

Water Resources Research

RESEARCH ARTICLE

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Special Collection:

Advances in large-scale hydrological modeling and prediction under global change

Key Points:

- We present a new Large-Sample Emulator (LSE) parameter calibration and regionalization approach for land hydrology models
- LSE outperforms a local Single-Site Emulator (SSE) in calibration, and LSE-based regionalization in unseen basins improves model performance
- We introduce a large-sample hydrological method using 627 US hydrological catchments for CTSM development and evaluation

Supporting Information:

Supporting Information may be found in the online version of this article.

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On Using AI-Based Large-Sample Emulators for Land/Hydrology Model Calibration and Regionalization

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Abstract AI-based model emulators have emerged as a pragmatic strategy for calibrating Earth System models or their components (e.g., land, atmosphere, ocean), circumventing the previously insurmountable hurdle of the process-heavy models' computational expense. Such emulators require large, spatially diverse data sets for training, however, which—in the land/hydrology context—contrasts with parameter estimation approaches that have traditionally emphasized optimizing model performance for individual basins, followed by similarity-based transfer schemes for parameter regionalization. Compared to calibrating basins individually, direct land/hydrology process model calibration approaches typically perform worse when trained jointly on large collections of basins. Building on insights from large-sample deep learning hydrologic modeling, this study introduces a Large-Sample Emulator (LSE) approach that unifies and streamlines process model parameter calibration and regionalization. Tested across 627 basins in the continental United States using the Community Terrestrial Systems Model (CTSM), the LSE approach consistently improves runoff predictions in all basins, outperforming the Single-Site Emulator (SSE) in both single-objective and multi-objective calibration tasks. Moreover, LSE-based regionalization in unseen basins, evaluated through spatial cross-validation, achieves better results than the default parameters in most cases. This LSE framework offers a promising strategy for effective large-domain process-based model calibration and regionalization.

1. Introduction

Land and hydrology modeling are essential, core capabilities in myriad water research related applications, spanning local operational flood forecasting to regional multi-decadal water security, global climate risk studies and global Earth System modeling. Process-based land/hydrology models (LHMs) inevitably require calibration (i.e., “parameter estimation”) and other configuration adjustments to achieve optimal performance for application-relevant outcomes. We adopt the phrase and acronym LHM deliberately, versus either “hydrology” or “land” model, to focus attention not only on hydrology models but also the oft-overlooked hydrological aspects of an Earth System Model (ESM) land component. These models, whether focused specifically on water cycle simulation (hydrologic models) or incorporating hydrology within broader geophysical processes (land models), are critical for understanding and managing water-related challenges. Many LHM model parameters cannot be estimated directly from observations or inferred without substantial uncertainty, which makes them suitable for calibration within acceptable theoretical ranges (Gupta et al., 1999). Model calibration has been a feature of operational, applied and research hydrology since its inception in the 1950s, given its early reliance on conceptual, bulk parameterizations of physical processes and enabled by the computational efficiency of the associated models (Duan et al., 1993). The hydrology community has developed numerous parameter optimization methods (Arsenault et al., 2014; Duan et al., 1993; Gill et al., 2006; Gupta et al., 1999; Tolson & Shoemaker, 2007), but many are infeasible for complex, computationally demanding process-based (PB) models, especially over large domains for which observational constraints may be sparse. Yet large-domain LHM optimization is a pressing need (Mizukami et al., 2017; Rakovec et al., 2019), given the use of such models in regional-to-national scale applications such as water prediction and water security assessment in the continental United States (CONUS), supporting water planning and policy (Cosgrove et al., 2024). Despite recent advances in the purely artificial intelligence (AI)-based LHMs (and differentiable models, a hybrid of PB and AI) (Shen et al., 2023), PB models are desired for hydroclimate vulnerability assessment studies because they support multi-variate causal narratives describing hydroclimate trends and variability.

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