Advancing AI and Deep Learning Applications in Hydrological Prediction: Insights on Regional Model Development

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The EGU General Assembly 2025

HS: Hydrological Sciences

HS3.6: Hydroinformatics: data analytics, machine learning, hybrid modelling, optimisation

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Optimization of Regional Hydrological Models

Optimized vs. Not Optimized!

Aim: Achieve the Highest Possible Accuracy in Predictions.

Regional Hydrology (e.g., Rainfall–Runoff Modeling) requires:

→ Simultaneous, accurate prediction of multiple timeseries across many locations.

This is a Multi-Objective Task.

It requires a Multi-Objective Optimization Approach.

Deep Learning (DLs) in Regional Hydrology

For Prediction, Deep Neural Networks (e.g., LSTMs, Transformers,…) have taken the lead.

📖 LSTMs outperform both regionally and individually calibrated physical hydrological models (Kratzert et al., 2024).

🧠 **But a critical question remains:**

Why do regional DL models perform exceptionally well in some catchments, but poorly in others? (Beven, 2020).

What brings Intelligence in a DNN is actually the Network!
The Network is shaped by Hyperparameters.

An imagination of a Deep Neural Network (DNN)

A Deep Neural Network (DNN) Architecture

Hyperparameters:

Network Settings that **Significantly Govern the Training Process** of a Learning Algorithm but **are not learned directly from the data during training.**

Hyperparameter Optimization is crucial in DNNs (Bergstra & Bengio, 2012).

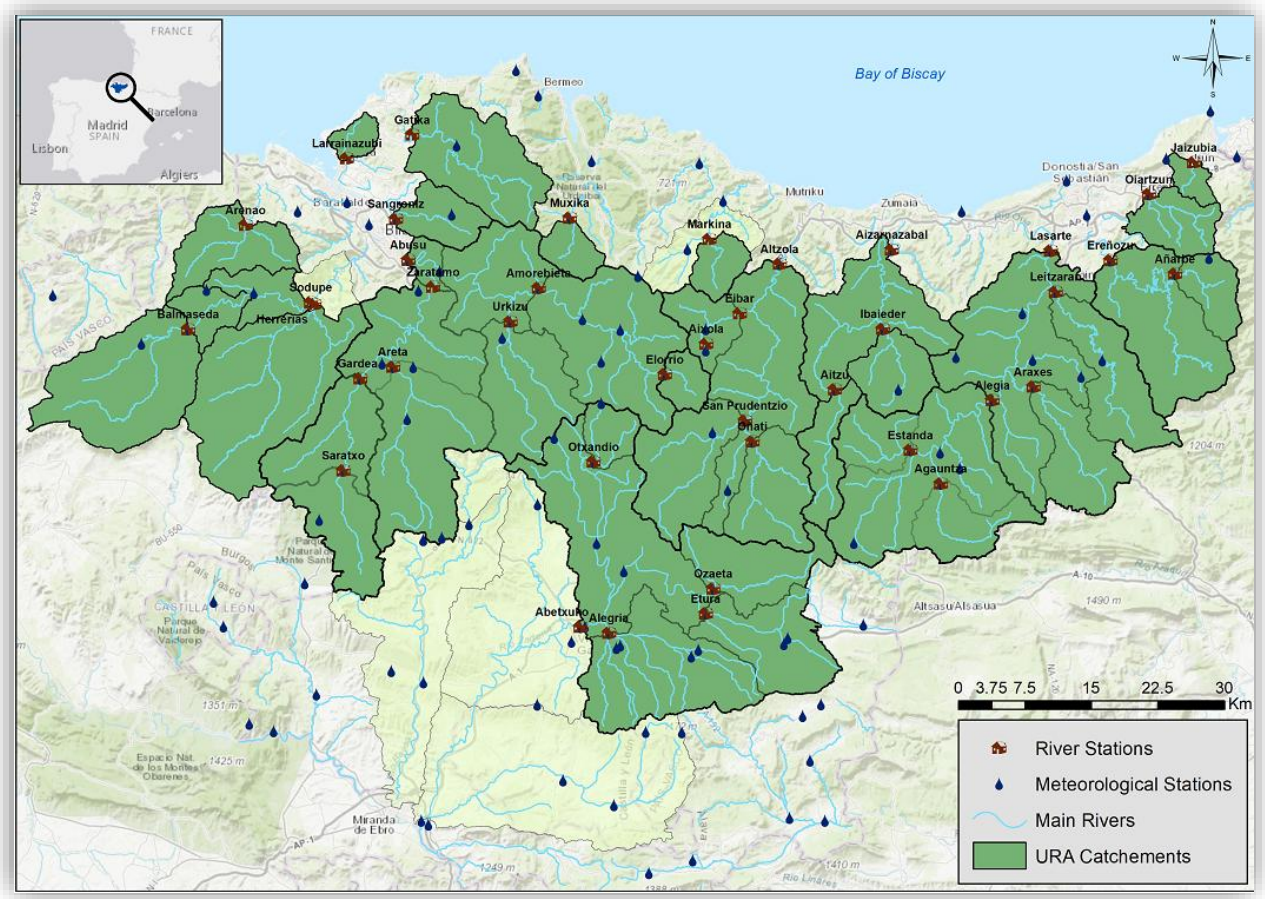
To Optimize LSTMs for Regional Rainfall-Runoff Modeling

