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Editorial

Coupled Numerical Modeling of Groundwater Flow and Surface Water Interactions

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1. Introduction

Groundwater and surface water form a connected resource whose exchange processes influence water availability, water quality, and aquatic environments [1]. Understanding that connectivity requires attention to the interfaces through which water, solutes, and heat move, and to the spatial and temporal scales at which these transfers become consequential. For hydrogeological practice, the central challenge is to predict the response of connected systems to changing boundary conditions and management interventions with sufficient confidence to support a defined decision.

Coupled numerical models provide a framework for examining these responses by representing interacting flow domains and, where necessary, associated transport processes. Their usefulness depends on the conceptual model, interface conditions, and observational constraints as well as the numerical coupling strategy [2]. Model complexity therefore needs to be justified by the processes controlling the prediction and by the evidence available to constrain them.

The Special Issue "Coupled Numerical Modeling of Groundwater Flow and Surface Water Interactions" brings together seven articles published in 2025–2026. The collection includes coupled process simulations alongside field investigations, spatial screening, remote sensing, hydrological attribution, and irrigation decision support. These studies examine different components of integrated hydrological prediction: identifying hydrological connections, representing their consequences, and relating system behavior to management objectives. These studies also show how observational data and process understanding can inform model development and evaluation.

2. Observations and Conceptual Foundations

Reliable characterization of recharge, water sources, and river geometry is essential for simulating groundwater–surface-water exchange. Three contributions address these foundations at different scales and with different types of evidence.

Zahra et al. integrate remote sensing, geographic information systems, and the Analytic Hierarchy Process to delineate groundwater recharge potential in Islamabad and Rawalpindi. Their multicriteria framework combines terrain, land cover, climatic, soil, and water-table information to identify spatial contrasts relevant to recharge protection and further investigation [contribution 3]. The resulting maps can help prioritize monitoring locations and further site investigations in urbanizing areas. Its output is a relative suitability classification; estimating recharge fluxes or sustainable abstraction requires additional

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hydraulic observations and water-balance analysis. Independent field testing is especially valuable where water-table observations also contribute to the mapping inputs.

Mondati et al. examine the Arrone River in the southern Sabatini Mountains of central Italy using serial discharge measurements, hydrochemistry, oxygen isotopes, and radon. The combined observations distinguish reaches strongly affected by human inputs from downstream sections with increasing groundwater influence, providing a spatially differentiated conceptual understanding of river–aquifer connectivity [contribution 5]. This distinction matters for numerical modeling: assigning all observed channel gains to a single groundwater source could misrepresent both hydraulic and chemical boundary conditions. Radon is used qualitatively in this investigation, and measured net discharge increments should be distinguished from independently resolved groundwater exchange fluxes. Identifying water sources and exchange pathways provides a stronger basis for developing and calibrating numerical models.

Nour-Eldeen et al. contribute an observational framework for the surface-water domain by combining Sentinel-2 imagery, field soundings, machine-learning bathymetry, and channel planform analysis along a regulated Nile reach. Their Random Forest model achieves a root-mean-square error of 0.93 m under random-split testing, increasing to 2.43 m under spatial-block testing [contribution 7]. The higher error under spatial-block testing indicates that model performance may deteriorate when predictions are extended to unsurveyed river reaches. Although groundwater exchange is not simulated, the work is relevant to the geometry required by subsequent river–aquifer models. Bathymetric uncertainty and the limits of temporal transfer must accompany such use; channel geometry alone does not determine riverbed conductance or seepage.

3. Coupled Flow and Transport Processes

The process-modeling contributions extend the assessment of connected waters beyond hydraulic heads and discharge to thermal conditions and salinity. The extent of coupling differs between the models, particularly in their treatment of interacting processes and boundary conditions.

Fakhari et al. develop three-dimensional coupled flow and heat-transport models for selected reaches of the Sainte-Marguerite and Berard rivers in Quebec. Their formulation links river flow with groundwater movement and heat exchange through the subsurface, supported by hydraulic and temperature observations. Comparisons with simulations excluding groundwater contribution indicate that groundwater inflow buffers river warming during the investigated heat waves [contribution 4]. The inclusion of a permafrost-affected setting broadens the hydrogeological context, although freezing and thawing are not dynamically resolved in these short event simulations. The results identify groundwater inflow as an important control on river temperature during heat waves. Translating modeled temperature moderation into ecological protection will require species-specific exposure criteria and appropriate spatial and temporal observations; fish survival is not directly simulated.

