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Women advancing research on hydrological processes: Preface

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This Special Issue (SI) of *Hydrological Processes* features invited contributions led by women scientists at an advanced career stage who have made sustained contributions to the study of hydrological processes, advancing the field. The papers, with contributions from 16 women from 8 countries, reflect a wide diversity of research topics and methods. The contributions were by invitation. Work by these featured colleagues have become benchmarks through which other studies have been measured and implemented, because of their original ideas, concepts and theories from thorough field-based observations and modelling experiments.

While this SI can only feature a few contributions, we recognize and want to emphasize that other women have and continue to produce outstanding scientific contributions to the field. We aimed to highlight female role models as lead authors and representing the breadth of the hydrologic sciences research they lead. This SI celebrates the whole community of women in STEM (science, technology, engineering, mathematics), not just the women scientists presented within this SI. Further working toward that goal, leadership from the journals *Hydrological Processes*, *Water Resources Research*, and *Earth Surface Processes and Landforms* have co-organized an online seminar series on 'Women Advancing River Research', (https://www.cee.psu.edu/events/women-advancing-river-research.aspx). We are convinced that the celebration of women role models and recognizing their contributions will help to reduce barriers and professional challenges, and perhaps inspire others to pursue careers in the hydrologic sciences.

We had initially planned to publish this SI much earlier, but the onset of the global COVID19 pandemic in 2020, which continues to date, caused delays. Several recent publications discuss issues researchers face due to COVID-19 and how the resulting changed circumstances differentially affect individuals based on gender. Early studies of impacts suggest that women's publishing rate has fallen relative to men's amid the pandemic (Frederickson, 2020; Viglione, 2020; Vincent-Lamarre et al., 2020). Several contributors to this SI certainly experienced just that—and had to work even harder to get their papers submitted amidst additional challenges related to family, caregiving, online teaching, and homeschooling, to name a few. Some planned contributions were disrupted entirely. The U.S. National Academies documented how the COVID-19 pandemic disrupted individual schedules and work environments, blurring the lines between personal and professional life; and how it disrupted work in institutional laboratories and facilities, as well as global scientific conferences, in their study of 'Impact of COVID-19 on the Careers of Women in Academic Sciences, Engineering, and Medicine' (NASEM, 2021). In the coming months and years, it will be critical that universities and research institutes account for the gender dynamics of pandemic impacts when considering recruitment, retention, and promotion of hydrologic scientists (Malisch et al., 2020, NASEM, 2021).

The obstacles imposed by COVID19 are just the latest example of professional challenges that disproportionately affect women's careers in hydrological science and beyond. The fact that women are underrepresented in STEM is well-documented in many countries. This is exemplified in reports about representation, diversity, and inclusion such as Hill et al., 2010 ('Why so few? Women in science, technology, engineering, and mathematics'), Bernard & Cooperdock, 2018 on geosciences ('No progress on diversity in 40 years') and NASEM (2020; 'Promising practices for addressing the underrepresentation of women in science, engineering, and medicine: opening doors'). Research also reveals that women have long faced more challenges in career advancement than men, with further inequity for women of colour. The myriad of reasons for this are well articulated in publications such as: 'Sexual harassment of women: climate, culture, and consequences in academic sciences, engineering, and medicine (NASEM, 2018)'; 'Do babies matter: gender and family in the ivory tower' (Mason et al., 2013); 'Faculty service loads and gender: are women taking care of the academic family?' (Guarino & Borden, 2017); 'Gender differences in recommendation letters for postdoctoral fellowships in geoscience' (Dutt et al., 2016); and 'Journals invite too few women to referee' (Lerback & Hanson, 2017). While we celebrate the accomplishments of the women included in this SI, we recognize that many voices are missing, and insights undiscovered, from our research community.

The hydrologic processes community is strongest and the science is advanced most quickly when colleagues of all genders work together collectively and collaboratively. The women featured in our SI have achieved international recognition for their scientific contributions. Many of their earlier publications have become benchmarks through which other studies have been measured and implemented. Further, these women have served as dedicated mentors to students, early career scientists, and colleagues. Mentors provide the support, guidance, and research opportunities that enable careers to develop and flourish and scientific progress to continue. This SI presents some excellent examples of these fruitful collaborations.