- **40 Catchments in Basque Country, north of Spain**
- **Humid and Flashy**
- **A New High-Quality Hourly Dataset**

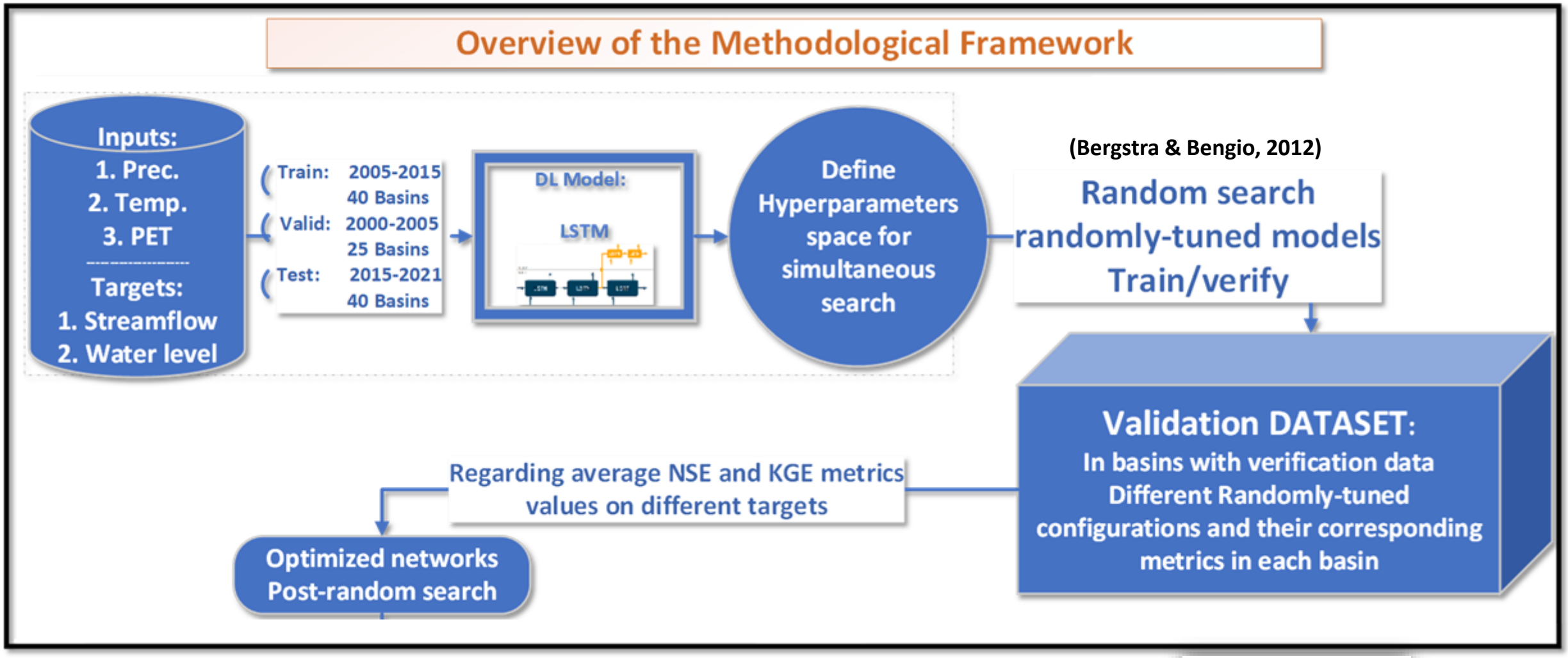
Available at your hands!

