



Calibration Strategies for IHACRES in Data-Scarce Environments: Addressing Equifinality and Parameter Uncertainty

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Hydrological rainfall-runoff models are essential tools for simulating and predicting watershed responses to meteorological forcings by linking precipitation and climate inputs with catchment characteristics such as land cover, topography, and soil properties. By representing key hydrological processes, these models support water resources management, extreme event forecasting, and infrastructure design. In semi-arid and data-scarce environments, modelling becomes particularly challenging due to high hydroclimatic variability and ephemeral flow regimes, often associated with limited or discontinuous observational records. Under these conditions, reliable rainfall-runoff simulations are essential not only for understanding catchment dynamics but also for supporting water resource management, including reservoir operation, allocation strategies, and drought risk mitigation. Regardless of their structure, all models require parameter calibration using observed data to ensure reliable reconstruction of hydrological response; this calibration represents a critical step, especially in data-limited contexts, where parameter uncertainty and equifinality pose significant challenges.

This study investigates the impact of different calibration strategies on model performance and parameter estimation under conditions of limited and incomplete observational data in a semi-arid region. The analysis was carried out using the IHACRES model (*Identification of unit Hydrographs And Components from Rainfall, Evaporation and Streamflow*; Jakeman, 1990), a parsimonious conceptual rainfall-runoff model specifically designed for applications in data-scarce environments. IHACRES consists of a non-linear loss module that converts rainfall into effective precipitation and a linear routing module that simulates both fast and delayed runoff components. The model was slightly modified and applied to several gauged catchments in Sicily (Italy), encompassing a wide range of climatic conditions and including many ephemeral streams. Calibration experiments were performed using a Monte Carlo approach and evaluated using both single- and multi-objective frameworks. Four complementary performance metrics were adopted as objective functions: Nash-Sutcliffe Efficiency (NSE), Kling-Gupta Efficiency (KGE), relative cumulative volume error (RVE), and an error metric based on flow duration curves signatures (D^*). Single-objective calibration optimized individual metrics, whereas multi-objective configurations combined time series accuracy, water balance consistency, and flow regime representation in bi-, tri-, and tetra-objective setups. Multi-objective calibration explicitly incorporated equifinality through Pareto dominance theory, identifying non-dominated parameter sets and quantifying trade-offs among competing objectives.

Results indicate that single-objective calibration may reproduce specific hydrograph features but can misrepresent overall water availability and flow regime characteristics. In contrast, multi-objective calibration approaches can jointly constrain hydrograph dynamics, cumulative water balance, and flow regime behavior as represented by flow duration curves, leading to more reliable estimates of both high and low flows. Pareto-optimal analysis also revealed functional relationships among model parameters, suggesting opportunities to reduce parameter dimensionality and derive empirical relationships to estimate one parameter from another. This study demonstrates that multi-objective approaches offer significant advantages in explicitly addressing equifinality-driven parameter uncertainty, and that integrating Pareto-based optimization with uncertainty quantification improves the robustness and interpretability of hydrological simulations.