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To cite this version:

Daniel Kingston, Nicolas Massei, Bastien Dieppois, David Hannah, Andreas Hartmann, et al.. Moving beyond the catchment scale: Value and opportunities in large-scale hydrology to understand our changing world. Hydrological Processes, 2020, 34 (10), pp.2292-2298. 10.1002/hyp.13729 . hal-02886410

HAL Id: hal-02886410

https://hal.science/hal-02886410v1

Submitted on 16 Apr 2021

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Received: 31 January 2020 | Accepted: 3 February 2020
DOI: 10.1002/hyp.13729

INVITED COMMENTARY

Moving beyond the catchment scale: Value and opportunities in large-scale hydrology to understand our changing world

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Funding information
University of Birmingham, Institute of Advanced Studies; German Research Foundation (DFG)

Hydrological research is often focused at the catchment scale; but there are significant benefits of taking a broader spatial perspective (i.e., comparative hydrology) to advance the understanding of hydrological processes, especially in the context of global change. Indeed, many of the recently described "unsolved problems in hydrology" (Blöschl et al., 2019) refer to either global-scale processes (e.g., climate change), the hydrology of major physiographic zones (e.g., semi-arid or snowmelt regions) or require extensive comparisons across catchments. Moving beyond the catchment-scale frequently provides more holistic insights into the varying spatio-temporal response of hydrological systems to climate variability and change, as well as to the myriad of other anthropogenic influences on water. This knowledge is key for both mitigation of, and adaption to, hazards under an increasingly changed water cycle (Abbott et al., 2019). Moreover, a large-scale viewpoint is essential to inform appropriate water management towards socio-economic development, water-food-energy security and ecosystem health (e.g., WWAP, 2019). Here we contest that taking a large-scale perspective can bring significant benefits to our understanding of hydrological processes under change. After making the case for large-scale hydrology in general, we then explain the benefit of a large-scale hydrology approach in investigating global change, its causes, as well as water management in the present day and in the future. We conclude by identifying challenges and opportunities to advance research in large-scale hydrology and hydrological process understanding beyond the individual catchment.

1 | FRAMING HYDROLOGICAL PROCESSES IN A LARGER-SCALE CONTEXT

For surface water, a river catchment provides a relatively clear and defensible boundary within which water is stored and fluxes can be investigated and quantified (although we note that groundwater reservoirs and subsurface flows may not correspond to surface topography). However, catchments do not exist in isolation from the outside

Submission to HPToday as an Invited Commentary

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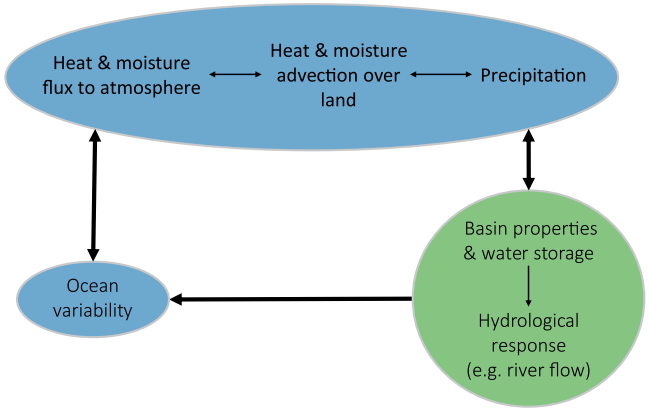

FIGURE 1 A conceptual model of the links between large-scale ocean–atmosphere variation and terrestrial hydrological variability, including the filtering effect of land surface conditions (adapted from Hannah, Fleig, Kingston, Stagge, & Wilson, 2014)

world. Meteorological inputs and outputs of water are the primary drivers of catchment hydrological variation, albeit modified by catchment properties (Bower, Hannah, & McGregor, 2004; Figure 1). Scales of meteorological variation are often larger than the catchment itself, with the water frequently originating from outside the catchment (i.e., the wider "air-shed"), even for continental-scale rivers (e.g., Brubaker, Dirmeyer, Sudradjat, Levy, & Bernal, 2001; Keune & Miralles, 2019). Thus, larger-scale atmospheric processes also influence the catchment water balance. These could be the hourly or daily variation characteristic of the regional meteorological setting, or the result of more organised climate system variation linked to large-scale ocean–atmosphere variability and teleconnections. For example, the El Niño Southern Oscillation (ENSO) is a leading mode of climate variability, impacting climate at temporal scales of 2–8 years across large swathes of the tropics and some mid-latitude regions (e.g., Capotondi et al., 2015; Deser, Alexander, Xie, & Phillips, 2010).

