flood-control operations during high-flow periods and enhancing water usage systems during droughts. Climate change will impact hydropower development and sustainability, imposing a more significant strain on the global energy system. Nevertheless, with suitable mitigation and adaptation strategies, hydropower can serve as a support and catalyst for environmental and societal development.

References

Aguiar, A. P. D., Vieira, I. C. G., Assis, T. O., Dalla-Nora, E. L., Toledo, P. M., Oliveira Santos-Junior, R. A., ... & Ometto, J. P. H. ,2016, Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon. Global change biology, 22(5), 1821-1840.

Alizadeh, O. ,2022, Advances and challenges in climate modeling. Climatic Change, 170(1-2), 18.

Almeida, R. M., Fleischmann, A. S., Brêda, J. P., Cardoso, D. S., Angarita, H., Collischonn, W., ... & Flecker, A. S. ,2021, Climate change may impair electricity generation and economic viability of future Amazon hydropower. Global Environmental Change, 71, 102383.

Alves, J. M., Vasconcelos Junior, F. C., Chaves, R. R., Silva, E. M., Servain, J., Costa, A. A., ... & dos Santos, A. C. ,2016, Evaluation of the AR4 CMIP3 and the AR5 CMIP5 Model and Projections for Precipitation in Northeast Brazil. Frontiers in Earth Science, 4, 44.

Annys, S., Ghebreyohannes, T., & Nyssen, J. ,2020, Impact of hydropower dam operation and management on downstream hydrogeomorphology in semi-arid environments (Tekeze, Northern Ethiopia), Water, 12(8), 2237.

Bhusal, A., Parajuli, U., Regmi, S., & Kalra, A. ,2022, Application of machine learning and process-based models for rainfall-runoff simulation in Dupage River basin, Illinois. Hydrology, 9(7), 117.

Bozorg-Haddad, O., Yari, P., Delpasand, M., & Chu, X. ,2022, Reservoir operation under influence of the joint uncertainty of inflow and evaporation. Environment, Development and Sustainability, 24(2), 2914-2940.

Brunner, M. I., Gurung, A. B., Zappa, M., Zekollari, H., Farinotti, D., & Stähli, M. ,2019, Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. Science of the Total Environment, 666, 1033-1047.

Carvalho, D., Rafael, S., Monteiro, A., Rodrigues, V., Lopes, M., & Rocha, A. ,2022, How well have CMIP3, CMIP5 and CMIP6 future climate projections portrayed the recently observed warming. Scientific Reports, 12(1), 11983.

Castro, C. V., & Maidment, D. R. ,2020, GIS preprocessing for rapid initialization of HEC-HMS hydrological basin models using web-based data services. Environmental Modelling & Software, 130, 104732.

Chadwick, C., Gironas, J., Barria, P., Vicuna, S., & Meza, F. ,2020, Assessing reservoir performance under climate change. When is it going to be too late if current water management is not changed?. Water, 13(1), 64.

Chaturvedi, A., Pandey, B., Yadav, A. K., & Saroj, S. ,2021, An overview of the potential impacts of global climate change on water resources. Water conservation in the era of global climate change, 99-120.

Corwin, D. L. ,2021, Climate change impacts on soil salinity in agricultural areas. European Journal of Soil Science, 72(2), 842-862.

Cotugno, A., Smith, V., Baker, T., & Srinivasan, R. ,2021, A framework for calculating peak discharge and flood inundation in ungauged urban watersheds using remotely sensed precipitation data: a case study in freetown, sierra leone. Remote Sensing, 13(19), 3806.

Dias, E. M. S., Pessoa, Z. S., & Teixeira, R. L. P. ,2023, ADAPTIVE GOVERNANCE AND WATER SECURITY IN THE CONTEXT OF CLIMATE CHANGE IN THE SEMI-ARID. Mercator (Fortaleza), 21, e21025.

El-Rawy, M., Batelaan, O., Al-Arifi, N., Alotaibi, A., Abdalla, F., & Gabr, M. E. ,2023,Climate change impacts on water resources in arid and semi-arid regions: a case study in Saudi Arabia. Water, 15(3), 606.

Falchetta, G., Gernaat, D. E., Hunt, J., & Sterl, S. ,2019, Hydropower dependency and climate change in sub-Saharan Africa: A nexus framework and evidence-based review. Journal of Cleaner Production, 231, 1399-1417.

Killingtveit, Å. ,2019, Hydropower. In Managing global warming (pp. 265-315). Academic Press.

Golla, B. ,2021, Agricultural production system in arid and semi-arid regions. International Journal of Agricultural Science and Food Technology, 7(2), 234-244.

