Towards more credible models in catchment hydrology to enhance hydrological process understanding: Preface

Jens Christian Refsgaard[1], Juliane Mai[2], Markus Hrachowitz[3], Sharad K. Jain[4], and Simon Stisen[1]

[1]De Nationale Geologiske Undersogelser for Danmark og Gronland
[2]University of Waterloo Department of Civil and Environmental Engineering
[3]Technische Universiteit Delft Afdeling Watermanagement
[4]Indian Institute of Technology Roorkee Department of Civil Engineering

September 5, 2023

Abstract

Catchment modelling has undergone tremendous developments during the past decades. In the 1970s, the focus was on simulation of catchment runoff with process descriptions and data inputs being lumped to the catchment scale. Later developments included spatially distributed models allowing data inputs and hydrological processes to be simulated at model grid scale, i.e. much finer than catchment scale. These models were able to explicitly simulate various processes such as soil moisture, evapotranspiration, groundwater and surface runoff. With the advancements in remote sensing technology and availability of high-resolution data, increased attention has in recent years been given to enhancing the capability of catchment models to reproduce spatial patterns and in this way improve our understanding of hydrological processes and the physical realism of catchment models. This development process has involved a wide spectrum of different aspects in the modelling process, reaching from an improved understanding of uncertainties in data, model parameters and model structures to new protocols for good modelling practices in water management. Recognizing the important role of biodiversity and social aspects, hydrologists are now extending the scope of their models to capture the interactions between water, biota and human social systems.

Towards more credible models in catchment hydrology to enhance hydrological process understanding: Preface

Jens Christian Refsgaard[1]

Juliane Mai[2,3,4]

Markus Hrachowitz[5]

Sharad K. Jain[6]

Simon Stisen[1]

[1] Department og Hydrology, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark

[2] Civil and Environmental Engineering, University of Waterloo, Waterloo, ON, Canada

[3] Computational Hydrosystems, Helmholtz Centre for Environmental Research–UFZ, Leipzig, Germany

[4] Center for Scalable Data Analytics and Artificial Intelligence–ScaDS.AI, Leipzig, Germany

[5] Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

[6] Department of Civil Engineering, Indian Institute of Technology, Roorkee, India

Introduction

Catchment modelling has undergone tremendous developments during the past decades. In the 1970s, the focus was on simulation of catchment runoff with process descriptions and data inputs being lumped to the catchment scale. Later developments included spatially distributed models allowing data inputs and hydrological processes to be simulated at model grid scale, i.e. much finer than catchment scale. These models were able to explicitly simulate various processes such as soil moisture, evapotranspiration, groundwater and surface runoff. With the advancements in remote sensing technology and availability of high-resolution data, increased attention has in recent years been given to enhancing the capability of catchment models to reproduce spatial patterns and in this way improve our understanding of hydrological processes and the physical realism of catchment models. This development process has involved a wide spectrum of different aspects in the modelling process, reaching from an improved understanding of uncertainties in data, model parameters and model structures to new protocols for good modelling practices in water management. Recognizing the important role of biodiversity and social aspects, hydrologists are now extending the scope of their models to capture the interactions between water, biota and human social systems.

This Special Issue (SI) of Hydrological Processes is the result of an open call for abstracts announced in October 2020. The SI comprises a collection of 14 papers authored and co-authored by 77 scientists from 37 research institutions in 16 countries. Based on the key focus for each of the papers we have grouped them into five thematic topics: (i) review papers; (ii) papers developing and testing new process descriptions; (iii) papers focusing on how model calibration can improve process descriptions; (iv) papers exploring how the use of multiple model structures can improve model performance and process descriptions; and (v) papers focusing on modelling uncertainties. The grouping of the papers into the five topics should be considered as indicative only, because all papers address more than one of the five themes. The key findings in the papers of this Special Issue are summarized in the following five topic sections.