👉

CASE STUDY



Overview of the Methodological Framework

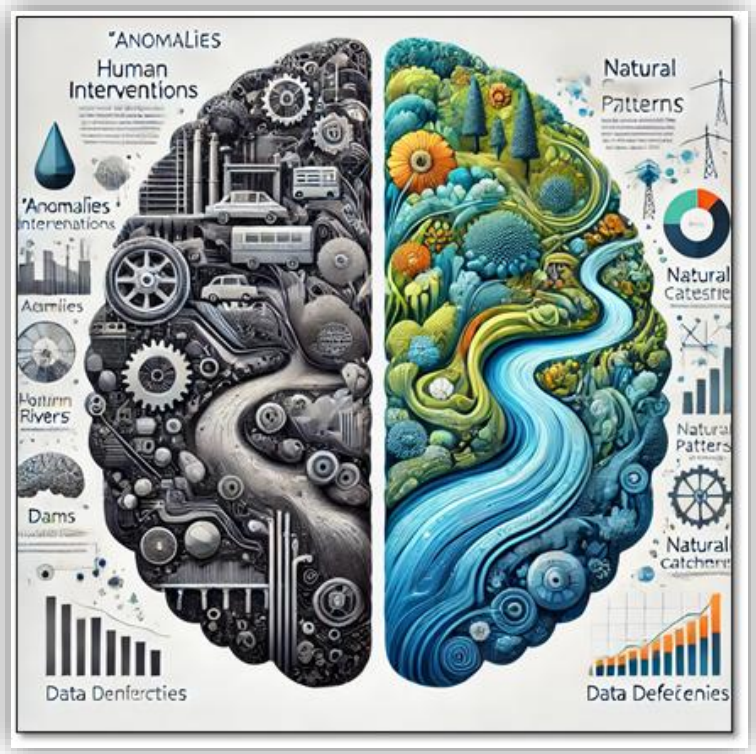


Post-Random Search Hyperparameter Optimization

- 📝 **Random Search efficiently** explores diverse regions of the hyperparameter space → **yielding multiple optimized regional DNNs**, each **statistically significantly different** in performance across catchments.

- One DNN may specialize in anomalous behaviors (e.g., human interventions,…).

- Another may capture natural flow regimes more effectively.



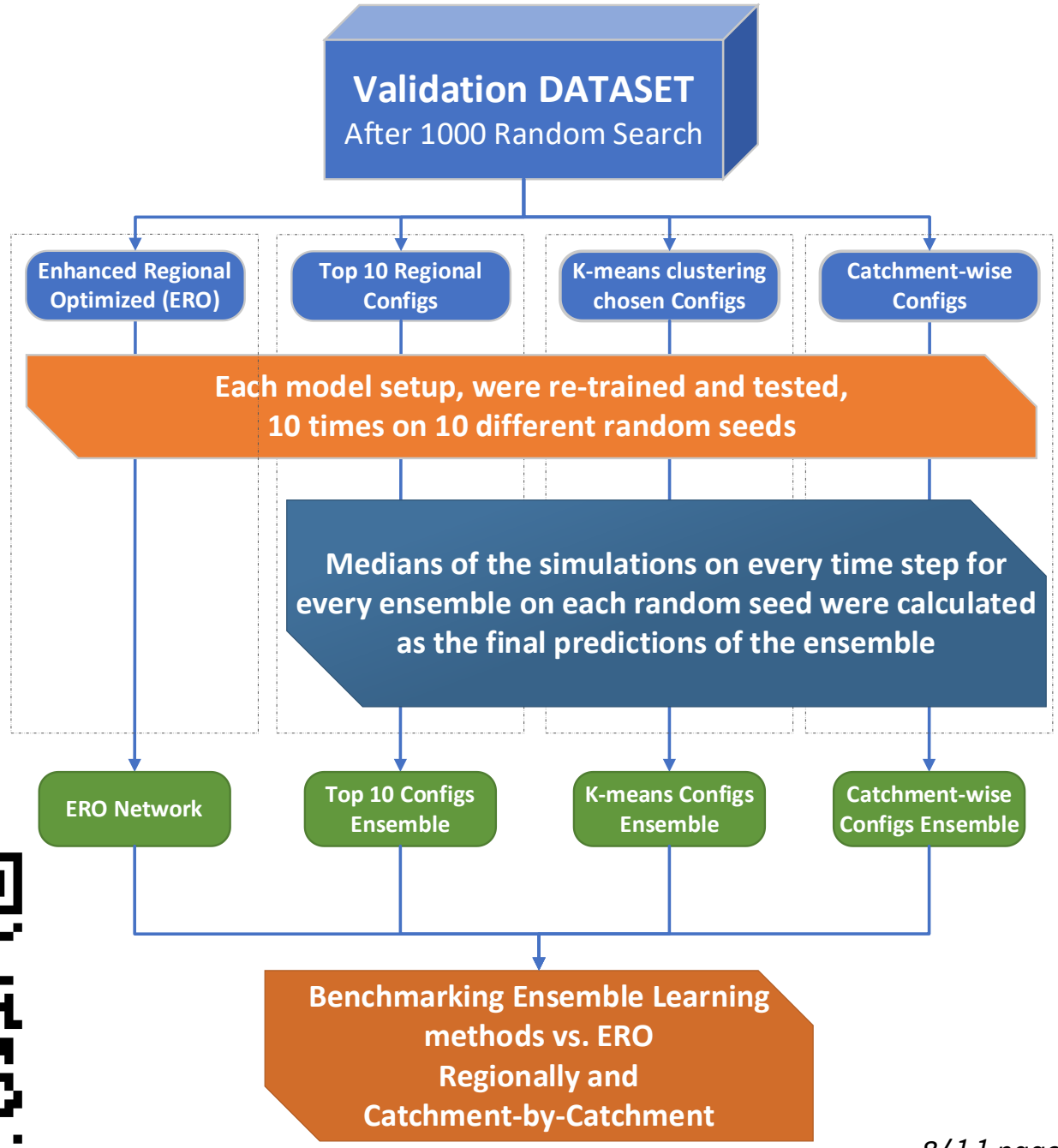
📌 Key Finding:

Different optimized regional DNNs "think and perform" differently across catchments — Reflecting Beven's "Uniqueness of the Place" paradigm (2000; 2020).

