A HOLISTIC ANALYSIS SYSTEM TO SUPPORT WATER RESOURCE POLICY DECISIONS UNDER CLIMATE CHANGE

Sanjeewa Punsiri Bandara Illangasingha
National Graduate Institute for Policy Studies (GRIPS)

Extended Summary

INTRODUCTION

The impacts of climate change are increasingly evident, as highlighted by the IPCC (2022), manifesting in disrupted precipitation patterns, altered evaporation rates, and shifts in water resource distribution and availability, affecting the entire water cycle (Caretta et al., 2022; IPCC, 2022). However, poor governance, gaps in applying science and technology to disaster risk reduction (DRR) policies, and economic and financial concerns hinder effective climate change adaptation in many regions. In response, global agendas have been formed to overcome these obstacles, aiming to enhance disaster resilience and build a sustainable society through advanced scientific knowledge. This research integrates these global agendas to develop a holistic framework for fostering a sustainable society by strengthening disaster resilience. A critical aspect of understanding disaster risk involves identifying climate behavior to address or mitigate floods and droughts.

Numerical climate projections, particularly General Circulation Models (GCMs), are vital for informing decisions on adaptation, mitigation, and resilience strategies to counter the adverse effects of climate change. However, lower-resolution model projections have uncertainties related to models, climate zones, and temporal that create considerable doubt in decision-making, especially at the local or regional level (Hawkins and Sutton, 2009; Illangasingha et al., 2023; Walker et al., 2003) and its quantification of uncertainty is challenging. Projecting future hydrological conditions is challenging due to the uncertainty in initial conditions. Therefore, a seamless hydrological modeling approach is crucial for reliable future water resources management. Identifying variations in low and high flow states, along with dry and wet conditions, is crucial. These variations can be effectively monitored using hydrometeorological indices, which serve as valuable tools for water resource management. By utilizing a seamless model, these variables can be transformed into actionable indices for water resource practitioners and decision-makers. However, the application of hydrological models for climate change and damage projection (Ludwig et al., 2009), coupled with the inadequate integration of hydrometeorological indices (Li et al., 2021), presents substantial challenges. Moreover, quantifying drought damage projections is particularly difficult in areas lacking historical drought damage data (IPCC, 2023), complicating effective disaster risk reduction (DRR). Water scarcity and abundance vary across different basins due to geographical and temporal differences, and climate change is expected to exacerbate the floods and droughts resulting from these variations. While some countries have implemented shared basin water and constructed water storage facilities, socio-economic factors and climate change implications across adjacent basins make utilizing these storage systems for water sharing challenging (Rollason et al., 2021). Therefore, it is vital to evaluate whether an integrated, connected river basin system can effectively address these climate change impacts utilizing existing storage capacities.

To address the above-identified research gaps, this study introduces a novel approach for quantifying the uncertainty of GCMs when applied at local or regional scales. In this critical analysis, five novel principles (Illangasingha et al., 2023) are introduced for utilising GCM outcomes in consensus development and decision-making. Furthermore, the research presents a seamless methodology for assessing climate change impacts on water availability and agricultural resilience by integrating hydrometeorological indices. In addition to the above-mentioned principles, the study presented five new guiding principles to guide this essential hydrology assessment. The study also introduces uncertainty quantification and paddy flood damage assessment and drought damage assessment methodologies in areas lacking previous drought risk management data. Additionally, it suggests utilizing existing water storage facilities to address climate change through inter-basin water sharing and flood and drought mitigation. The applicability of these approaches was tested in diverse regions, in Sri Lanka, which comprises nine distinct basins. A meteorological assessment was conducted using reliable GCMs to identify climate change signals, thereby aiding the decision-making process. The main objective is to develop a comprehensive holistic analysis system that facilitates informed water resource policy decisions in the face of climate change risks by introducing effective disaster risk reduction strategies.

