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Spatially weighted fine-tuning of LSTMs for improved streamflow predictions in ungauged catchments

Ashkan Shokri[1], **James C. Bennett**[1] **and David E. Robertson**[1]

[1]*Commonwealth Scientific and Industrial Research Organisation (CSIRO), Clayton 3168, Australia*
Email: ash.shokri@csiro.au

Abstract: Long Short-Term Memory (LSTM) networks can outperform both the Bureau of Meteorology's Australian Water Resources Assessment–Landscape (AWRA-L) and widely used conceptual models such as GR4J across many Australian catchments. When trained across hundreds of basins (equally weighted), LSTMs learn generalisable hydrological patterns and can produce reliable predictions even in ungauged basins. However, as our earlier experiments (Shokri et al., 2025) show, performance in spatially out-of-sample (SooS) evaluations remains heterogeneous: some catchments perform very well, while others, particularly in drier or more hydrologically unique regions, perform poorly. This lower tail of the distribution is a key challenge for national-scale prediction.

A parallel experiment with the GR4J model suggested a potential remedy. Using an inverse-distance-squared weighted (IDW) regionalisation, where parameters for an ungauged basin were inferred from nearby calibrated catchments, GR4J avoided very poor predictions and improved performance in underperforming basins. This indicates spatially weighted local information can improve predictions where purely global calibration underperforms.

We extend this idea to LSTM models via two stages: (i) training a single continental-scale LSTM on all CAMELS-AUS catchments to learn broad hydrological patterns; and (ii) applying spatially informed fine-tuning for each left-out (ungauged) catchment. In this fine-tuning stage, the model updates on donor catchments, with training loss weighted by spatial proximity using an IDW scheme. This design allows the LSTM to retain large-sample training benefits while adapting to regional hydrological behaviour.

We hypothesis that IDW-weighted fine-tuning of LSTMs will lift the performance in previously poorly performed catchments. For catchments that already perform well, we expect minimal change, but for poorly performed catchments we expect measurable improvement.

We test this hypothesis using the CAMELS-AUS (Fowler et al., 2021) dataset, comprising 218 minimally impacted catchments across Australia, under spatially and spatiotemporally out-of-sample validation. Model evaluation focuses on NSE and bias metrics across the catchment distribution. Comparisons are drawn against (a) globally trained LSTM with no fine-tuning, (b) GR4J with IDW regionalisation. This design allows us to quantify the added value of spatial weighting for LSTM fine-tuning, while benchmarking against established conceptual model strategies.

We saw improvement in results in general in spatially out-of-sample tests. Spatially weighted fine-tuning of LSTMs shifted the overall NSE distribution upwards, with gains evident across much of the catchment population. While low NSE scores were still present, the fine-tuning consistently improved performance compared to the baseline continental LSTM. This demonstrates that combining large-sample machine learning with regionalised weighting finetuning can deliver broad performance gains and improve reliability in many basins, though challenges remain in the lowest-performing catchments.

This study contributes a novel methodological advance by introducing distance-weighted loss functions into the fine-tuning of deep learning models for hydrology. More broadly, it illustrates how concepts from regionalisation in conceptual modelling can be translated into data-driven approaches.

Keywords: *Hydrological modelling, ungauged catchment, deep learning, long short-term memory (LSTM)*

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