Bearing in mind these regional-to-continental, hemispheric and global scale controls on weather and climate, it is clear that a large-scale climate perspective is required to hypothesise and develop understanding of the first-order drivers of river flow (and hydrological variation in general) at any given location. This approach has been pursued successfully in Western Europe with definition of the role of the North Atlantic Oscillation (NAO) for regional climate variation and subsequently for river flow (Kingston, Lawler, & McGregor, 2006; Wanner et al., 2001). Such reduction of large-scale climate-hydrology connections to a statistical relationship between a hydrological time series and a large-scale climate index is potentially very powerful, and can form the basis for much improved understanding of hydroclimatic dynamics, and even hydrological predictability (e.g., Ionita, Lohmann, Rimbu, & Chelcea, 2012). However, this approach can also result in the oversimplification of the cascade of processes driving climate and river flow at a given location (Hannah, Fleig, Kingston, Stagge, & Wilson, 2014; Kingston, Lawler, & McGregor, 2006). In many locations, commonly invoked climate indices (including the NAO or ENSO) may also be poor hydrological predictors (e.g., Giuntoli, Renard, Vidal, & Bard, 2013). For these reasons, it is often advisable to begin large-scale hydrological studies with an "environment-to-climate" approach to investigate climate drivers—that is, the detection of unknown or hidden climate indices directly from hydrological data (Renard & Thyer, 2019).

At the same time as requiring a large-scale climatological approach to river catchment response, a large-scale hydrological perspective is critical too. By moving from investigation of the large-scale climate drivers of hydrological variation at single locations to large areas, it becomes possible to determine the spatial coherence of climate-hydrology relationships, and thus the likely large-scale mechanisms. For example, by studying the large-scale pressure fields associated with gridded precipitation variation across Europe, Lavers, Prudhomme, and Hannah (2013) were able to detect a continental-scale signature of strong and weak positive and negative relationships between precipitation and the NAO.

A large-scale hydrological perspective requires looking down (at catchment properties), as well as looking up the climate system and across other catchments (Figure 1). By taking into account characteristics such as the role of groundwater or land-use in determining the hydrological processes controlling storage and fluxes of water, it becomes possible to better identify the nature and variability of large-scale climate-land surface-water relationships. Demonstrating this possibility, Laizé and Hannah (2010) showed how catchment elevation and permeability influenced the strength of river flow relationships to regional climate and atmospheric circulation patterns. Subsurface catchment properties can act as a particularly strong filter on climate variability. Large groundwater systems tend to filter out short-term variation and instead show more pronounced multi-annual to decadal-scale variation (e.g., Cuthbert et al., 2019; Hanson, Dettinger, & Newhouse, 2006; Sidibe et al., 2019), which may also be transferred to or received from areas beyond the catchment boundary (Bouaziz et al., 2018; Fan, 2019). In contrast, short-term (up to interannual) variations tend to be dominant in steep catchments with shallow groundwater systems (Sidibe et al., 2019) or in catchments with strong subsurface heterogeneity (Hartmann, 2016). In other locations, snow storage and melt from winter into summer may result in strong seasonal differences in the connection from large-scale climate to land surface hydrology (Harpold et al., 2017; Milner et al., 2017).

In addition to spatial variation in subsurface or vegetation characteristics, large-scale land-use change may alter regional-scale climate-hydrology relationships over time. In some cases, land-use change may supplant climate change as the primary long-term driver of hydrological change (Vicente-Serrano et al., 2019; Wine & Davison, 2019). For example, extensive deforestation in humid tropical locations such as the Amazon basin fundamentally alters land-atmosphere recycling of water and consequently surface water availability (Spracklen, Arnold, & Taylor, 2012). Streams can also substantially be altered by groundwater pumping (de Graaf, Gleeson, van Rens, Sutanudjaja, & Bierkens, 2019; Zipper et al., 2019). Elsewhere, direct and indirect use of water may lead to large-scale modification of climate-driven patterns of hydrological variation, as increasingly recognised in terms of the difficulty in differentiating between natural and human-influenced drought events (Van Loon et al., 2016a, 2016b).