METHODOLOGY

A large number of GCMs have been analyzed to develop an approach for selecting reliable models that accurately represent regional or local climate characteristics for informed decision-making. GCM outputs were then downscaled and bias-corrected for regional or local domains utilising data from a dense network of gauge stations for precipitation. The climate sensitivity of each model was identified and discrepancies among the outcomes of the five chosen models were investigated to ensure reliable decision-making for diverse basins. The DIAS CMIP5 tool, combined with CMIP5 climatological variables and an online interface, was used in a variety of simulations and analysis. The GCMs' performance was evaluated by comparing them to observations and reanalysis data spanning 1980 to 2005. Based on this evaluation, I chose five high-performing GCMs and tested their accuracy in replicating present climate conditions with Japan's JRA55 reanalysis data. I then examined the wind vector (WV) and meridional wind (MW) components, comparing climatological data. The selected GCM data were then statistically downscaled and bias-corrected using an Inverse Distance Weighting (IDW) method in conjunction with a three-step bias correction (Nyunt et al., 2016) to regional/local high-dense rainfall network data. This downscaling and bias correction method was also used to project rainfall data for the near (NF), mid (MF), and far (FF) futures under the RCP8.5 scenario, with a more conservative approach to account for community-based aspects. I looked at seasonality and annual variability in spatial climatic patterns to determine the sensitivity of GCM outputs. Discrepancies in future climate variable projections were explained by variations in MW and WV during the Southwest Monsoon (SWM) and Northeast Monsoon (NEM) seasons, taking into account the strength or weakness of these climatic factors. The methodology was evaluated in nine different regions by analysing observed and bias corrected GCM regional data from nine basins. Confidence and trend analyses were carried out to improve decision-making in tackling future climate issues, ensuring that the findings are appropriate for future use in climate resilience and adaption plans.

WEB-RRI (Rasmy et al., 2019) models were set up for eight basins using remote sensing, vegetation indices, ground data, and dynamic forcing data. These models were calibrated and validated for both low and high flow conditions for a longer durations. Future hydrological conditions were projected using downscaled and bias-corrected GCM data. Hydrometeorological indices for rainfall, streamflow, soil moisture, and evapotranspiration (WEB-RRI model outputs) were utilized to characterize flood and drought conditions. Long-term water availability was assessed using standardized precipitation, streamflow, soil moisture, and evapotranspiration indices (SPI, SSI, SSMI, SETI) calculated from basin averages using the Gamma function (McKee et al., 1993). Flood damage in paddy fields was evaluated based on inundation, while drought damage was assessed using hydrometeorological indices and past drought damage relationships (UN-SPIDER, 2022).

A comprehensive framework with four key elements—Data Input, Simulation, Analysis, and Decision-making—was developed for the evaluation of water resources planning and analysis. This framework was applied to climate change risk assessment by integrating hydrological and Water Resources Planning models with disaster risk reduction and benefit evaluation. The WEB-RRI model was setup for six basins to compute discharges, which were then coupled with the WEAP (Jack and Purkey, 2005) model. Relevant input data, including reservoir data, canals capacities, losses, demand site requirements, inflow stream data, etc were incorporated for simulations through multiple scenarios, including various basin and interbasin diversions. Water coverages for demand sites were computed, and the effects and benefits of these interventions were evaluated to guide further decision-making.