Lv et al. use three-dimensional density-dependent groundwater flow and solute-transport modeling to investigate saline groundwater pumping as a barrier to seawater intrusion. Their numerical experiments show how hydraulic conductivity anisotropy interacts with pumping rate and screen elevation to influence barrier performance [contribution 2]. The simulations distinguish between limiting saltwater-wedge extent and reducing salt mass within the aquifer. These objectives may require different pumping configurations and should be evaluated separately. The marine boundary is prescribed rather than dynamically coupled to an ocean model. The idealized simulations consequently provide guidance for testing management strategies, with field heterogeneity and transient marine forcing remaining important requirements for site application.

4. Hydrological Change and Management Decisions

Management interventions modify water demand and hydrological partitioning, while regional change can expose processes omitted from local models. Two contributions address these wider dimensions.

Moudi et al. link Internet of Things observations with machine learning prediction and multiobjective irrigation allocation, comparing watermelon and saffron in an Iranian agricultural setting. Under the study's local crop and economic assumptions, the comparison favors saffron in terms of modeled water allocation and economic return [contribution 1]. The framework combines irrigation-demand prediction with water allocation and economic optimization. A further extension would be to quantify how irrigation decisions affect groundwater abstraction, return flows, recharge, and river discharge. Reduced allocation should not automatically be interpreted as reduced basin depletion or aquifer recovery, because these outcomes depend on consumptive use, return flows, and subsequent water-use decisions. Those physical responses are not calculated in the present framework.

Yang et al. assess runoff reduction in 14 major Loess Plateau catchments during 1961–2009 using seven Budyko-based climate elasticity formulations. Changes in annual precipitation and potential evapotranspiration explain only part of the observed decline, leaving substantial residual contributions in many catchments [contribution 6]. Vegetation change, ecological engineering, and increasing water demand provide evidence consistent with human influence. Nevertheless, the residual cannot be assigned uniquely to human activity: storage changes, groundwater exchange, climatic characteristics absent from annual indicators, and methodological uncertainty can also contribute. These findings indicate that changes in water storage and human water use should be considered in process-based models, as Budyko-based attribution alone cannot identify the underlying hydrological mechanisms.

5. Research Priorities and Closing Perspective

Three research needs are particularly evident across the seven studies. The first is to strengthen independent constraints on exchange and source terms. Hydraulic heads, stream gauging, temperature, tracers, and subsurface characterization should be combined across seasons and contrasting flow conditions. These observations can test recharge hypotheses, distinguish natural inflows from engineered inputs, and identify exchange pathways that a model must represent. Agreement with calibration data should be evaluated separately from prediction at new locations or during events outside the calibration period.

Second, the processes included in a model should reflect the specific hydrological problem being investigated. Streambed properties, geological heterogeneity, anisotropy, and uncertain channel geometry may alter exchange predictions. Density feedback is essential where salinity controls flow, and heat transport requires suitable thermal and atmospheric boundary conditions. Where freezing processes matter over the prediction horizon, a fixed permafrost representation needs explicit justification. Additional process complexity should be assessed through sensitivity analysis and comparison with simpler alternatives, together with numerical convergence and conservation checks. In coupled implementations, reported water, solute, and energy budgets should make interface-transfer errors visible.

Third, model uncertainty and predictive performance beyond the calibration setting require greater attention. Errors in bathymetry, recharge estimates, source budgets, material properties, and boundary forcing should be carried into the outputs used for decisions. Spatially separated and temporally independent evaluation can reveal limitations obscured by random data partitioning. Alternative conceptual models also deserve examination where the observations permit several plausible explanations. For reproducibility, studies should document coupling procedures, parameterization, discretization, boundary conditions, and calibration objectives, and make model inputs and evaluation data accessible where possible.

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Fourth, management scenarios should be evaluated against measurable changes in groundwater storage, streamflow, water quality, and other relevant hydrological variables. Irrigation allocation and abstraction scenarios need to be evaluated against changes in aquifer storage, streamflow, salinity, or thermal exposure at relevant scales. Objectives should be stated before optimization: controlling wedge extent differs from removing salt, and improving irrigation allocation does not by itself establish an ecological benefit. The studies illustrate how model outputs and management objectives must be defined together; their integration into shared modeling frameworks remains an opportunity for further research.

The seven studies cover field-based characterization, numerical simulation, hydrological attribution, and water-management optimization. They show how observational data, process-based models, and management analyses can address different aspects of groundwater–surface-water interactions. Future research should focus on better constraining exchange processes with independent observations, quantifying predictive uncertainty, and linking model outputs to specific hydrological and management outcomes. Future models should link physically resolved exchanges to measurable water-management outcomes.

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