Review papers

Refsgaard et al. (2022) review developments in hydrological modelling of catchment response over the past 60 years. Several important advancements have driven these developments. Scientists now have much better understanding of hydrological processes, leading to their improved representation in models. Another advancement is improved availability of data – more variables, at higher frequency, and observed at more places. Multi-band remote sensing data at higher spatial and temporal resolutions and algorithms to compute data of missing variables at the required scales by using the satellite data have added to the richness of databases. Scientists also have access to increasing computational power, enabling them to use larger volumes of data and an ensemble of models. However, it has also been realized that such developments have not necessarily resulted in better modelling approaches. In addition, Refsgaard et al. (2022) illustrate the importance of spatial resolution and improved data resolutions in a case study, where a model setup was run at 100 m and 500 m resolutions. While the two models perform equally well for simulation of catchment discharge, the underlying processes such as streamflow partitioning differ significantly.

The paper by Wheater et al. (2022) reviews recent developments and discusses scientific and technical challenges of large-scale cold region hydrological modelling with a focus on the Canadian community hydrological land surface scheme MESH (Modélisation Environmental Communautaire – Surface and Hydrology). Cold regions are crucial for a large part of the global population and face major and rapid changes due to global warming. At the same time the hydrology is particularly complex, because it includes cold region processes such as permafrost, frozen soil, snow and glaciers, where hydrological processes often are controlled by phase change energetics. Modelling of large river basins in cold regions are often subject to relatively sparse data coverage and application of remote sensing data has recently shown important benefits. A key conclusion is that cold region hydrology is particularly sensitive to temperature changes and that even small biases in forcing data from global climate models pose large challenges. Wheater et al. (2022) furthermore conclude that the understanding and description of hydrological processes related to permafrost and frozen soil as well as certain glacier processes poses significant challenges and scopes for improvement.

New process descriptions

The study by Bronstert et al. (2023) focuses on description of infiltration excess (Hortonian surface runoff) in catchment models. In particular, they investigate the importance of micro- and macropores in the infiltration process. The study is based on good datasets from well instrumented infiltration/infiltration-excess experiments and observations at three spatial scales: point, field and catchment (115 km^2). Two modelling hypotheses were then tested against these field data, namely an approach without macropores, which is traditionally used in catchment models, and an approach based on double-porosity soil enabling a combined modelling of high infiltration rates in macropores and dampened soil moisture distribution after termination of infiltration. The results from tests at point and field scale suggest that both modelling approaches are capable of reproducing soil moisture dynamics, but that the inclusion of macropores results in more realistic soil hydraulic parameters. The results from catchment scale show that the macropore based approach is more robust in reproducing flood hydrographs for different rainfall intensities and generally outperforms the modelling approach without macropores. Altogether Bronstert et al. (2023) conclude that macropores are of high relevance for infiltration and soil moisture dynamics during periods of high intensity rainfall and therefore should be considered in catchment modelling focusing on simulation of flood events.

While it is well known that stream discharge in vegetated catchments during dry periods can exhibit natural fluctuations of up to 10% daily, the capability of catchment models to reproduce such behavior and explain the underlying processes has so far rarely been tested. Le Cecilia et al. (2022) use the CATHY physically-based integrated surface-subsurface hydrological model to study the complex processes generating diel streamflow fluctuations in a 2.67 km^2agricultural catchment in Switzerland. After demonstrating that the model is capable of satisfactorily simulating the diel streamflow fluctuations, including the timing of short-living streamflow peaks attributed to irrigation, the model was subsequently used to test alternative hypotheses for which processes may contribute to these fluctuations. The results show that evapotranspiration is the dominant process generating diel fluctuations, while changes in saturated hydraulic conductivity due to diel soil temperature fluctuations caused an amplitude of the diel streamflow signal 10 times smaller than evapotranspiration.

The study by Riazzi et al. (2022) uses a travel time tracking method to simulate stream electrical conductivity (EC) using high frequency (hourly) monitoring data from the 369 km^2 Duck River catchment in Tasmania, Australia. Two modelling approaches are tested. The first approach assumes that evapotranspiration is the only process driving the changes in EC, while the second assumes that the water salinity in catchment storages is a function of water age in these storages. The results show that the two hypotheses are equally successful in simulating EC concentrations and tracking its event and seasonal dynamics, and hence it is not possible to differentiate which of the two underlying hypothesis are better supported by the available observational data. Given that EC data from operational observation networks is much more widely available than other tracer data, Riazzi et al. (2022) conclude that using EC data to calibrate travel time models is a promising approach.