2 | SCALE MATTERS: INTERACTIONS ACROSS SPACE AND TIME

Catchment-scale hydrological outputs are determined by a range of large-scale inter-dependent interactions across the ocean–atmosphere-land surface system (Figure 1). However, while these links typically occur at spatial scales beyond that of the catchment, there is still some scale dependency. For example, although anthropogenic climate change is a global-scale phenomenon (albeit with different regional implications), modification of climate inputs/outputs by land surface conditions occurs primarily at the regional scale. These different large-scale hydrological drivers vary over different timescales (Figure 2), and may even vary through time in different ways (i.e., monotically, abruptly, randomly or cyclically). Patterns of climate variation range from the typical weekly-to-monthly variation of annular modes (Thompson & Wallace, 2000), the seasonal to interannual variability of ENSO (Capotondi et al., 2015), to decadal-scale patterns such as the Interdecadal Pacific Oscillation (Salinger, Renwick, & Mullan, 2001). In contrast, anthropogenic forcing of the climate system from greenhouse gas emission occurs more monotically on decadal to centennial scales (against a background of higher frequency oscillations that may be impacted by humans too), whereas large-scale changes in farming practice or infrastructure development (e.g., reservoir construction) may result in more abrupt changes. As such, a long-term and multi-scale temporal perspective is essential to fully characterise and contextualise the large-scale drivers of hydrological variation. In such terms, not only is stationarity no longer a useful construct for water resource management (Milly et al., 2008), but was never likely to have been a satisfactory approach (Taylor, 2009).

Together, Figures 1 and 2 indicate that different components of the ocean–atmosphere-land surface system interact—and as these interactions occur at different spatial and temporal scales, amplification or attenuation of some part of the initial climate drivers of hydrological variation may occur. So, catchment properties may modify the climate sensitivity of hydrological variables at timescales from seasonal to decadal, and long-term climate oscillations may modulate anthropogenically-driven variability and trends (e.g., Vernon-Kidd & Kiem, 2010). Meanwhile, continued climate (or land-use) change may fundamentally alter climate-hydrology relationships, as the Earth's major climate zones expand or contract under increased temperatures, leading to change in large-scale bio-climatic and physiographic regimes.

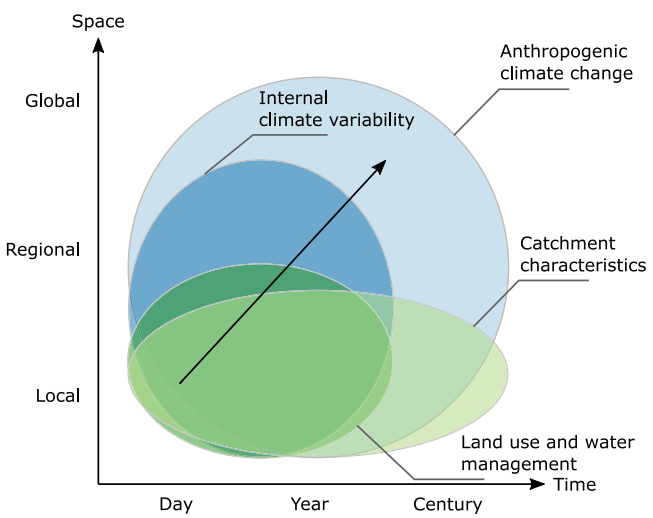

FIGURE 2 Spatio-temporal scales and associated dynamics characterising hydrological system variability