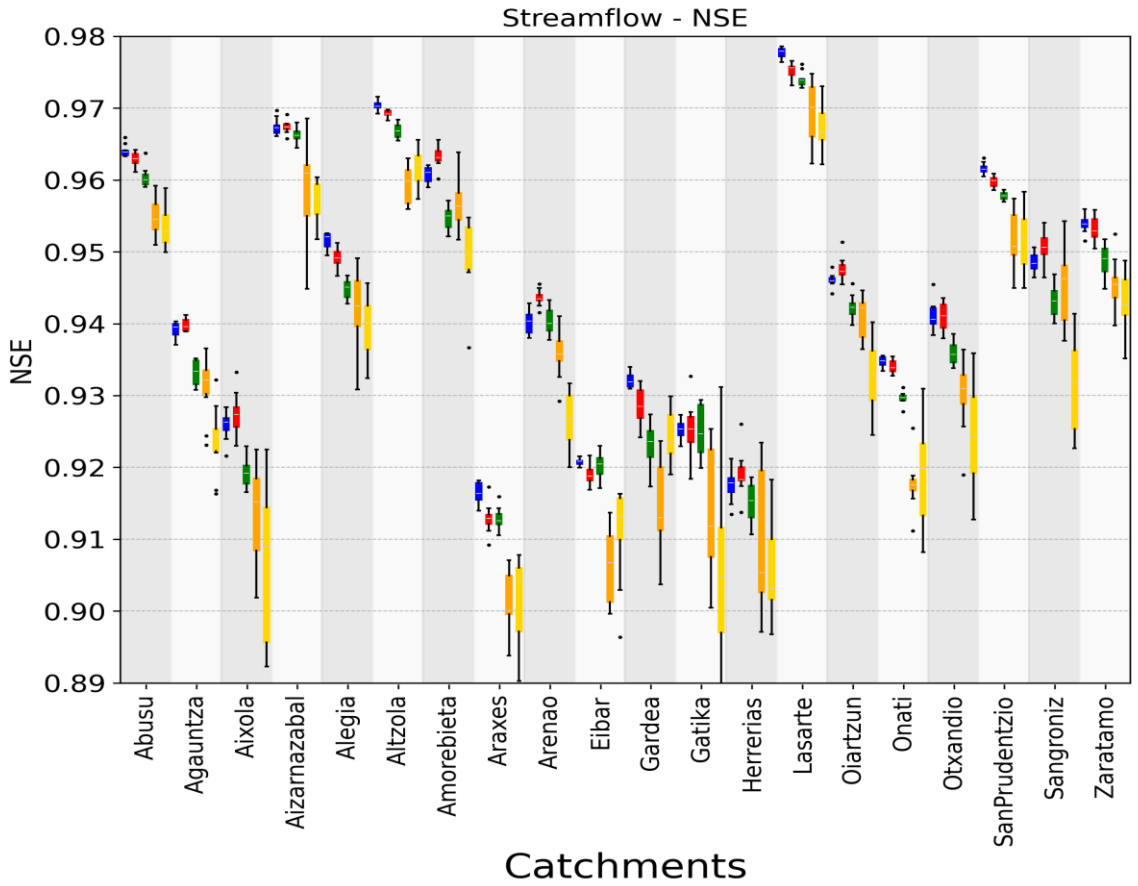
Ensemble Deep Learning

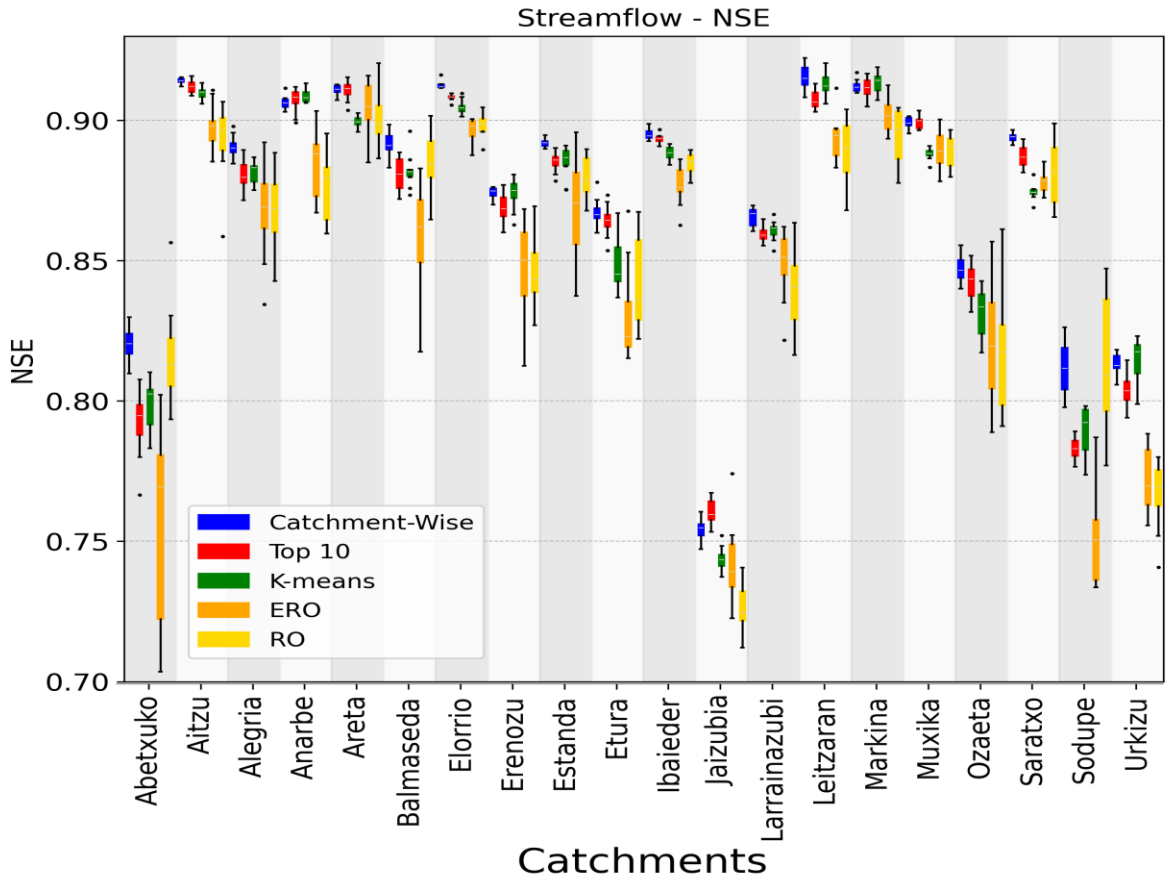
🧪 Hypothesis:

The collective synergy — or "crowd wisdom" — of multiple regionally optimized LSTM networks outperforms any single optimized LSTM network for regional hydrological prediction.