Gütschow, J., Jeffery, M. L., Günther, A., & Meinshausen, M. ,2021, Country-resolved combined emission and socio-economic pathways based on the Representative Concentration Pathway (RCP) and Shared Socio-Economic Pathway (SSP) scenarios. Earth System Science Data, 13(3), 1005-1040.

Hargrove, W. L., Heyman, J. M., Mayer, A., Mirchi, A., Granados-Olivas, A., Ganjegunte, G., ... & Walker, W. S. ,2023, The future of water in a desert river basin facing climate change and competing demands: A holistic approach to water sustainability in arid and semi-arid regions. Journal of Hydrology: Regional Studies, 46, 101336.

Ho, E., Budescu, D. V., Bosetti, V., van Vuuren, D. P., & Keller, K. ,2019, Not all carbon dioxide emission scenarios are equally likely: A subjective expert assessment. Climatic Change, 155, 545-561.

Huang, J., Ji, M., Xie, Y., Wang, S., He, Y., & Ran, J. ,2016, Global semi-arid climate change over last 60 years. Climate Dynamics, 46, 1131-1150.

Huang, W., Duan, W., & Chen, Y. ,2022, Unravelling lake water storage change in Central Asia: Rapid decrease in tail-end lakes and increasing risks to water supply, *Journal of Hydrology*, 614, 128546.

Ibrahim, M., Al-Mashaqbah, A., Koch, B., & Datta, P. ,2020, An evaluation of available digital elevation models (DEMs) for geomorphological feature analysis. Environmental Earth Sciences, 79(13), 336.

IPCC ,2021, Summary for Policymakers. The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Ismail, Z., & Go, Y. I. (2021). Fog-to-Water for Water Scarcity in Climate-Change Hazards Hotspots: Pilot Study in Southeast Asia. Global Challenges, 5(5), 2000036.

Kahaduwa, A., & Rajapakse, L. ,2022, Review of climate change impacts on reservoir hydrology and long-term basin-wide water resources management. Building Research & Information, 50(5), 515-526.

Lange, M. A.,2019, Impacts of climate change on the Eastern Mediterranean and the Middle East and North Africa region and the water–energy nexus. Atmosphere, 10(8), 455.

Li, W., Lin, K., Zhao, T., Lan, T., Chen, X., Du, H., & Chen, H. ,2019, Risk assessment and sensitivity analysis of flash floods in ungauged basins using coupled hydrologic and hydrodynamic models, *Journal of Hydrology*, 572, 108-120.

Liu, H., Chen, J., Zhang, L., Sun, K., & Cao, W. ,2021, Simulation effects of clean water corridor technology on the control of non-point source pollution in the Paihe River basin, Chaohu lake. Environmental Science and Pollution Research, 28, 23534-23546.

Liu, Y., Liu, H., Wang, L., Xu, M., Cohen, S., & Liu, K. ,2021, Derivation of spatially detailed lentic habitat map and inventory at a basin scale by integrating multispectral Sentinel-2 satellite imagery and USGS Digital Elevation Models, *Journal of Hydrology*, 603, 126876.

Lu, S., Dai, W., Tang, Y., & Guo, M. ,2020, A review of the impact of hydropower reservoirs on global climate change. Science of the Total Environment, 711, 134996.

Lutz, A. F., Immerzeel, W. W., Gobiet, A., Pellicciotti, F., & Bierkens, M. F. ,2013, Comparison of climate change signals in CMIP3 and CMIP5 multi-model ensembles and implications for Central Asian glaciers. Hydrology and Earth System Sciences, 17(9), 3661-3677.

Maier, H. R., Guillaume, J. H., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H.,2016, An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together?. Environmental modelling & software, 81, 154-164.

Mankin, J. S., Seager, R., Smerdon, J. E., Cook, B. I., & Williams, A. P. (2019). Mid-latitude freshwater availability reduced by projected vegetation responses to climate change. Nature Geoscience, 12(12), 983-988.

Maran, S., Volonterio, M., & Gaudard, L. ,2014, Climate change impacts on hydropower in an alpine catchment. Environmental Science & Policy, 43, 15-25.

McSweeney, C. F., Jones, R. G., Lee, R. W., & Rowell, D. P. ,2015, Selecting CMIP5 GCMs for downscaling over multiple regions. Climate Dynamics, 44, 3237-3260.

Meinshausen, M., Nicholls, Z. R., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., ... & Wang, R. H. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geoscientific Model Development, 13(8), 3571-3605.

Mirdashtvan, M., Najafinejad, A., Malekian, A., & Sa'doddin, A. ,2021, Sustainable water supply and demand management in semi-arid regions: optimizing water resources allocation based on RCPs scenarios. Water Resources Management, 35, 5307-5324.

