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Editorial: Advances in integrated surface—subsurface hydrological modeling

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Editorial on the Research Topic
Advances in integrated surface—subsurface hydrological modeling

Aims and scope of the Research Topic

Integrated surface–subsurface hydrological models (ISSHMs) are at the heart of contemporary water science, combining surface flow dynamics with complex groundwater interactions at multiple scales, from hillslopes to entire continents. As global water systems are increasingly impacted by climate change, anthropogenic pressures, and infrastructure development, the demand for holistic, process-based modeling frameworks has intensified. This Research Topic in *Frontiers in Water* assembles cutting-edge contributions that advance the theoretical, methodological, and practical applications of ISSHMs. Collectively, these works address challenges in coupling, scaling, data assimilation, model accuracy, and computational efficiency, with implications spanning flood forecasting, groundwater management, sediment transport, and climate resilience (Figure 1).

Innovations in model coupling and subgrid representation

One of the persistent challenges in integrated modeling lies in resolving hydrological processes across spatial and temporal scales. Peeples and Maxwell tackle this directly through the development of a subgrid channel formulation within the ParFlow model, offering a refined approach to representing channel hydraulics in coarse-resolution models. Their method significantly reduces flow bias compared to conventional coarse grids, thereby enhancing the accuracy of flood and streamflow simulations in large domains.

Similarly, Paniconi et al. explore model response and numerical challenges across hillslope and catchment scales using CATHY, revealing the hidden instabilities and limitations in ISSHMs under highly heterogeneous and nonlinear conditions. Their empirical findings underscore the necessity of robust coupling strategies, particularly in long-term simulations with dynamic boundary conditions and complex feedbacks.

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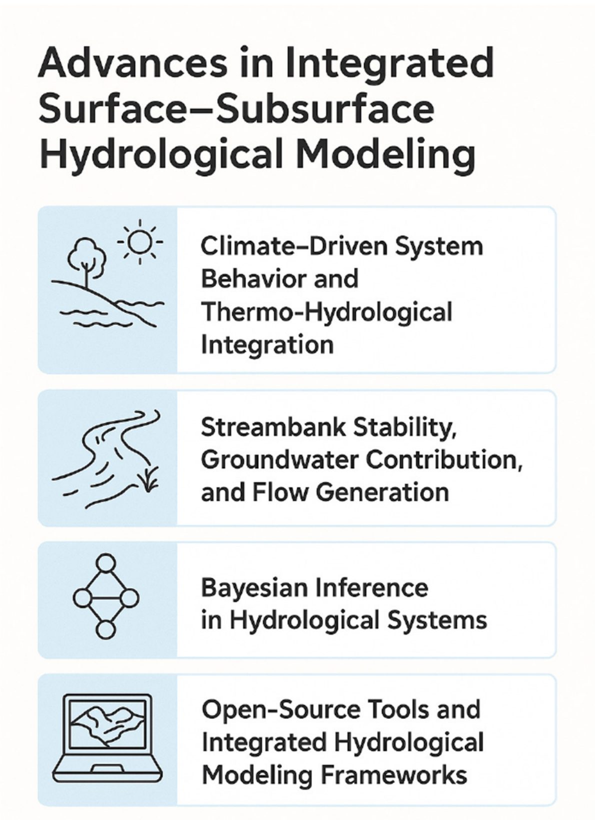

FIGURE 1
Summary of main contributions to the Research Topic.

Subsurface dynamics, climate sensitivity, and hydrological function

Understanding how subsurface systems respond to climatic, structural, and anthropogenic forcings remains a critical frontier in hydrological science. Tsypin et al. address this through a 62-year thermo-hydrological simulation of the North German Basin, combining climate-driven recharge variability from a hydrologic model with geologic heterogeneity in a groundwater flow model. Their modeling results highlight how permeability contrasts, structural dips, and recharge dynamics jointly shape groundwater flow and heat propagation, providing insight into subsurface climate memory and geothermal potential.

In the southern hemisphere, Moore et al. employ a Bayesian hydrochemical approach (BACH) to distinguish shallow and deep groundwater flow contributions to streamflow in New Zealand. Their findings reveal that deep, slow groundwater contributes significantly to streamflow—even during high-flow conditions—demonstrating the year-round relevance of deep aquifers.

Similarly, von Trapp et al. quantify bedrock groundwater contributions in a mountainous catchment using Radon data with a combined mass-balance and 1D steady-state advective solute transport model, accounting for groundwater inflow into the stream. Their findings reveal that bedrock groundwater discharge can supply up to 44% of streamflow during dry seasons, highlighting the hydrologic importance of deep and fractured bedrock in flow generation, especially in headwater systems.

Wei et al. introduce a streambank stability module into HydroGeoSphere, coupled with the surface water operations model, OASIS. Their study shows how reservoir releases and groundwater pumping interact with bank geometry to drive slope instability, emphasizing the need to include infrastructure and anthropogenic stressors in river basin models.

Advances in forecasting and operational hydrological modeling

ISSHMs also play a pivotal role in near real-time forecasting. Patakchi Yousefi et al. investigate the utility of deep learning-based precipitation correction in enhancing integrated hydrologic model accuracy. Although their U-Net CNN model effectively reduces forecast bias, the study finds that uncorrected ECMWF precipitation often leads to better soil moisture simulations, highlighting a paradox where better input statistics do not guarantee better hydrological performance. This result underscores the complex, nonlinear relationships between meteorological input and hydrological response, and the need for careful validation of machine learning corrections in operational workflows.

Goergen et al. demonstrate the predictive capabilities of ParFlow in reconstructing the catastrophic July 2021 floods in the Eifel-Ardennes region. Their ensemble hindcast approach captures both timing and magnitude of the floods without tuning, illustrating the potential of physics-based ISSHMs for disaster reconstruction and analysis. They also provide new perspectives on soil buffering capacity and the role of antecedent saturation in modulating flood severity.

Outlook and future directions

The collective contributions in this Research Topic reflect a vibrant and interdisciplinary community pushing the frontiers of integrated surface-subsurface hydrological modeling. Future work will need to address persistent challenges in:

- coupling hydrological, ecological, and socio-economic processes;
- incorporating machine learning within physically-based frameworks;
- improving computational efficiency for high-resolution, long-term simulations;
- quantifying uncertainties in scenarios of climate and land-use change.

As data availability expands and computing power increases, these integrated frameworks will become central to the design of resilient, data-informed water management systems.

Author contributions

MC: Writing – original draft. OS: Writing – review & editing. HA: Writing – review & editing.

Conflict of interest

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