In contrary to other papers studying individual hydrological processes or the impact of process descriptions on discharge or solute fluxes at the catchment output, Gaur et al. (2022) evaluate how well a spatially distributed hydrological model is able to reproduce observed spatial patterns within the catchment. They use the MIKE SHE with 5 km x 5 km resolution to simulate the hydrological response of the 19,276 km^2 Subarnarekha catchment in Eastern India. The study compares model simulations with remote sensing derived patterns for evapotranspiration and soil moisture. The comparison is made using three spatial performance metrics, i.e.

joint empirical orthogonal functions (EOF), fractional skill scores (FSS) and spatial efficiency (SPAEF). The results demonstrate the potential and value of hydrological model calibration to observed spatial patterns across time.

Model calibration and improved process understanding

Beven et al. (2022) present a novel invalidation approach to calibrate an ensemble of Dynamic Topmodel parameter sets in a study examining the potential for hillslope storage bunds to mitigate the effects of downstream flooding in the 209 km^2 River Kent catchment in UK. The model invalidation approach is based on a GLUE-like methodology, where the acceptability thresholds in a first goodness-of-fit step is defined to reflect the uncertainty associated with input and discharge data. 118 realizations out of 100,000 survived evaluations of hydrograph peaks in three years with major floods. While most model calibrations are confined to such goodness-of-fit measures of how well models perform in discharge simulations, Beven et al. (2022) introduced an additional evaluation step, where only the simulations with at least 10% of the area producing overland flow during the largest storm were accepted. This fitness-for-purpose measure reduced the acceptable realizations to 67. Altogether, the 67 surviving realizations are not necessarily those that give the highest Nash-Sutcliffe efficiency values, but those that are considered most suitable for assessing the impact of certain flood mitigation measures in the catchment.

De Lavenne et al. (2022) use the HYPE model for 111 catchments spread across the USA to evaluate the effect of calibration against both discharge and sediment data instead of only discharge data and to evaluate five hypotheses for overland flow process descriptions. The results confirm previous findings that inclusion of a second data set (in this case sediment) in a multi-objective calibration approach generally lead to significantly improved simulations for sediment concentrations with only a slightly reduced performance for discharge. The five overland flow modelling hypotheses consist of the existing formulation using three parameters and four new formulations using one or two parameters. The results show that the performance for discharge simulations is not improved by the new hypotheses, while the performances for sediment concentrations are improved. In addition, equifinality is reduced by the new hypothesis due to a lower number of model parameters.

La Folette et al. (2022) study streamflow simulation in the 16.9 km^2 Elder Creek catchment in Northern California, where the geology is characterized by fractured bedrock overlain by a, typically thin (0.5 m), soil layer. This is the first study where unsaturated weathered bedrock water storage is explicitly incorporated in a catchment model and used as a calibration target. They calibrate a lumped rainfall-runoff model against three observations targets: i) only streamflow data; ii) only rock moisture data; and iii) both streamflow and rock moisture data. The calibration is performed by evaluating 10,000 parameter sets using the concept of pareto optimality. The results show that the model calibrated against both streamflow and rock moisture data is capable of accurately simulating the dynamics in rock moisture and streamflow, while a calibration against streamflow data alone may result in relatively poor simulation of rock moisture dynamics and a calibration against rock moisture alone may result in relatively poor simulation of streamflow dynamics. Furthermore, the results show that the calibrated parameter values appear more physically realistic when calibrating against both streamflow and rock moisture data. The study concludes that incorporation of rock moisture data can lead to a more robust model, that without sacrificing the accuracy of streamflow simulations can provide increased accuracy of some model results and decreased parameter uncertainty.

Exploring multiple model structures

Astagneau et al. (2022) hypothesize that the response of a catchment to high-intensity rainfall events is highly heterogeneous due to complex interactions among the hydrological processes at short temporal and spatial scales. The aim of their study is to improve the simulation of summer floods by using a lumped conceptual rainfall–runoff model. They modify the GR5H model and test three hypotheses: i) large rainfall intensities increase the volume of effective rainfall, ii) large rainfall intensities induce a faster routing of effective rainfall to the catchment outlet, and iii) a combination of these two hypotheses. A large database consisting of 10,652 flood events in 229 French catchments are used. The results show that when the storages and fluxes of a lumped conceptual model dynamically depend on rainfall intensities, the errors in flood volume are less (at least in simulations at hourly time step). It is noted that these conclusions specifically hold good for a particular model structure and further testing with other models and the data from other regions would be required to establish the wider applicability. Since intense rainfall events do not last long, the intensity-dependent functions are triggered for very small number of time steps. To address the calibration issues arising due to the above hypotheses, Astagneau et al. (2023) suggest regionalizing the parameters of the intensity-dependent function.