Morante-Carballo, F., Montalván-Burbano, N., Quiñonez-Barzola, X., Jaya-Montalvo, M., & Carrión-Mero, P. ,2022, What do we know about water scarcity in semi-arid zones? A global analysis and research trends. Water, 14(17), 2685.

Mortezaeipooya, S. S., Ashofteh, P. S., Golfam, P., & Loáiciga, H. A. ,2022, Evaluation of water supply system performance affected by climate change with MODSIM modeling and reservoir efficiency indicators, *Arabian Journal of Geosciences*, 15(19), 1580.

Mtilatila, L., Bronstert, A., Shrestha, P., Kadewere, P., & Vormoor, K. ,2020, Susceptibility of water resources and hydropower production to climate change in the tropics: the case of Lake Malawi and Shire River Basins, SE Africa. Hydrology, 7(3), 54.

Munir, M. M., Shakir, A. S., Rehman, H. U., Khan, N. M., Rashid, M. U., Tariq, M. A. U. R., & Sarwar, M. K. ,2022,Simulation-Optimization of Tarbela Reservoir Operation to Enhance Multiple Benefits and to Achieve Sustainable Development Goals. Water, 14(16), 2512.

Muratoglu, A., Iraz, E., & Ercin, E. ,022, Water resources management of large hydrological basins in semi-arid regions: Spatial and temporal variability of water footprint of the Upper Euphrates River basin. Science of The Total Environment, 846, 157396.

Nguyen, H., Mehrotra, R., & Sharma, A. ,2020, Assessment of climate change impacts on reservoir storage reliability, resilience, and vulnerability using a multivariate frequency bias correction approach. Water resources research, 56(2), e2019WR026022.

Nikolaou, G., Neocleous, D., Christou, A., Kitta, E., & Katsoulas, N. ,2020, Implementing sustainable irrigation in water-scarce regions under the impact of climate change. Agronomy, 10(8), 1120.

Omid, A. (2022). Advances and challenges in climate modeling. Climatic Change, 170(1-2).

Pandi, D., Kothandaraman, S., & Kuppusamy, M. ,2021, Hydrological models: a review. International Journal of Hydrology Science and Technology, 12(3), 223-242.

Qin, P., Xu, H., Liu, M., Xiao, C., Forrest, K. E., Samuelsen, S., & Tarroja, B. (2020). Assessing concurrent effects of climate change on hydropower supply, electricity demand, and greenhouse gas emissions in the Upper Yangtze River Basin of China. Applied Energy, 279, 115694.

Rafique, A., Burian, S., Hassan, D., & Bano, R. ,2020, Analysis of operational changes of Tarbela Reservoir to improve the water supply, hydropower generation, and flood control objectives. Sustainability, 12(18), 7822.

Raju, K. S., & Kumar, D. N. ,2020, Review of approaches for selection and ensembling of GCMs. *Journal of Water and Climate Change*, 11(3), 577-599.

Raulino, J. B., Silveira, C. S., & Lima Neto, I. E. ,2021,Assessment of climate change impacts on hydrology and water quality of large semi-arid reservoirs in Brazil. *Hydrological Sciences Journal*, 66(8), 1321-1336.

Ren, K., Huang, S., Huang, Q., Wang, H., Leng, G., Fang, W., & Li, P. ,2020,. Assessing the reliability, *resilience and vulnerability of water supply system under multiple uncertain sources. Journal of Cleaner Production*, 252, 119806.

Riggins, B. A. ,2022, Climate Change Exacerbates the Impacts of Small Hydropower Projects (Doctoral dissertation, San Francisco State University).

Şen, Z. ,2021, Reservoirs for water supply under climate change impact—a review. Water Resources Management, 35, 3827-3843.

Sharafati, A., Pezeshki, E., Shahid, S., & Motta, D. ,2020, Quantification and uncertainty of the impact of climate change on river discharge and sediment yield in the Dehbar river basin in Iran. *Journal of Soils and Sediments*, 20, 2977-2996.

Siabi, E. K., Awafo, E. A., Kabo-bah, A. T., Derkyi, N. S. A., Akpoti, K., Mortey, E. M., & Yazdanie, M. ,2023, Assessment of Shared Socioeconomic Pathway (SSP) climate scenarios and its impacts on the Greater Accra region. Urban Climate, 49, 101432.

Singh, P. K., & Chudasama, H. ,2021, Pathways for climate change adaptations in arid and semi-arid regions. *Journal of cleaner production*, 284, 124744.

Slingo, J., & Palmer, T. ,2011, Uncertainty in weather and climate prediction. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369(1956), 4751-4767.

