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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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Hydrology of Warm Humid Regions Unesco, 1993 **Proceedings of the Workshop on Applications of Remote Sensing in Hydrology** G. W. Kite, Anthony Wankiewicz, Canadian Climate Centre, National Hydrology Research Institute (Canada), Canadian Water Resources Association, 1990 The two principal topics of this workshop were hydrological modelling and microwave radiometry The hydrologic models session concentrated on applications of GOES NOAA and Landsat data in various hydrologic watershed models and contained discussion on means of increasing the utility of satellites for hydrologic modellers The microwave hydrology session focused on promising applications and the benefits of this method of data collection for monitoring modelling and forecasting at field and basin scales The publication includes the texts of all session presentations and related workshops A list of participants concludes the proceedings *Treatise on Water Science*, 2010-09-01 Water quality and management are of great significance globally as the demand for clean potable water far exceeds the availability Water science research brings together the natural and applied sciences engineering chemistry law and policy and economics and the Treatise on Water Science seeks to unite these areas through contributions from a global team of author experts The 4 volume set examines topics in depth with an emphasis on innovative research and technologies for those working in applied areas Published in partnership with and endorsed by the International Water Association IWA demonstrating the authority of the content Editor in Chief Peter Wilderer a Stockholm Water Prize recipient has assembled a world class team of volume editors and contributing authors Topics related to water resource management water quality and supply and handling of wastewater are treated in depth Hydrological Basis of Ecologically Sound Management of Soil and Groundwater International Union of Geodesy and Geophysics. General Assembly, 1991 Tracers in Hydrology Norman E. Peters, 1993 Hydrological Processes and Water Management in Urban Areas International Hydrological Programme. Symposium, 1990 *Coastal Hydrology and Processes* American Institute of Hydrology. Meeting, 2006 **Regionalization in Hydrology** Max A. Beran, 1990 The Hydrological Basis for Water Resources Management Uri Shamir, Chen Jiaqi, 1990

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Table of Contents Proceedings Regionalization In Hydrolo G

1. Understanding the eBook Proceedings Regionalization In Hydrolo G
 - The Rise of Digital Reading Proceedings Regionalization In Hydrolo G
 - Advantages of eBooks Over Traditional Books
2. Identifying Proceedings Regionalization In Hydrolo G
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Proceedings Regionalization In Hydrolo G
 - User-Friendly Interface
4. Exploring eBook Recommendations from Proceedings Regionalization In Hydrolo G
 - Personalized Recommendations
 - Proceedings Regionalization In Hydrolo G User Reviews and Ratings
 - Proceedings Regionalization In Hydrolo G and Bestseller Lists
5. Accessing Proceedings Regionalization In Hydrolo G Free and Paid eBooks
 - Proceedings Regionalization In Hydrolo G Public Domain eBooks
 - Proceedings Regionalization In Hydrolo G eBook Subscription Services
 - Proceedings Regionalization In Hydrolo G Budget-Friendly Options

6. Navigating Proceedings Regionalization In Hydrolo G eBook Formats
 - ePub, PDF, MOBI, and More
 - Proceedings Regionalization In Hydrolo G Compatibility with Devices
 - Proceedings Regionalization In Hydrolo G Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Proceedings Regionalization In Hydrolo G
 - Highlighting and Note-Taking Proceedings Regionalization In Hydrolo G
 - Interactive Elements Proceedings Regionalization In Hydrolo G
8. Staying Engaged with Proceedings Regionalization In Hydrolo G
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Proceedings Regionalization In Hydrolo G
9. Balancing eBooks and Physical Books Proceedings Regionalization In Hydrolo G
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Proceedings Regionalization In Hydrolo G
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Proceedings Regionalization In Hydrolo G
 - Setting Reading Goals Proceedings Regionalization In Hydrolo G
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Proceedings Regionalization In Hydrolo G
 - Fact-Checking eBook Content of Proceedings Regionalization In Hydrolo G
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
 - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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