Uncertainty in Climate Projection Indicators for Flood Risk Assessment of Dam Infrastructure

Jack W. Warden[1], M. Reza Najafi[2] and Hamidreza Shirkhani[3]
Department of Civil and Environmental Engineering, Faculty of Engineering, Western University, London, Ontario, Canada N6A 5B9[1,2]
E-mail: jwarden6@uwo.ca[1]
E-mail: mnajafi7@uwo.ca[2]

National Research Council of Canada, Ottawa, Canada[3]
E-mail: hamidreza.shirkhani@nrc-cnrc.gc.ca[3]

ABSTRACT

Projected changes in extreme precipitation are increasingly considered in dam safety and flood risk assessments, yet substantial uncertainty limits their direct application in engineering practice. This study evaluates climate model uncertainty in precipitation-based indicators relevant to flood impact assessment for dams. Using a multi-model ensemble of dynamically downscaled climate projections under a single emissions scenario, flood-relevant indicators describing extreme magnitude, frequency, and accumulation are derived and analyzed. Uncertainty is quantified as inter-model variability, enabling assessment of confidence in projected changes. Results emphasize the importance of uncertainty-aware interpretation of climate indicators to support robust, climate-informed dam safety evaluations.

KEYWORDS: Climate Change, Flooding, Dam Safety, Infrastructure,

1 INTRODUCTION

Design and safety assessment of dam infrastructure increasingly require consideration of projected changes in extreme precipitation under a changing climate. Climate projections provide critical information for evaluating future flood hazards; however, their direct application in impact assessments is complicated by substantial uncertainty, particularly in metrics relevant to dam safety such as extreme rainfall magnitude and frequency (Fluixá-Sanmartín et al., 2018; IPCC, 2021; Myhre et al., 2019).

For engineering applications, it is not sufficient to identify projected changes alone. Understanding how uncertainty propagates into flood-relevant indicators is essential for interpreting projection reliability and for supporting robust, climate-informed dam design and management decisions (Fluixá-Sanmartín et al., 2018; Ozkan et al., 2023). This research focuses on evaluating climate model uncertainty in precipitation-based indicators used for flood impact assessment, with an emphasis on their relevance to dam safety.

2 CLIMATE DATA AND PROJECTION FRAMEWORK

This study employs a multi-model ensemble of dynamically downscaled regional climate projections evaluated under a single emissions scenario. All simulations are analyzed on a common spatial grid and within a consistent modelling framework to isolate uncertainty arising from climate model structure rather than from scenario differences or internal variability.

Projected changes are assessed across historical and future periods, allowing comparison of baseline and future climate conditions relevant to flood risk. Future periods are based on the use of a Global Warming Levels approach. This approach reflects the structure of many climate datasets commonly used in applied engineering studies and supports direct interpretation of model-driven uncertainty (Bush & Lemmen, 2019; Seneviratne et al., 2016).

3 FLOOD RELEVANT CLIMATE INDICATORS

A suite of precipitation-based climate indicators relevant to dam safety and flood impact assessment is derived from the climate projections. These indicators are selected to reflect key hydrological stressors influencing dam performance, including:

- Magnitude of extreme precipitation events,
- Frequency of threshold exceedance,
- Accumulation-based metrics associated with flood generation.

Indicator selection and formulation are informed by established climate-impact frameworks and dam safety literature, including CLIMDEX-based indices and extreme-event metrics commonly used in infrastructure assessments (ETCCDI, n.d.; Fluixá-Sanmartín et al., 2018; Myhre et al., 2019). Indicators are computed consistently across all models to ensure comparability of projected changes and associated uncertainty.

4 QUANTIFICATION OF MODEL UNCERTAINTY

Uncertainty in projected changes is quantified as inter-model variability across the ensemble of climate projections. For each indicator, uncertainty is evaluated using variance-based metrics that characterize the spread of model responses relative to the ensemble mean, providing a direct measure of confidence in the projected signal (Ozkan et al., 2023; Schwarzwald & Lenssen, 2022).

By focusing exclusively on climate model structural uncertainty, this analysis provides a clear assessment of how differences in model formulation and physical representation influence projected changes in flood-relevant indicators. This targeted focus avoids conflating uncertainty sources and enables transparent interpretation of projection confidence for impact assessment purposes, consistent with current engineering-facing climate analyses (Fluixá-Sanmartín et al., 2018; Seneviratne et al., 2016).

5 APPLICATION TO DAM SAFETY AND FLOOD RISK DECISION MAKING

The quantified uncertainty in climate indicators is evaluated in the context of dam safety and flood impact assessment. Results highlight how model uncertainty varies across indicators and spatial domains, influencing confidence in projected changes relevant to design thresholds and operational decision-making (Bush & Lemmen, 2019; Ozkan et al., 2023).

Rather than prescribing deterministic future values, this work emphasizes uncertainty-aware interpretation of climate projections. By identifying indicators with relatively robust signals versus those dominated by model spread, the analysis supports more defensible use of climate information in dam safety evaluations.

To facilitate exploration and interpretation of results, the indicator calculations and uncertainty metrics are implemented within a web-based interface, which is currently in development. The tool functions as a visualization and analysis platform, allowing users to interactively examine projected changes and associated uncertainty across indicators and locations. The scientific analysis, however, remains independent of the delivery mechanism.

6 CONCLUSIONS AND FUTURE WORK

This research presents a structured assessment of climate model uncertainty in flood-relevant precipitation indicators used for dam impact assessment. By centering on indicators, projections, and uncertainty quantification, the work advances scientific understanding of how climate projection uncertainty affects flood resilience evaluations for dam infrastructure. This work has let to the development of a comprehensive dataset of indicator projections, along with their associated uncertainties. This data will provide a valuable resource to practitioners working with dams, allowing them to assess potential risks through the interface currently under development.

Future work will extend this framework to additional indicators and uncertainty sources, including emissions scenario uncertainty and internal climate variability, to support more comprehensive climate-informed dam safety assessments.

7 ACKNOWLEDGEMENTS

The authors acknowledge the support from the Climate Resilient Built Environment initiative of the National Research Council Canada for this study

REFERENCES

Bush, E., & Lemmen, D. S. (2019). *Canada's Changing Climate Report*. Government of Canada.

ETCCDI. (n.d.). *Climdex*. Retrieved March 10, 2025, from https://www.climdex.org/

Fluixá-Sanmartín, J., Altarejos-García, L., Morales-Torres, A., & Escuder-Bueno, I. (2018). Review article: Climate change impacts on dam safety. *Natural Hazards and Earth System Sciences*, *18*(9), 2471–2488. https://doi.org/10.5194/nhess-18-2471-2018

Intergovernmental Panel On Climate Change. (2021). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157896

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M., & Stohl, A. (2019). Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports*, *9*(1), 16063. https://doi.org/10.1038/s41598-019-52277-4

Ozkan, I., Kadhom, B., Roshani, E., Shirkhani, H., Hiedra-Cobo, J., Cusson, D., & Nkinamubanzi, P.-C. (2023). *Adaptation of dams to climate change: Gap analysis* (p. 194 p.). National Research Council of Canada. Construction Research Centre. https://doi.org/10.4224/40002994

Schwarzwald, K., & Lenssen, N. (2022). The importance of internal climate variability in climate impact projections. *Proceedings of the National Academy of Sciences*, *119*(42), e2208095119. https://doi.org/10.1073/pnas.2208095119

Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R., & Wilby, R. L. (2016). Allowable CO2 emissions based on regional and impact-related climate targets. *Nature*, *529*(7587), Article 7587. https://doi.org/10.1038/nature16542