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Editorial

Advances in Catchment Science through Integrated Hydrological Modelling and Monitoring

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Environmental research is rapidly evolving toward an integration of different disciplines, and this is also reflected in hydrology and the hydrological modelling community. Models can be integrated by combining different physical processes within the same compartment or cycle (e.g., surface, subsurface, groundwater flow, geochemistry and geomorphology) [1] and/or different compartments of the terrestrial system (e.g., atmosphere and biosphere) [2,3]. The integration of models entails also several technical and technological aspects related to (i) coupling techniques, (ii) data integration (e.g., data assimilation and machine learning approaches) and (iii) computation offloading.

The development and use of integrated models pose several challenges. The level of complexity achieved when integrating many processes and components makes it difficult to comprehensively understand and interpret the model results in all their facets, questioning their reliability and application for operational purposes. An increased number of physical processes implies a larger number of parameters, state variables and unknowns, which could lead to overparameterisation and equifinality [4]. Coupling physical processes occurring at different temporal and spatial scales (e.g., fast surface runoff and slow groundwater flow) can lead to a loss of accuracy, unless complex numerical techniques are adopted. It is also important to remark that many physical interactions across the terrestrial compartments are not explicitly resolved but rather rely on parameterisations that are difficult to constrain with observations [5]. This could lead to biases in representing feedback mechanisms between model components [6]. Software architecture is becoming increasingly more complex and difficult to maintain, requiring advanced skills in software engineering and high performance computing [7]. Finally, the large volume of information usually produced by numerical simulations that integrate many physical processes across the terrestrial compartments and over long periods hinges to the challenge of the 4 V's of big data and research reproducibility [8].

This special issue focuses on hydrological models based on mechanistic formulations of the coupled physical, biological and geochemical processes of terrestrial systems. By providing a holistic view of the integrated water, energy and matter cycles, such models strive to define a unified and physically consistent framework for testing and validating advanced scientific hypotheses [9]. Moreover, as suitable models for long-term climate simulations, they represent promising decision support tools for the definition of new water management strategies and natural hazard mitigation policies [10]. Thanks to the increasing availability of computational resources and data, integrated modelling approaches have received growing attention in recent years [11].

Within this framework, this *Water* Special Issue collects five research contributions from over 25 authors on recent developments and applications of physics-based hydrological models, integrating mass and energy processes in catchments at different scales and with different approaches.

Gatel et al. [12] present a global sensitivity analysis performed on a vineyard hillslope affected by transport of pesticides, i.e., reactive solutes, simulated with the CATHY model [13]. The overall goal of this study is to model migration and fate of reactive solutes in natural environments, which is a highly complex process, and to identify the most important parameters. Gatel et al. found that pesticide transport is highly controlled by the saturated hydraulic conductivity and the retention curve shape parameter n. This implies a strong role for parameter interactions associated with the exchange processes represented in the model. Their results highlight that, at the hillslope scale, an accurate quantification of contaminant fluxes and concentrations requires a physically based model with a full computation of the Richards equation regulating water flow and an explicit description of the transport of reactive tracers.

The work of Daneshmand et al. [14] deals with a similar problem, but at the catchment scale. In this case, they used the integrated surface–subsurface hydrological model MIKE-SHE [15], whereby water and salt fluxes are simulated in a number of afforestation scenarios. Compared to CATHY, MIKE-SHE is also physically based, but more conceptualised, and therefore more flexible and computationally efficient. In this modelling application, the authors explore the potential of integrated surface–subsurface models to simulate salt transport processes leading to soil salinisation, which is a major environmental issue in arid and semi-arid regions, including the possible impacts of land use and climate change.

Li et al. [16] address the integration of different models working at different scales to simulate runoff formation in mountain catchments, where the process has both a fast surface and a slow baseflow component, making its simulation and forecasting a significant hydrological challenge. Li et al. proposed an efficient integrated modelling approach, whereby the baseflow is treated as a black box and forecasted using a long-term memory method, while the surface flow is simulated using a spatio-temporal variable source mixed runoff generation module, based on hydrological response units constructed from eco-geomorphological units. This model application is indicative of the challenges arising with integrated models aiming to cover processes with different characteristics spatial and temporal scales.

Bizhanimanzar et al. [17] compare an externally linked (MOBIDIC-MODFLOW) [18,19] and a physically based (MIKE SHE) surface water–groundwater model in their capability to capture the integrated hydrologic responses of the Thomas Brook catchment, in Canada. The performance and advantages of the two models were evaluated from an applied point of view. It was found that, while the physically based model is more accurate, the externally linked model is more effective in terms of computational efficiency, showing its potential for modelling groundwater–surface water interactions at regional scale.

Finally, Bottazzi et al. [20] present a new approach for estimating evapotranspiration in a modular, component-based eco-hydrological modelling framework, New-Age [21]. In this case, the model integration focus is given by the coupling of physiological processes controlling plant transpiration and soil hydrological processes. The most interesting advancement lies in the use of different and alternative components in a modular modelling framework, based on the Open Modelling System [22], whereby integration is intended both in terms of processes and code structure. This could be a promising approach to seamlessly integrate different or alternative modelling approaches.

In summary, this Special Issue effectively highlights some of the various challenges posed by the integration of hydrological models, such as the coupling of different processes (e.g., water flow and solute transport, both at the catchment [14] and at the hillslope scale [12]), spatio-temporal scaling issues [16], pros and cons related to use of fully physics-based integrated approaches as compared to more simplified and/or conceptual models [17], and the coupling of different eco-hydrological modules in a component-based integrated framework [20].

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