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A hybrid quantile deep learning ensemble framework catering to streamflow uncertainty and extreme events

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Abstract: Recent floods in the New South Wales region of Australia provide evidence of increasing hydrological extremes driven by climate change. Accurate streamflow modelling, especially extreme flows, is critical for water resource management and flood predictions. Traditionally, conceptual hydrological models such as GR4J have served as reliable tools for streamflow simulation due to their parsimonious structure and interpretability. However, these models often struggle to capture the dynamics of extreme flow and lack the ability to leverage multiple data sources. Alternatively, machine learning methods have shown promising results with the ability to learn complex data patterns, with the ability to leverage various data sources at once, but lack interpretability of conceptual models. In our previous work, we introduced a hybrid rainfall-runoff model called DeepGR4J (Kapoor et al. 2023) that enhanced the GR4J rainfall-runoff model by substituting its routing component with a deep learning architecture, resulting in improved predictive accuracy, especially in arid catchments. Despite outperforming the traditional models, DeepGR4J lacked a robust method to quantify predictive uncertainty, which is crucial for reliable flood forecasting.

In this study, we propose an ensemble quantile-based extension of DeepGR4J called QDeepGR4J that integrates quantile regression into the hybrid modelling framework to quantify predictive uncertainty in streamflow predictions. QDeepGR4J employs an ensemble of hybrid quantile deep learning architectures that together predict multiple streamflow quantiles (e.g., 5th, 50th, and 95th percentiles), thereby constructing a 90% prediction interval to capture data uncertainty. We construct an ensemble using various neural network architectures, such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, trained using a hierarchical approach. This approach first calibrates the GR4J production storage parameters via differential evolution and then trains the neural networks with a tilted loss function appropriate for quantile regression. We evaluate the model's performance using the CAMELS-AUS dataset (Fowler et al. 2021), a large-scale hydrometeorological dataset covering 222 Australian catchments with diverse climate and physiographic conditions.

The results show that the proposed QDeepGR4J ensemble improve the predictive accuracy (as measured by Nash-Sutcliffe Efficiency & Root Mean Squared Error) and uncertainty interval quality (as measured by interval score) compared to baseline quantile deep learning ensembles. A qualitative measure of flood risk is computed and evaluated against the observed streamflow extremes. The evaluation results demonstrate the suitability of the QDeepGR4J ensemble as an early warning system for flood events. Our experiments show that QDeepGR4J achieves high True Positive Rates (TPR) in identifying flood events at 3-year and 5-year recurrence intervals. Therefore, QDeepGR4J represents a significant step toward more reliable and interpretable streamflow forecasting, with important implications for flood risk management.

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