RESULTS & DISCUSSION

GCM sensitivity varies both spatially and temporally, revealing significant climate change signals across different basins. These signals show seasonal and annual variations. Average annual precipitation in each basin is projected to increase in the near, middle, and far future. The Southwest Monsoon and Inter-Monsoon-2 are likely to strengthen, while the Northeast Monsoon and Inter-Monsoon-1 are expected to weaken, except for the NEM in the near future. GCM results vary due to inherent assumptions and simplifications. Different GCM developers apply unique boundary constraints and parameterizations to approximate small-scale processes, affecting model projections (Randall et al., 2007). The spatial resolution of GCMs also impacts projections, with finer resolutions requiring more computational power. Additionally, various greenhouse gas emission scenarios contribute to a wide range of potential climate outcomes, sometimes leading to directional ambiguity between models. Uncertainty in climate models arises from factors such as limited understanding of physical processes, computational limitations, and natural variability, even when initial conditions and emissions scenarios are consistent. Selvarajah et al. (2021) project that annual precipitation in the Mahaweli basin will likely increase in the near future under the RCP8.5 scenario, consistent with this research findings. Similarly, Sirisena et al. (2021) suggest that the Southwest Monsoon in Sri Lanka's Kalu River basin (western basin) may strengthen by the late 21st century, aligning with this research's far-future projections. ADB. (2022) also confirms this research projection for increasing SWM and declining IM-1 precipitation in the central mountain region. These findings validate the research results and underscore the importance of seasonal analysis in climate studies, as emphasized by Galavi et al. (2019), for effective water resources management. Climate signals in terms of hydrology exhibit seasonal and annual variations, directly influencing water availability. In near future, annual flow is projected to decrease in some basins, with increases expected in the mid to far future. Extreme high flows are anticipated to rise throughout the 21st century, leading to more frequent severe floods. Drought projections, particularly for agricultural droughts, remain uncertain. By integrating hydro-meteorological indices such as SPI, SSI, SSMI, and SETI, I defined future wet and dry conditions. Projections for wet conditions show clear trends, though they vary by basin and across NF, MF, and FF time slots. In contrast, dry condition projections exhibit significant uncertainty, with inconsistent results among models. Therefore, while wet condition projections are relatively clear, drought trends remain uncertain, making it difficult to draw definitive conclusions. Hydrometeorological indices can play a crucial role in drought monitoring. As climate change progresses, its impact will intensify, with both drought and flood damages to paddy fields and communities expected to increase. Without diversion, the water demands during both the Yala and Maha seasons cannot be fully met, with the Yala season being particularly critical. The existing system can remain sustainable even with a 25% flow uncertainty. Most future demands can be met through the combined resources of the different diversions. The demands of new areas are achievable. Continuous water sharing is essential to meet the drinking water needs of water-stressed areas in the northern basin. Expanding agricultural sites will yield significant economic benefits, and the socio-economic conditions in the northern regions can improve due to better water availability and accessibility, without compromising the existing system. Water sharing among basins will also help reduce drought and flood risks of the recipient basins and donor basins. The results provided crucial insights for decision-making and highlighted future evaluation needs.

CONCLUSION

In this study, I developed a comprehensive analysis system that integrates scientific, engineering, socio-economic, and policy approaches to address the impacts of climate change on water resources. By utilizing GCM data under the RCP 8.5 scenario, I focused on understanding extreme climate risks across key basins in Sri Lanka. This work addresses significant research gaps by introducing five novel principles for utilizing GCM outputs at regional or local scales, enhancing informed decision-making. Additionally, it presents five guiding principles for guiding the analyzing water availability and agricultural resilience. The study demonstrated the effectiveness of quantifying GCM uncertainty at these scales by identifying climate sensitivity and addressing model discrepancies across diverse environments. This seamless approach provides a framework for projecting climate change impacts on water availability and agricultural resilience across different basins, even under uncertain conditions. The methodology introduced for quantifying drought damage projections in areas with limited historical data represents a key innovation, filling a critical gap. Additionally, I proposed a new framework for using existing water storage systems to manage trans-basin water sharing as a strategy to mitigate climate change impacts. This proved that water-sharing systems can enhance societal robustness even under climate change scenarios. These contributions are significant as they offer a holistic framework that can be applied globally to assess the effects of climate change on water resources and agricultural resilience. The policy implications of this study are profound, highlighting the need for adaptive water resource management and disaster risk reduction strategies. For instance, proposed water diversion projects in flood-prone and drought-affected regions could mitigate risks while enhancing water availability and quality. This integrated approach strengthens societal resilience to climate change, ensuring sustainable development and preparedness for future challenges. The framework's adaptability makes it a valuable tool not only for Sri Lanka but also for other regions facing similar climatic challenges, contributing to global climate resilience efforts.

REFERENCES

ADB, 2022. Climate Change Risk Profile of the Mountain Region in Sri Lanka. Asian Development Bank. https://doi.org/DOI: http://dx.doi.org/10.22617/TCS220177

Caretta, M.A., Mukherji, A., Arfanuzzaman, M., R.A. Betts, A.G., Hirabayashi, Y., Lissner, T.K., Liu, J., Gunn, E.L., Morgan, R., Mwanga, S., Supratid, S., 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Developments in Petroleum Science. Cambridge University Press, Cambridge, UK and New York. https://doi.org/doi:10.1017/9781009325844.006

Galavi, H., Kamal, M.R., Mirzaei, M., Ebrahimian, M., 2019. Assessing the contribution of different uncertainty sources in streamflow projections. Theor. Appl. Climatol. 137, 1289–1303. https://doi.org/10.1007/s00704-018-2669-0