Saavedra et al. (2022) investigates if hydrological consistency in contrasting climate periods can be improved by sampling the model space with a simple pareto framework and if such a model selection procedure can reduce uncertainties in precipitation elasticities and temperature sensitivities. They use the Framework for Understanding Structural Error (FUSE) to produce 78 different hydrological model structures from four different conceptual parent models. To test the ability of models to predict impacts of climate change, they perform differential split-sample tests of the models by calibrating on dry periods and evaluating on wet periods and vice versa. The models are tested on three catchments in Peru with areas ranging from 3545 km^2 to 9586 km^2. The results show that it is possible to identify some model structures that robustly simulate catchment-scale hydrology under different climate conditions, and that these are not necessarily the structures that perform the best for traditional efficiency metrics. The results also show that the model selection procedure resulted in a significant reduction in the spread in precipitation elasticities and temperature sensitivities.

Sinha et al. (2022) perform an intercomparison test of the GR4J lumped conceptual model against the spatially distributed mHM model using data from 50 catchments in UK. The models are calibrated by optimizing the Nash-Sutcliffe efficiency. Subsequently, the model performances in validation periods are evaluated by four performance metrics as well as five hydrological signatures characterizing the ability of the models to reproduce different components of the flow. The results support previous findings that a lumped conceptual models can perform equally well, and in some cases slightly better, than a more complex model, when the modelling objective is limited to discharge simulation.

Modelling uncertainties

Feigl et al. (2022) present a novel method of analyzing errors of process-based models attributing the model errors at each time step to specific input variables and model settings. This approach is helping to understand where model processes might need improvement, model input data might be of low quality or where model processes might be missing. The presented approach is a novel combination of (a) Machine Learning (using a data-driven model to learn predicting model errors), (b) Shapley Additive exPlanations and Principal Component Analysis (attributing errors to model inputs and variables), and (c) clustering (deriving groups of time steps that show similar error generation characteristics). The methodology is applied to the water temperature model HFLUX for a 3.45 km^2 Canadian catchment. The results show that errors can be clustered in three groups related to specific processes indicating where model adjustments can lead to improved performance.

Moraga et al. (2022) present a new framework to quantify and partition the uncertainty in hydrological projections originating from climate models and natural climate variability. The approach is tested in the 478 km^2 Kleine Emme and the 1730 km^2Thur mountainous catchments in Switzerland. The study uses one emission scenario and nine climate models. The outputs of the climate models are stochastically downscaled using a two-dimensional weather generator producing a 90-member ensemble covering the period 2010-2089, and the hydrology is simulated using the spatially distributed TOPKAPI-ETH model. The results show that uncertainty of the annual streamflow projections is dominated by stochastic uncertainty due to large natural variability of precipitation. The same applies to extreme high flows. In contrary, snowmelt and liquid precipitation exhibit robust climate signals illustrating that streamflow uncertainty during warm seasons and at high altitudes are dominated by climate model uncertainty.

Conclusions

The 14 papers in the Special Issue present novel developments and perspectives in catchment hydrological modelling enhancing our understanding of hydrological processes and contributing to solving real-life problems. The wide spectrum of approaches described in the papers illustrates that improved understanding of hydrological processes is not limited to better process equations but also can be achieved through model evaluation including one or more of the following approaches: tests on multiple catchments with varying hydrological regimes, calibration using multiple data types, analyses of alternative model structures and uncertainty analyses.