We briefly introduce the contributors and their papers below. The subject matters of the papers address how we can enhance our understanding of hydrological processes, but they are also interdisciplinary and extremely timely with focuses on the dynamics of eco-hydrological processes, climate change, and human behaviour:

Dr. Christine Alewell is a Professor at the University of Basel, Switzerland. She is an expert in biogeochemistry, soil chemistry and soil degradation of natural and semi-natural ecosystems. One focus of her research is on the development of indicators for wetland degradation and regeneration. In their paper, Alewell et al. (2021), they assessed the main phosphorus binding states in operating constructed wetlands to assess phosphorus saturation and indications on phosphorus recycling potential of filter materials. They showed that phosphorus accumulation increased with age of the investigated vertical flow constructed wetlands in all three investigated filter materials (fluviatile sands, zeolite-and clinopyroxene-dominated lava sands) and most of the phosphorus was accumulated in the upper horizons.

Dr. Ann-Kristin Bergstrom is a Professor at Umeå University, Sweden. Her research concerns effects of environmental and climate change on the productivity and the food web structure of northern aquatic ecosystems. Her current main focus is on how global climate change is affecting lake water biogeochemistry, and what possible impacts these biogeochemical changes have on lake productivity and the ecosystem services of northern pristine lakes. In her Invited Commentary (Bergström, 2020) she discusses which changes in water delivery rhythm (timing, frequency, and magnitude of spring flood episodes) northern lakes are facing and how hydrological intensification influences the delivery of terrestrial DOM and nutrients, and lake water retention times. She illustrates how change in magnitudes of water input and its seasonal rhythm affect whether lakes act as 'shunts' or 'chemostats'. Still, only little research exists on the specific impact of lake water retention time on pelagic food webs relative to the role of changes in lake DOM.

Dr. Louise Bracken is a Professor at the University of Durham, UK. Her research is focused on the dynamic and complex relationships between the processes that generate and supply fine sediment within rivers, and those that move the sediment through the river system. Bracken et al. (2020) showed how innovation and understanding of hydrological processes are intimately linked. Innovation is central to delivering behaviour change to address the sustainable development goals (SDGs) but is important to furthering scientific understanding of hydrological processes. Using an example from NE England, they demonstrated that the design of an innovation ecosystem was crucial to its success. It could be used as a model to integrate innovation and research more widely to further scientific understanding and deliver behaviour change within organizations to address the SDGs.

Dr. Susan L. Brantley is Distinguished Professor of Geosciences and Director of the Earth & Environmental Systems Institute, Pennsylvania State University, USA. She is an expert on chemical, biological, and physical processes associated with the circulation of aqueous fluids in shallow hydrogeologic settings. She is a leading figure within the research community on the Critical Zone. Brantley and Lebedeva (2021) summarized the importance of reaction fronts and their relationships with the land-air interface and water table. They explored how reaction fronts act like 'valves' where reaction-induced porosity changes re-orient water flow directions. They suggest that reactive transport models could be run for geologically long simulation times to determine the weathering-induced porosity architecture of headwaters and to predict the distribution of important fronts, prior to development of hydrological models. Their conceptualization can inform better models of subsurface porosity and permeability, perhaps replacing the general treatment of the subsurface as a black box in groundwater models.

Dr. Georgia (Gia) Destouni is a Professor at Stockholm University, Sweden. She is a pioneer in the field of solute transport in the integrated, heterogeneous soil-groundwater system at large scales with a focus on encompassing the entire terrestrial pathways of the hydrologic cycle including the whole subsurface system. Their paper, Destouni et al. (2021) develops a methodology for distinguishing and quantifying some general key differences in stream water concentration and load behaviour versus discharge between tracer and pollutant contributions of currently active sources at the surface and those of legacy sources from earlier surface inputs, waste deposits and land contamination. This is applied to multi-catchment analysis of chloride and metal data measured over 1990–2018 around the major Lake Mälaren in Sweden. The results show widespread prevalence of legacy sources with overall greater legacy than active contributions for both chloride and the metals, and with active contributions playing a greater role for the former than the latter. Such source distinction and quantification is essential for effective mitigation of waterborne environmental pollution.

Dr. Heleen De Wit is a Senior Research Scientist at the Norwegian Institute of Water Research NIVA and an Associate Professor at the University of Oslo, Norway. She is an expert in catchment biogeochemistry, carbon cycling and water quality. De Wit et al. (2020) presents the results from an international collaboration integrating long-term data on concentrations and fluxes of total nitrogen and phosphorus from 69 Nordic headwater catchments, spanning the range of Nordic climatic and environmental conditions, including natural sites and sites impacted by agricultural and forest management. Concentrations and fluxes of total nitrogen and phosphorus were highest in agricultural catchments, intermediate in forestry-impacted and lowest in natural catchments, and were positively related to percent agricultural land cover and summer temperature. If the shift toward a low-carbon and resource-efficient society will be associated with intensification of agricultural and forest production and increased use of fertilizer, new challenges for protection of water quality will arise. The need for sustained funding of long-term monitoring of managed and unmanaged, natural catchments is also emphasized.

