XXVI SIMPÓSIO BRASILEIRO DE RECURSOS HIDRÍCOS

CLIMATE AND CATCHMENT SIGNATURES OF THE BRAZILIAN STREAMFLOW REGIME

Abderraman R. Amorim Brandão[1], Admin Husic[2], André Almagro[3], Dimaghi Schwamback[1,4], and Paulo Tarso Sanches de Oliveira[1,3]

Palavras-Chave – Machine Learning, Aridity index, Extreme streamflow.

INTRODUCTION

Between 1970 and 2019, hydrometeorological disasters claimed more than two million lives worldwide; in South America alone, they caused 58 000 deaths and US$ 100.9 billion in economic losses—nearly 60 % from floods and 7 % from droughts (WMO, 2021). Flood generation arises from nonlinear interactions among atmospheric triggers and catchment attributes—antecedent moisture, area, geometry, land use, and rainfall characteristics—processes rarely captured by traditional studies that focus almost exclusively on precipitation (Sharma et al., 2018). Recent advances show that machine-learning techniques outperform classical hydrological models in representing these dynamics, while explainable AI methods—especially SHapley Additive exPlanations (SHAP)—quantify not only the importance but also the direction of each predictor's influence on streamflow.

Despite this progress, debate persists over which factor dominates hydrological extremes—climate forcing or catchment physical properties—compounded by the scale problem that hinders transferring laws from small to large basins (Blöschl et al., 2019). This study examines 735 Brazilian watersheds to determine whether climate variables or catchment characteristics more strongly control low (Q_5), mean (Q_{mean}), and high (Q_{95}) streamflows.

MATERIALS AND METHODS

We analysed 735 gauged catchments distributed across Brazil's ~8.5×10^6 km² territory, spanning 12 Köppen sub-climates from the humid Amazon to the semi-arid Northeast. Catchment attributes and streamflow records were extracted from the CAbra database, which provides daily discharge and 30-year normals for climate, land cover, soil, geology and topography. For each basin we derived three streamflows—low (Q_5), (Q_{mean}) and high (Q_{95}) percentiles—together with 16 candidate predictors that represent climate forcing (e.g. aridity, rainfall seasonality), landscape structure (e.g. NDVI, forest fraction), subsurface properties (porosity, permeability, soil carbon) and basin geometry (area, slope, elevation).

A Random Forest Regressor (Scikit-learn) was trained on the full dataset with stratified 10-fold cross-validation, using mean-squared error as the loss function and reporting R^2 and MSE to gauge performance. Ensemble size and tree depth followed Breiman's (2001) guidelines to balance bias and variance. Classical variable-importance scores (mean decrease in impurity) isolated the strongest controls on each flow percentile, after which SHAP values were computed to reveal how increases or decreases in each predictor shift the predicted discharge. This combination of RF and SHAP provides both robust, nonlinear prediction and mechanistic insight, allowing us to pinpoint thresholds and regional patterns that govern drought and flood behaviour across tropical South America.

RESULTS

The Random Forest models achieved high skill—$R^2 = 0.87$ for Q_5, 0.94 for Q_{mean}, and 0.93 for Q_{95}, with mean-squared errors from 0.01 to 0.67 $m^3\ s^{-1}$—indicating robust representation of flow variability across Brazil's 735 catchments. Variable-importance rankings from both RF and SHAP converge on the aridity index as the dominant control on every flow class, eclipsing the other 15 descriptors. For low flows, aridity combines with precipitation seasonality, subsurface porosity, elevation and slope to depress discharges, whereas an increase in these same catchment factors (e.g., porosity) can partially offset drought conditions. Mean flows are next most sensitive to soil organic carbon, total precipitation and basin area. High flows respond to a broader mix: low aridity, deep soils and larger bare-soil fractions amplify Q_{95}, while high aridity, sandy soils and strong rainfall seasonality dampen peaks.

Spatial SHAP maps reveal that the attribute most responsible for flow reduction flips between climate and terrain depending on region. Climate factors dominate low-flow suppression in nearly half the basins—especially the Caatinga and northeastern Cerrado—whereas catchment traits (land cover, topography, geology) control mean-flow declines in the South, Southeast and Amazon. For flood peaks, climate attributes again curb discharges in the drought-prone Northeast, but catchment structure dictates attenuation elsewhere. Biome-level diagnostics reinforce these patterns: in the Amazon, rising aridity slightly raises minimum flows but added seasonality reverses the gain; in the Cerrado, aridity and seasonality together bolster both low and high flows; in the Caatinga, heightened aridity drives lows toward zero; and in the Pantanal and Pampa, geomorphic factors (area, soil depth, porosity) can outweigh climatic penalties. Collectively, these findings confirm that while aridity is the universal first-order control, the balance between climate forcing and catchment architecture—and therefore the levers for adaptation—varies sharply among Brazil's biomes.

CONCLUSIONS

Random Forest models interpreted with SHAP show that aridity (PET/P) is the first-order control on Q_5, Q_{mean} and Q_{95} across 735 Brazilian basins: flows fall steeply once PET/P exceeds $\approx$ 1.3. Climate largely governs low flows nationwide, whereas land cover, soil and terrain dictate flood peaks in regions such as the Cerrado, Pantanal and Pampa. These findings give transferable roadmap for pinpointing drought- and flood-mitigation levers in tropical catchments.

ACKNOWLEDGEMENTS

This study was supported by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES), Finance Code 001, under the first author's grant no. 88887.184632/2025-00.

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