REFERENCES

Astagneau, P. C., Bourgin, F., Andréassian, V., Perrin, C. (2022). Catchment response to intense rainfall: Evaluating modelling hypotheses. Hydrological Processes, 2022;36:e14676.*https://doi.org/10.1002/hyp.14676*

Beven, K., Page, T., Hankin, B., Smith, P., Kretzsmar, A., Mindham, D., Chappell, N. (2022). Deciding on fitness-for-purpose-of models and of natural flood management. Hydrological Processes, 2022;36:e14752.*https://doi.org/10.1002/hyp.14752*

Bronstert, A., Niehoff, D., Schiffler, G. R. (2023). Modelling infiltration and infiltration excess: The importance of fast and local processes. Hydrological Processes, 2023;37:e14875.*https://doi.org/10.1002/hyp.14875*

De Lavenne, A., Lindström, G., Strömqvist, J., Pers, C., Bartosova, A., Arheimer, B. (2022). Evaluation of overland flow modelling hypothesis with a multi-objective calibration using discharge and sediment data. Hydrological Processes, 2022;36:e14767.*https://doi.org/10.1002/hyp.14767*

Feigl, M., Roesky, B., Herrnegger, M., Schulz, K., Hayashi, M. (2022). Learning from mistakes – Assessing the performance of uncertainty in process-based models. Hydrological Processes, 2022;36:e14515.*https://doi.org/10.1002/hyp.14515*

Gaur, S., Singh, B., Bandyopadhyay, A., Stisen, S., Singh, R. (2022). Spatial pattern-based performance evaluation and uncertainty analysis of a distributed hydrological model. Hydrological Processes, 2022;36:e14586.*https://doi.org/10.1002/hyp.14586*

La Cecilia, D., Camporese, M. (2022). Resolving streamflow diel fluctuations in a small agricultural catchment with an integrated surface-subsurface hydrological model. Hydrological Processes, 2022;36:e14768.*https://doi.org/10.1002/hyp.14768*

La Folette, P. T., Hahm, W. J., Rempe, D. M., Dietrich, W. E., Brauer, C. C., Weerts, A. H., Dralle, D. N. (2022). Multicriteria analysis on rock moisture and streamflow in a rainfall-runoff model improves accuracy of model results. Hydrological Processes, 2022;36:e14536.*https://doi.org/10.1002/hyp.14536*

Moraga, J. S., Peleg, N., Molnar, P., Fatichi, S., Burlando, P. (2022). Uncertainty in high-resolution hydrological projections: Partitioning the influence of climate models and natural climate variability. Hydrological Processes, 2022;36:e14695.*https://doi.org/10.1002/hyp.14695*

Refsgaard, J. C., Stisen, S., Koch, J. (2022). Hydrological process knowledge in catchment modelling – Lessons and perspectives from 60 years development. Hydrological Processes, 2022;36:e14463.*https://doi.org/10.1002/hyp.14463*

Riazzi, Z., Western, A. W., Bende-Michl, U. (2022). Modelling electrical conductivity variation using a travel time distribution approach in the Duck River catchment, Australia. Hydrological Processes, 2022;36:e14721.*https://doi.org/10.1002/hyp.14721*

Sinha, S., Hammond, A., Smith, H. (2022). A comprehensive intercomparison study between a lumped and a fully distributed hydrological model across a set of 50 catchments in the United Kingdom. Hydrological Processes, 2022;36:e14544.*https://doi.org/10.1002/hyp.14544*

Saavedra, D., Mendoza, P. A., Addor, N., Llauca, H., Vargas, X. (2022). A multi-objective approach to select hydrological models and constrain structural uncertainties for climate impact assessments. Hydrological Processes, 2022;36:e14446.*https://doi.org/10.1002/hyp.14446*

Wheater, H. S., Pomeroy, J. W., Pietroniro, A., Davison, B., Elshamy, M., Yassin, F., Rokaya, P., Fayad, A., Tesemma, Z., Princz, D., Loukili, Y., DeBeer, C. M., Ireson, A. M., Razavi., S., Lindenschmidt, K.-E., Elshorbagy, A., MacDonald, M., Abdelhamed, M., Haghnegahdar, A., Bahrami, A. (2022). Advances in modelling large river basins in cold regions with Modélisation Environmentale Communautaire – Surface and Hydrology (MESH), the Canadian hydrological land surface scheme. Hydrological Processes, 2022;36:e14557.*https://doi.org/10.1002/hyp.14557*