As well as requiring a system-wide approach to studying the cascade of processes linking large-scale variation to catchment outputs, a temporally-holistic perspective is necessary. By investigating large-scale atmospheric processes dynamics according to time-scale (e.g., Lovejoy, 2015), it becomes more possible to clarify the relative importance of different contributions to large-scale hydrological variation and apparent trends (e.g., Haustein et al., 2019). Similarly, characterising long-term hydrological persistence can also be insightful for understanding extreme events and observed hydrological variations under climate change (Markonis & Koutsoyiannis, 2016). For a comprehensive characterisation of climate and hydrology oscillatory relationships, multi-resolution statistical techniques (e.g., wavelet-based methods) are particularly well suited: these enable investigation of climate-hydrology relationships across a full range of the time-series spectra (Anctil & Coulibaly, 2004; Labat, Godderis, Probst, & Guyot, 2004). Investigating time-series relationships in this way can reveal the temporal variability in the strength of large-scale relationships (Dieppois, Durand, Fournier, & Massei, 2013) or their time-scale dependence (Massei et al., 2017), whereas linear correlation omits such specificity (Kingston, Webster, & Sirguey, 2016).

3 | CHALLENGES AND OPPORTUNITIES IN LARGE-SCALE HYDROLOGY

Key challenges and opportunities for advancing large-scale hydrological research relate to the use (and availability) of data and models to unravel processes across nested space–time domains. Notably, data availability (and the ability to validate model outputs) are often most limited in areas where the need is greatest, such as remote and topographically complex montane "water towers" (Immerzeel et al., 2020; Kaser, Grosshauser, & Marzeion, 2010). It is self-evident (but cannot be overstated) that for a large-scale perspective to hydrology, large-scale data are needed for climate, land and hydrology variables, at a satisfactory resolution and extent and with comprehensive metadata. However, challenges remain in terms of the maintenance of hydrological data networks (Beven et al., 2020; Hannah et al., 2011; Ruhi, Messager, & Olden, 2018). A particular problem for hydrological variables is the "spatial footprint" of the area represented by an individual river gauge (in comparison to a point temperature or precipitation measurement) in determining time series homogeneity. This is reflected by the aforementioned difficulty of separating human influence from natural drivers of hydrological drought (Van Loon et al., 2016a, 2016b). For such reasons, endeavours such as large-scale hydrological data rescue (e.g., Le Gros et al., 2015), reconstructing long-term and large-scale

high-resolution climate datasets (Devers, Vidal, Lauvernet, Graff, & Vannier, 2020) and corresponding near-natural hydrological datasets (e.g., Hanel et al., 2018; Moravec, Markonis, Rakovec, Kumar, & Hanel, 2019) are central in understanding the large temporal and spatial variations of hydrology. Compatibility between, or merging of, national-scale datasets (e.g., Caillouet, Vidal, Sauquet, Graff, & Soubeyroux, 2019; Keller et al., 2015) would be a further advance, as would improved quality assessment of large repositories such as the Global Runoff Data Centre under the auspices of the World Meteorological Organisation.

Compared to hydrological data, climate observations are more widely available, or more easily and robustly simulated as in the case of reanalysis data. In part because of this disparity, climate data are sometimes substituted for hydrological data. A common example is the increasing use of meteorological indices such as the SPEI as proxies for hydrological drought (e.g., Stagge, Kingston, Tallaksen, & Hannah, 2017; Vicente-Serrano, Beguería, & López-Moreno, 2010). Whilst undoubtedly an opportunity to advance understanding of large-scale drought dynamics, it can also be a challenge to obtain hydrologically meaningful information from such indices—that is, standardised index values versus discharge thresholds for irrigation abstractions, transport or electricity generation (Van Lanen et al., 2016). Most significantly, such meteorological indices are unable to take direct account of the impact of stores and fluxes within the terrestrial/sub-surface hydrological system.

With the continuing limitations to observational networks, remote sensing and model data are increasingly used instead of (or to complement) observations of the hydrological cycle. Data obtained from the GRACE earth observation system for terrestrial water has led to one of the biggest step-changes in hydrological data availability in recent years. Notwithstanding its relatively coarse resolution, GRACE has led to substantial advances in understanding the nature and drivers of global changes in freshwater availability (e.g., Rodell et al., 2018).