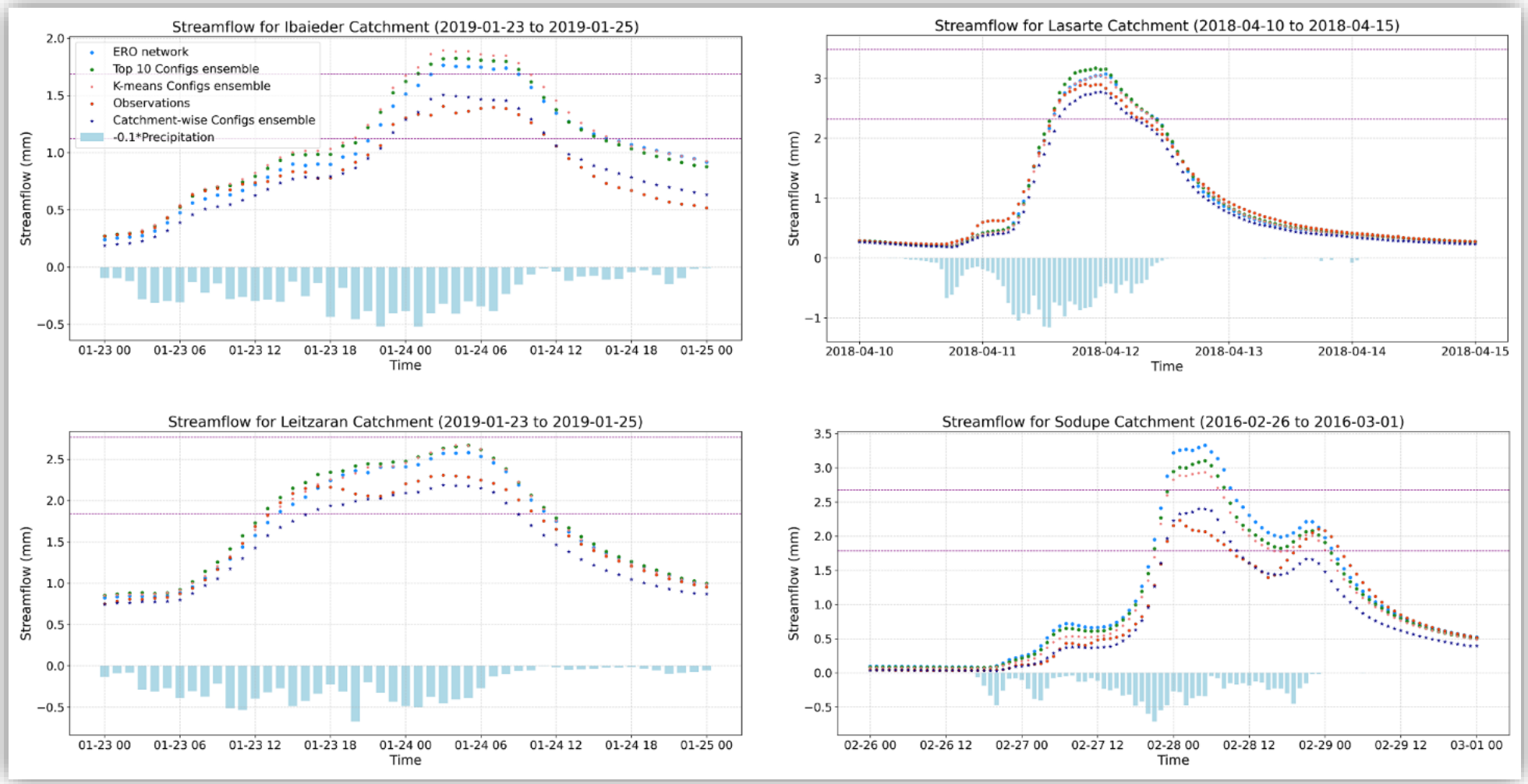


Ensemble Deep learning
Robustness & Higher Accuracy of the Results





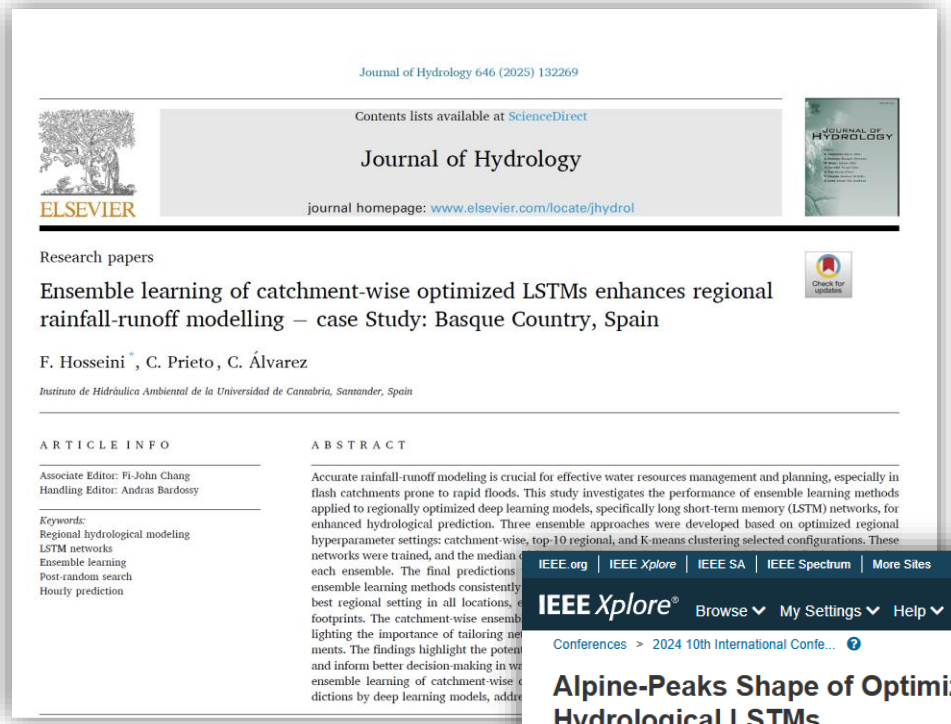
Catchment-Wise Ensemble Improves Hydrographs for events



- The **<u>catchment-wise ensemble</u> significantly reduces overestimation tendencies of LSTMs during peak flow events**, yielding predictions that better align with observed values.