Srikrishnan, V., Lafferty, D. C., Wong, T. E., Lamontagne, J. R., Quinn, J. D., Sharma, S., ... & Lee, B. S. ,2022, Uncertainty analysis in multi-sector systems: Considerations for risk analysis, projection, and planning for complex systems. Earth's Future, 10(8), e2021EF002644.

Srinivas, R., Singh, A. P., Dhadse, K., & Garg, C. ,2020, An evidence based integrated watershed modelling system to assess the impact of non-point source pollution in the riverine ecosystem. *Journal of cleaner production*, 246, 118963.

Stammer, D., Engels, A., Marotzke, J., Gresse, E., Hedemann, C., & Petzold, J. ,2021, Hamburg Climate Futures Outlook 2021: Assessing the plausibility of deep decarbonization by 2050.

Sun, Y. ,2020, The achievement, significance and future prospect of China's renewable energy initiative. International Journal of Energy Research, 44(15), 12209-12244.Sun, G., Wei, X., Hao, L., Sanchis, M. G., Hou, Y., Yousefpour, R., ... & Zhang, Z. ,2023, Forest hydrology modeling tools for watershed management: A review. Forest Ecology and Management, 530, 120755.

Swain, S. S., Mishra, A., Sahoo, B., & Chatterjee, C. ,2020, Water scarcity-risk assessment in data-scarce river basins under decadal climate change using a hydrological modelling approach. *Journal of Hydrology*, 590, 125260.

Tariku, T. B., Gan, K. E., Tan, X., Gan, T. Y., Shi, H., & Tilmant, A. ,2021, Global warming impact to River Basin of Blue Nile and the optimum operation of its multi-reservoir system for hydropower production and irrigation. Science of The Total Environment, 767, 144863.

Tayyeh, H. K., & Mohammed, R. (2023). Analysis of NASA POWER reanalysis products to predict temperature and precipitation in Euphrates River basin. Journal of Hydrology, 619, 129327.

Tayyeh, H. K., & Mohammed, R. ,2024, Vulnerability and resilience of hydropower generation under climate change scenarios: Haditha dam reservoir case study. Applied Energy, 366, 123308.

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., ... & Ziehn, T. ,2020, Climate model projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6. Earth System Dynamics Discussions, 2020, 1-50.

Tegegne, G., & Kim, Y. O. ,2020, Representing inflow uncertainty for the development of monthly reservoir operations using genetic algorithms. *Journal of Hydrology*, 586, 124876.

Thushara De Silva, M., & Hornberger, G. M. ,2019, Assessing water management alternatives in a multipurpose reservoir cascade system in Sri Lanka. *Journal of Hydrology*: Regional Studies, 25, 100624.

Tran-Anh, Q., Ngo-Duc, T., Espagne, E., & Trinh-Tuan, L. ,2023, A 10-km CMIP6 downscaled dataset of temperature and precipitation for historical and future Vietnam climate. Scientific Data, 10(1), 257.

Verma, S., Verma, M. K., Prasad, A. D., Mehta, D., Azamathulla, H. M., Muttil, N., & Rathnayake, U. ,2023, Simulating the Hydrological Processes under Multiple Land Use/Land Cover and Climate Change Scenarios in the Mahanadi Reservoir Complex, Chhattisgarh, India. Water, 15(17), 3068.

Wang, Y. S., & Gu, J. D. ,2021, Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. International Biodeterioration & Biodegradation, 162, 105248.

Wang, Z., Zhang, L., Cheng, L., Liu, K., Ye, A., & Cai, X. ,2020, Optimizing operating rules for a reservoir system in Northern China considering ecological flow requirements and water use priorities. Journal of Water Resources Planning and Management, 146(7), 04020051.

Wu, Q., Lane, C. R., Wang, L., Vanderhoof, M. K., Christensen, J. R., & Liu, H. ,2019, Efficient delineation of nested depression hierarchy in digital elevation models for hydrological analysis using level-set method. JAWRA Journal of the American Water Resources Association, 55(2), 354-368.

Yang, L., Feng, Q., Yin, Z., Deo, R. C., Wen, X., Si, J., & Liu, W. ,2020, Regional hydrology heterogeneity and the response to climate and land surface changes in arid alpine basin, northwest China. Catena, 187, 104345.

Yuan, L., Sinshaw, T., & Forshay, K. J. ,2020, Review of watershed-scale water quality and nonpoint source pollution models. Geosciences, 10(1), 25.

Zittis, G., Almazroui, M., Alpert, P., Ciais, P., Cramer, W., Dahdal, Y., ... & Lelieveld, J. ,2022, Climate change and weather extremes in the Eastern Mediterranean and Middle East. Reviews of Geophysics, 60(3), e2021RG000762.