Dr Tanya Doody is a Principal Research Scientist leading high impact spatial eco-hydrological projects in the Land and Water business unit of Australia's national science agency, CSIRO. She has significant experience in quantifying the water requirements of vegetation and at times, their impact on water resources. This involves ecophysiological field-based research to underpin remote sensing tools to scale regionally to improve our understanding of the effects of flood regimes on the health of water-dependent ecosystems. Her riparian research informs integrated catchment water planning and management both in Australia and internationally. With a collaborative contribution (Doody et al., 2021) this manuscript investigates application of water via drip irrigation to long term drought stressed and disconnected semi-arid woodlands (*Eucalyptus largiflorens*). Currently, little is known about volumes of water that would provide ecological benefits to trees in these woodlands and reduce water stress. This contribution advances semi-arid floodplain management by demonstrating that with innovation, providing water to these areas is possible and that relatively small volumes will realize benefits, build future resilience and protect high conservation value riverine woodlands.

Dr. Louise Heathwaite is a Distinguished Professor in the Lancaster Environment Centre, Lancaster University, UK. She is recognized internationally as an authority on diffuse environmental pollution and in particular understanding the pathways of nitrogen and phosphorus loss from agricultural land to water, and the implications for freshwater quality. She is also credited with advancing the 'Critical Source Areas' concept. Their paper Heathwaite et al. (2021) synthesizes the physical hydrology and biogeochemistry process-based understanding for a lowland groundwater-fed river, representative of systems where the river is continuously recharged by groundwater throughout the year. The results illustrate the critical importance of incorporating hydrogeological process understanding both beneath the riverbed, and from the wider landscape setting, in predictive tools if we are to capture appropriately the role of the hyporheic zone for nitrate processing and its consequences for groundwater-fed river metabolics under a changing climate. A second paper, Heathwaite and Bieroza (2021) advances the understanding of the interplay between hydrological flushing and in-stream biogeochemical cycling during storm events for multiple parameters and hydrological years. The authors mined a high-frequency dataset and used two key hydrochemical indices, hysteresis and flushing index to evaluate the diversity of concentration-discharge relationships in a third order agricultural stream. They demonstrate how hydrochemical indices can be used to fingerprint the effect of hydrological disturbance on freshwater quality and can be useful in understanding the impacts of global change on stream ecology.

Dr. Susan Hubbard is the Associate Lab Director for Earth & Environmental Sciences Area at *Berkeley Laboratory* and an Adjunct Professor at UC Berkeley, USA. Her research focuses on quantifying how complex environmental systems function, with a particular emphasis on the development of geophysical approaches to remotely sense hydrological, geochemical, biological and geomechanical processes. In their Invited Commentary, Hubbard et al. (2020) discuss emerging technologies and collaboration modes that are critical for developing generalizable insights about and predictive understanding of complex catchment hydrobiogeochemical behaviour; important for underpinning optimized natural resource management. They propose that emerging technologies should be able to seamlessly unify sensing systems, data infrastructure, and computational tools to allow near real-time, autonomous communication and feedback. They urge the hydrological community to advance observation-data-modelling systems to improve catchment characterization and prediction within and across watershed observatories, and eventually enable near real-time information for resource managers.

Dr. Julia Jones is a Distinguished Professor and Program Head of Geography in the College of Earth, Ocean, Atmospheric Science, Oregon State University at Corvallis, USA. Her research focuses on the effects of climate change, land use modifications and disturbances on hydrology, geomorphology, and water quality. In her contribution, she analyses how large managed water resource systems respond to multi-decadal changes in the timing and magnitude of streamflow. Through a case study of the international (US-Canada) Columbia River Basin, USA, Jones and Hammond (2020) demonstrate that by combining publicly available historical data on streamflow with concepts from paired-watershed analyses and metrics of water resource performance, it is possible to detect, evaluate, and effectively manage water resource systems in large river basins. Results of the study indicate that water resource management systems in large river basins are increasingly vulnerable to changes in streamflow associated with climate change and land management, and emphasize the need to maintain long-term, publicly available streamflow records at gages, both in unregulated headwater catchments upstream of reservoirs, and in rivers downstream of reservoirs.