Model data for the terrestrial hydrological cycle can be used to advance understanding of continental and global scale patterns. Here, discrete catchment-scale model output may be analysed for similar or disparate catchments using the same (Caillouet, Vidal, Sauquet, Devers, & Graff, 2017) or different models (Todd et al., 2011). Increasingly, large-scale (multi-catchment) modelling exercises are used to characterise large-scale hydrological variation. These range from mesoscale models applied across continental-scale landmasses (e.g., Hanel et al., 2018) to fully global-scale hydrological models that are in many cases linked to the land surface schemes of atmosphere–ocean and earth system models (e.g., Schewe et al., 2014). Ongoing multi-institution comparison and validation efforts have enabled increased understanding of the strengths and weaknesses of these modelling systems (e.g., WaterMIP, Haddeland et al., 2011; Prudhomme et al., 2014). However, models are still fundamentally limited in their representation of many key hydrological processes, such as lateral re-distribution by hillslope processes (Chifflard et al., 2019) or by the absence of many important landscape heterogeneities (Hartmann, Gleeson, Wada, & Wagener, 2017). Critically, hydrological models generally do not consider anthropogenic (i.e., land-use) impacts on the hydrological cycle. Furthermore, such models (and data products from remote sensing) are still ultimately underpinned by station-based observations of land surface conditions—making provision of widespread, accessible and high quality data both a key challenge and opportunity for advancing [large-scale] hydrological research.

Alongside opportunities and challenges associated with hydrological modelling, representation of the climate system in models is a further frontier for advancing hydrological understanding at large spatial scales. Whilst the ever-increasing resolution of numerical weather prediction and general circulation models enables more detailed simulation of weather and climate, key questions remain in relation to how skilfully large-scale relationships (at different temporal resolutions) are captured by these models. For example, there is evidence that models typically underestimate decadal variability in the Pacific Ocean (Henley et al., 2017), but provide overestimations in the north Atlantic (Menary et al., 2015). As well as problems with model physics (Deser, Phillips, Bourdette, & Teng, 2012; Hawkins & Sutton, 2009), there are also challenges in terms of how to interpret model output—that is, whether model performance in simulating hydroclimatic variables results from realistic large-scale climate processes, or from other compensating biases (e.g., Dieppois et al., 2019). Such information should precede the development of seamless prediction systems or bias-corrected climate change scenarios for water resources. Similarly, in some cases more skilful forecasts for a particular variable may result from use of different model variables—for example, improved forecasts of extreme precipitation events by using forecast vapour flux rather than precipitation itself (Lavers, Zsoter, Richardson, & Pappenberger, 2017).

4 | MOVING BEYOND THE CATCHMENT TO CONNECT PROCESSES ACROSS SCALES

Herein, we have argued that a large-scale perspective to studying hydrology is critical for understanding hydrological processes in the connected terrestrial and atmospheric compartments of the water cycle and to connect the drivers of change across scales. Large-scale variation in weather and climate at multiple timescales is the ultimate control on hydrological variation, albeit modified by catchment properties. Indeed, divergence of hydrological variation from large-scale climate patterns gives important information about the importance of local-scale atmospheric conditions and role of catchment properties. Catchment properties are often seen as static; but they change over time as a result of anthropogenic land-use change, and/or the accumulated pressures from climate variation or change—leading to further changes in climate-hydrology relationships that are best understood from a large-scale viewpoint. A more holistic large-to-small spatial and temporal perspective is essential for improving our models and understanding of where water comes from and where it goes, and the role of the catchment as a filter of climate drivers across scales. In the context of global change and the increasingly modified Anthropocene water cycle, this research

approach is more critical than ever for sustainable water resources management.

ACKNOWLEDGEMENTS

This paper forms a contribution to the UNESCO-IHP EURO FRIEND-Water programme. The paper was primarily written whilst the lead author held a visiting Vanguard Fellowship at the Institute of Advanced Studies, University of Birmingham, UK. A.H. was supported by the Emmy-Noether-Programme of the German Research Foundation (DFG).

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How to cite this article: Kingston DG, Massei N, Dieppois B, et al. Moving beyond the catchment scale: Value and opportunities in large-scale hydrology to understand our changing world. *Hydrological Processes*. 2020;1–7. https://doi.org/10.1002/hyp.13729