Find out more details on our publications:

Including: Methods, Results, Codes, Data,…



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Research papers

Ensemble learning of catchment-wise optimized LSTMs enhances regional rainfall-runoff modelling – case Study: Basque Country, Spain

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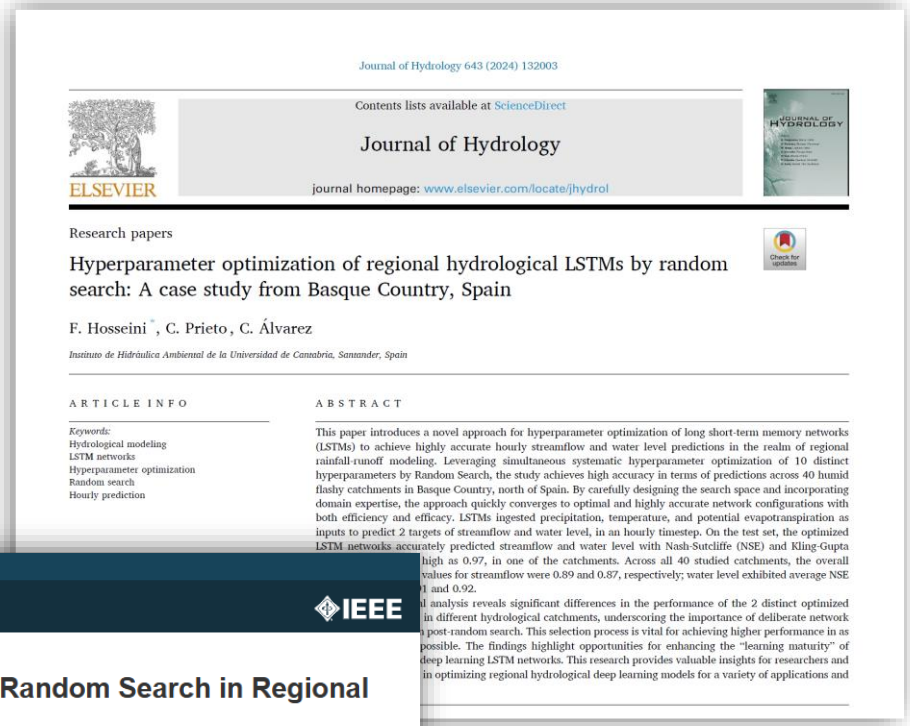
Post-random search
Hourly prediction