Hawkins, E., Sutton, R., 2009. The potential to narrow uncertainty in regional climate predictions. Bull. Am. Meteorol. Soc. 90, 1095–1107. https://doi.org/10.1175/2009BAMS2607.1

Illangasingha, S., Koike, T., Rasmy, M., Tamakawa, K., 2023. A holistic approach for using global climate model (GCM) outputs in decision making. J. Hydrol. 626, 130213. https://doi.org/10.1016/j.jhydrol.2023.130213

IPCC, 2023. Summary for Policymakers: Synthesis Report. Clim. Chang. 2023 Synth. Report. Contrib. Work. Groups I, II III to Sixth Assess. Rep. Intergov. Panel Clim. Chang. 1–34.

IPCC, 2022. Summary for Policymakers-Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. https://doi.org/doi:10.1017/9781009325844.001

Jack, S., Purkey, D., 2005. Water Evaluation And Planning System -USER GUIDE, Weap (Water Evaluatin and Planning system) User Guide. Stockholm Environment Institute.

Li, Y., Lu, H., Yang, K., Wang, W., Tang, Q., Khem, S., Yang, F., Huang, Y., 2021. Meteorological and hydrological droughts in Mekong River Basin and surrounding areas under climate change. J. Hydrol. Reg. Stud. 36, 100873. https://doi.org/10.1016/j.ejrh.2021.100873

Ludwig, R., May, I., Turcotte, R., Vescovi, L., Braun, M., Cyr, J.F., Fortin, L.G., Chaumont, D., Biner, S., Chartier, I., Caya, D., Mauser, W., 2009. The role of hydrological model complexity and uncertainty in climate change impact assessment. Adv. Geosci. 21, 63–71. https://doi.org/10.5194/adgeo-21-63-2009

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Eighth Conf. Appl. Climatol. https://doi.org/https://climate.colostate.edu/pdfs/relationshipofdroughtfrequency.pdf

Nyunt, C.T., Koike, T., Yamamoto, A., 2016. Statistical bias correction for climate change impact on the basin scale precipitation in Sri Lanka, Philippines, Japan and Tunisia. Hydrol. Earth Syst. Sci. Discuss. 1–32. https://doi.org/10.5194/hess-2016-14

Randall, D.., Wood, R.., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., Taylor, K.E., 2007. Climate Models and Their Evaluation. IPCC Fourth Assess. Rep. Clim. Chang. 2007.

Rasmy, M., Sayama, T., Koike, T., 2019. Development of water and energy Budget-based Rainfall-Runoff-Inundation model (WEB-RRI) and its verification in the Kalu and Mundeni River Basins, Sri Lanka. J. Hydrol. 579, 124163. https://doi.org/10.1016/j.jhydrol.2019.124163

Rollason, E., Sinha, P., Bracken, L.J., 2021. Interbasin water transfer in a changing world: A new conceptual model. Prog. Phys. Geogr. 0, 1–27. https://doi.org/10.1177/03091333211065004

Selvarajah, H., Koike, T., Rasmy, M., Tamakawa, K., Yamamoto, A., Kitsuregawa, M., Zhou, L., 2021. Development of an integrated approach for the assessment of climate change impacts on the hydro-meteorological characteristics of the mahaweli river basin, Sri Lanka. Water (Switzerland) 13. https://doi.org/10.3390/w13091218

Sirisena, T.A.J.G., Maskey, S., Bamunawala, J., Ranasinghe, R., 2021. Climate Change and Reservoir Impacts on 21st-Century Streamflow and Fluvial Sediment Loads in the Irrawaddy River, Myanmar. Front. Earth Sci. 9, 1–16. https://doi.org/10.3389/feart.2021.644527

UN-SPIDER, 2022. Agriculture Drought Monitoring and Hazard Assessment using Google Earth Engine [WWW Document]. Agric. Drought Monit. Hazard Assess. using Google Earth Engine Disclaimer. URL https://www.un-spider.org/advisory-support/recommended-practices/recommended-practice-agriculture-drought-monitoring/in-detail

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P., Krayer von Krauss, M.P., 2003. Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integr. Assess. 4, 5–17. https://doi.org/10.1076/iaij.4.1.5.16466