Dr. Jessica Lundquist is a Professor at the University of Washington, USA. Her research focuses on spatial patterns of snow and weather in the mountains and how those patterns are likely to affect streamflow and water resources in a changing climate. Her approaches address interactions between atmospheric science and hydrologic science in complex terrain, interactions between forest cover and snow, as well as the integration of data collection and physical modelling at multiple spatial scales. In their paper, Lundquist et al. (2021) trace the history of modelling snow interception to demonstrate how people frequently select parameterizations that were included in pre-existing models rather than re-evaluating the underlying field experiments. Because the dominant snow interception processes fundamentally change in different environments, many parameterizations are not transferable. The paper outlines how land surface models should update their parameterizations to be consistent with all available observations and better represent how changes to forest cover and climate will impact water resources and albedo.

Dr. Anne Nolin is a Professor at the University of Reno, USA. She has decades of experience on the interactions of climate with mountain snowpacks and glaciers, and mountains as social-ecological systems. She is a recognized leader in snow remote sensing and pioneered the development of snow and ice mapping techniques to augment in situ observations and modelling. Nolin et al. (2021) demonstrate how traditional snow metrics may not be able to adequately capture the changing nature of snow cover. The multiple impacts of a changing snowpack require a suite of climate indicators derived from readily measured or modelled data that serve as proxies for relevant snow-related and climate-driven processes. Such indicators need to capture snowpack changes over space and time, but not being overly simplistic or too complicated in their interpretation. They present a targeted set of spatially explicit, multi-temporal snow metrics for multiple sectors, stakeholders, and scientists, incl. metrics based on satellite data from NASA's Moderate Resolution Imaging Spectroradiometer and climate model outputs.

Dr. Christina (Naomi) Tague is a Professor of Ecohydrology and Ecoinformatics at the University of California at Santa Barbara, USA. She is an expert on the interactions between hydrology and ecosystem processes and, specifically, how eco-hydrologic systems are altered by changes in land use and climate. Much of her work involves developing and using spatial simulation models to integrate data from multiple field-based monitoring studies in order to generalize results to larger catchments. In their paper, Tague and Frew (2021) discuss that novel, sophisticated ecohydrologic models present a barrier to their widespread use and credibility. They argue that for an effective advancement of our understanding of how plants and water interact, we must improve how we visualize not only model outputs, but also the underlying theories that are encoded within the models. They outline a framework for increasing the usefulness of ecohydrologic models through better visualization.

Dr. Doerthe Tetzlaff is a Professor of Ecohydrology at the Humboldt-Universität and Head of the Department at the Leibniz Institute of Freshwater Ecology & Inland Fisheries, Berlin, Germany. Her research aims at understanding the spatial and temporal variability of how catchments function hydrologically at different scales; understanding the physical processes that generate stream flow, and the way these processes influence the hydrochemistry and hydroecology of streams. Tetzlaff et al. (2021) present results from an international inter-comparison study using stable isotopes of water in plant stem (xylem) and soils. Their findings suggest that the xylem water of angiosperms was influenced by the isotopic composition of water retained in the soil weeks or months prior to plant sampling, whereas gymnosperms generally did not exhibit such a memory effect. They also discuss several future research challenges which need to be addressed to improve understanding of soil–plant–atmosphere interactions.

Dr. Cherie Westbrook is a Professor in the Department of Geography & Planning, and Global Institute for Water Security at the University of Saskatchewan, Canada. She is an expert on the co-evolution of ecological and hydrological processes that explain wetland structure, function and resilience (and especially beaver impacts to wetlands) informing policy and regulatory discussions about their conservation, management and restoration. Westbrook et al. (2020) provide new insights about the opportunities and risks of relying on beaver as a nature-based flood solution. Obviously, beaver dams are unlikely to provide 100% flood protection. However, they can transiently store water even in large rainfall events, and so this nature-based solution should be included in regional water management strategies. Further understanding is needed on how water is stored and transmitted through beaver ponds with variable dam structural integrity.

Dr. Ellen Wohl is a Professor of Geology and University Distinguished Professor Department of Geosciences, Colorado State University, USA. She is an expert in physical-ecological interactions in river ecosystems, implications of physical riverine complexity for organic carbon storage, large wood in river floodplains and the effects of beaver activities on downstream fluxes of material in river corridors. Wohl and Scamardo (2021) showed that the longitudinal distribution of channel-spanning logjam populations is resilient to disturbance, based on investigating the temporal patterns of intra-reach and inter-reach logjam distribution densities over a decade that included substantial variations in snowmelt peak flow and a large rainfall flood. Such resilience of the longitudinal distribution of log-jams and associated changes in river corridor form and function suggest that introducing wood or engineered logjams to beads in small to moderate rivers can create persistent benefits in river corridors.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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