ABSTRACT

Accurate rainfall-runoff modeling is crucial for effective water resources management and planning, especially in flash catchments prone to rapid floods. This study investigates the performance of ensemble learning methods applied to regionally optimized deep learning models, specifically long short-term memory (LSTM) networks, for enhanced hydrological prediction. Three ensemble approaches were developed based on optimized regional hyperparameter settings: catchment-wise, top-10 regional, and K-means clustering selected configurations. These networks were trained, and the median d
each ensemble. The final predictions
ensemble learning methods consistently
best regional setting in all locations,
footprints. The catchment-wise ensemb
lighting the importance of tailoring ne
ments. The findings highlight the poten
and inform better decision-making in w
ensemble learning of catchment-wise
dictions by deep learning models, addr



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Research papers

Hyperparameter optimization of regional hydrological LSTMs by random search: A case study from Basque Country, Spain

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ARTICLE INFO

Keywords:
Hydrological modeling
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ABSTRACT

This paper introduces a novel approach for hyperparameter optimization of long short-term memory networks (LSTMs) to achieve highly accurate hourly streamflow and water level predictions in the realm of regional rainfall-runoff modeling. Leveraging simultaneous systematic hyperparameter optimization of 10 distinct hyperparameters by Random Search, the study achieves high accuracy in terms of predictions across 40 humid flashy catchments in Basque Country, north of Spain. By carefully designing the search space and incorporating domain expertise, the approach quickly converges to optimal and highly accurate network configurations with both efficiency and efficacy. LSTMs ingested precipitation, temperature, and potential evapotranspiration as inputs to predict 2 targets of streamflow and water level, in an hourly timestep. On the test set, the optimized LSTM networks accurately predicted streamflow and water level with Nash-Sutcliffe (NSE) and Kling-Gupta
high as 0.97, in one of the catchments. Across all 40 studied catchments, the overall
values for streamflow were 0.89 and 0.87, respectively; water level exhibited average NSE
1 and 0.92.
l analysis reveals significant differences in the performance of the 2 distinct optimized
in different hydrological catchments, underscoring the importance of deliberate network
post-random search. This selection process is vital for achieving higher performance in as
possible. The findings highlight opportunities for enhancing the "learning maturity" of
deep learning LSTM networks. This research provides valuable insights for researchers and
in optimizing regional hydrological deep learning models for a variety of applications and

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Alpine-Peaks Shape of Optimized Configurations Post Random Search in Regional Hydrological LSTMs

Publisher: IEEE Cite This PDF

Farzad Hosseini Hossein Abadi ; Cristina Prieto Sierra ; Cesar Álvarez Díaz All Authors

32 Full Text Views

Abstract

Document Sections

I. Introduction

II. Method and Materials

III. Results

Abstract:

In hydrological prediction, Long Short-Term Memory networks (LSTMs) hold promise, yet precise hyperparameter tuning remains challenging, especially for regional prediction across multiple catchments. This study addresses the challenge by employing a random search approach to simultaneously tune 10 distinct hyperparameters with two learning rate schedules, for hourly streamflow and water level predictions across 40 catchments in Basque Country, Spain. Exploration of 1000 random configurations revealed an optimization landscape akin to Alpine peaks in the hyperparameters space, with promising settings emerging, each showing high accuracy in several basins, but not everywhere. Post-random search analysis identified top-

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PREVIEW
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Advancing AI and Deep Learning Applications in Hydrological Prediction: Insights on Regional Model Development

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The application of artificial intelligence and deep learning (DL) in hydrological sciences presents significant challenges and opportunities, particularly in regional and large-scale modeling. Building on the foundational works of Valiela (2000) and Beven (2020)—which underscore the importance of catchment-wise performance evaluation and uniqueness of the place in regional model comparisons—this study investigates nuanced implementation of deep neural networks (DNNs), specifically Long Short-Term Memory (LSTM), for regional rainfall-runoff predictions. Insights from recent advancements in LSTM-based rainfall-runoff modeling (Kratzert et al., 2024) and ensemble learning of catchment-wise regional LSTMs (Hosseini et al., 2024, 2025) emphasize the critical role of network architecture and training strategies.

Findings reveal regionally optimized DNNs with identical neurons (e.g., LSTM cells) but differing architectures (hyperparameters) can exhibit meaningfully distinct behaviors on the same dataset. For instance, one model captured region-wide generalizable patterns by greedily prioritizing overall accuracy in natural basins but underperforming in specific catchments. While another optimized version emphasized on anomalies (e.g., data deficiencies or snow processes) or human-induced influences (regulated flows), leading to improved accuracy in specific locations. Ensemble deep learning, combined with systematic hyperparameter optimization of regional LSTMs, effectively mitigates these discrepancies by synthesizing diverse learning perspectives into robust and accurate predictions, align with “wisdom of the crowd” principle (Surowiecki, 2004). This approach enhances the potential scalability of “one-size-fits-all” large-scale hydrological DNN, advancing the development of high-accuracy regional hydrological models.

Despite computational challenges, the findings underscore the potential of large-scale hydrological models powered by intelligent agents, environment-aware frameworks (Russell & Norvig, 2020), emphasizing the transformative interplay of DL architectures, ensemble strategies, and scalability in AI-driven hydrological modeling.

References

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Kratzert, F., et al., 2024, HESS Opinions: Never train a Long Short-Term Memory (LSTM) network on a single basin, HESS, 28 (17), pp. 4187-4201

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Hosseini, F., et al., 2025, Ensemble learning of catchment-wise optimized LSTMs enhances regional rainfall-runoff modelling. *Jhydrol*, *646*, 132269. 10.1016/j.jhydrol.2024.132269

Surowiecki, J., 2004, The Wisdom of Crowds: Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies, and Nations. Doubleday.

Russell, S., & Norvig, P., 2020. Artificial intelligence: A modern approach. Pearson

Supplementary Document for EGU25 Abstract Presentation

Advancing AI and Deep Learning Applications in Hydrological Prediction: Insights on Regional Model Development

***Hosseini, F.**, Prieto, C., and Álvarez, C. (2025): Advancing AI and Deep Learning Applications in Hydrological Prediction: Insights on Regional Model Development, EGU General Assembly 2025, Session HS3.6: Hydroinformatics: data analytics, machine learning, hybrid modelling, optimization, Vienna, Austria, 27 Apr–2 May 2025, EGU25-2018, https://doi.org/10.5194/egusphere-egu25-2018, 2025.*

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We are pleased to share the outcomes of our PhD research project focusing on deep learning in hydrology and rainfall-runoff modeling with the esteemed EGU community.

This abstract presentation offers a very concise overview of recently published papers and ongoing research in this field, including our developed methodologies and key findings on the behavior of deep neural networks (LSTMs) in regional hydrology. For those interested in a deeper dive, we invite you to explore the following publications and resources:

Published Works

- **Hosseini, F., Prieto, C., & Álvarez, C. (2025).**
  Ensemble learning of catchment-wise optimized LSTMs enhances regional rainfall-runoff modeling.
  ***Journal of Hydrology**, 132269.*
  https://doi.org/10.1016/j.jhydrol.2024.132269
- **Hosseini, F., Prieto, C., & Álvarez, C. (2024).**
  Hyperparameter optimization of regional hydrological LSTMs by random search.
  ***Journal of Hydrology**, 132003.*
  https://doi.org/10.1016/j.jhydrol.2024.132003
- **Hosseini, F., Prieto, C., & Álvarez, C. (Pre-print under review, 2025).**
  An Explainable AI Approach for Interpreting Regionally Optimized Deep Neural Networks in Hydrological Prediction.
  Available at SSRN:
  https://ssrn.com/abstract=5195507
  or http://dx.doi.org/10.2139/ssrn.5195507

- **Hosseini, F., Prieto, C., & Álvarez, C. (2024, Oct. 17–18).**
  Alpine-peaks shape of optimized configurations post random search in regional hydrological LSTMs.
  *10th **IEEE International Conference on Optimization and Applications** (ICOA), Almería, Spain.*
  https://doi.org/10.1109/ICOA62581.2024.10754182
- **Hosseini, F., Prieto, C., Nearing, G., Álvarez, C., & Gauch, M. (2024, Apr. 14–19).**
  Hydrological significance of input sequence lengths in LSTM-based streamflow prediction.
  ***EGU General Assembly 2024**, Vienna, Austria.*
  https://doi.org/10.5194/egusphere-egu24-571
- **Hosseini, F., Prieto, C., & Álvarez, C. (2024, Dec. 9–13).**
  Ensemble Deep Learning Can Solve the Catchments' Uniqueness Dilemma in Regional Rainfall-Runoff Modeling.
  ***AGU Annual Meeting 2024**, Washington, D.C., USA.*
  https://agu.confex.com/agu/agu24/meetingapp.cgi/Paper/1524990

Research Dataset and Codes

- **Hosseini, F. (2024).**
  URA dataset — 40 Basque Country catchments hourly hydro-meteorological data [Dataset].
  Zenodo.
  https://doi.org/10.5281/zenodo.13220528
- **Hosseini, F. GitHub**
  https://github.com/farzadhoseini

We welcome feedback, questions, and collaboration inquiries during and after the EGU General Assembly 2025.

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