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

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Hydrological research is often focused at the catchment scale; but there are significant benefits from taking a broader spatial perspective (i.e. comparative hydrology) to advance 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 (Abbot 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 understanding hydrological processes under change. After making the case for a need for large-scale hydrology, we then explain the benefit of a large-scale hydrology approach for investigating global change, its causes, as well as water management in the present day and into the future. We conclude by identifying challenges and opportunities to advance research in large-scale hydrology and hydrological process understanding beyond the individual catchment.

Framing hydrological processes in a larger-scale context

For surface water, a river catchment provides a relatively clear and defensible boundary within which water stores 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 world. Meteorological inputs and outputs of water are the primary driver 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 generally originating from outside that catchment (i.e. the wider 'airshed'), even for continental-scale rivers (e.g. Brubaker, Dirmeyer, Sudradjat, Levy & Bernal 2001; Keune & Miralles, 2019). Larger-scale atmospheric processes influence those weather systems. 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 model 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. Deser, Alexander, Xie & Phillips, 2010; Capotondi et al., 2015).

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 more generally) 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 (Kingston et al., 2006; Hannah et al., 2014). 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 investigating 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 a single location 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 to the climate system and across to other catchments (Figure 1). By taking into account characteristics such as the role of groundwater or land use in determining the hydrological processes controlling stores and fluxes of water, it becomes possible to better identify the nature and variability of larger-scale climate-land surface-water relationships. Demonstrating this possibility, Laize 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 shorter-term variation and instead show more pronounced multi-annual to decadal-scale variation (e.g. Hanson, Dettinger & Newhouse, 2006; Cuthbert et al., 2019; Sidibe et al., 2019), which may also be transferred to or received from areas beyond the catchment boundary (Fan, 2019; Bouaziz et al., 2018). In contrast, shorter 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 Beek, 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, b).

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 characterise and contextualise the large-scale drivers of hydrological variation fully. 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.

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).

Challenges and opportunities in large-scale hydrology

Key challenges and opportunities for advancing large-scale hydrological research relate to 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’ (Kaser, Grosshauser & Marzeion, 2010; Immerzeel et al., 2020). 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 (Hannah et al. 2011; Ruhi, Messager & Olden, 2018; Beven et al., in press). 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, b). 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, Gradd & Vannier, 2019) and corresponding near-natural hydrological datasets (e.g. Hanel et al., 2018; Moravec et al., 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 Organization (WMO).

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. Vicente-Serrano, Begueria & Lopez-Moreno, 2010; Stagge, Kingston, Tallaksen & Hannah, 2017). 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 – i.e. standardised index values vs. discharge thresholds for irrigation abstractions, transport or electricity generation (Van Lanen et al., 2016). Most significantly, such meteorological indices are unable to take into account 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 et al., 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 et al, 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 (NWP) and general circulation models (GCMs) 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 (Hawkins & Sutton, 2009; Deser, Phillips, Bourdette & Teng, 2012), there are also challenges in terms of how to interpret model output – i.e. 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 skillful forecasts for a particular variable may result from use of different model variables –

e.g. improved forecasts of extreme precipitation events by using forecast vapour flux rather than precipitation itself (Lavers, Zsoter, Richardson & Pappenberger, 2017).

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-scaler 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.

References

Abbott, B. W., Bishop, K. H., Zarnetske, J. P., Hannah, D. M., Frei, R. J., Minaudo, C., … Pinay, G. A water cycle for the Anthropocene. *Hydrological Processes*, 2019, 33, 3046-3052. https://doi.org/10.1002/hyp.13544

Anctil, F. & Coulibaly, P. (2004). Wavelet analysis of the interannual variability in Southern Québec Streamflow. *Journal of Climate*, 17, 163-173.

Beven K., Asadullah A., Bates P., Blyth E., Chappell N., Child S., … Wagener T. (in press), Developing observational methods to drive future hydrological science: can we make a start as a community? *Hydrological Processes - HPToday Invited Commentary*.

Bloschl, G., Bierkens, M. F. P., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., … Zhang, Y. (2019). Twenty-three unsolved problems in hydrology (UPH) – a community perspective. *Hydrological Sciences Journal*, 64, 1141-1158, DOI: 10.1080/02626667.2019.1620507

Bouaziz, L., Weerts, A., Schellekens, J., Sprokkereef, E., Stam, J., Savenije, H. & Hrachowitz, M. (2018). Redressing the balance: Quantifying net intercatchment groundwater flows. *Hydrology and Earth System Sciences*, 22, 6415–6434. doi:10.5194/hess-22-6415-2018

Bower, D., Hannah, D.M. & McGregor, G.R. (2004), Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes*, 18, 2515-2543. doi:10.1002/hyp.1479

Brubaker, K. L., Dirmeyer, P. A., Sudradjat, A., Levy, B. S. & Bernal, F. (2001). A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River basin, *Journal of Hydrometeorology*, 2, 537-557.

Caillouet, L., Vidal, J.-P., Sauquet, E., Graff, B., & Soubeyroux, J.-M. (2019). SCOPE Climate: a 142-year daily high-resolution ensemble meteorological reconstruction dataset over France, *Earth System Science Data*, 11, 241-260, https://doi.org/10.5194/essd-11-241-2019

Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J., Braconnot, P., … Yeh, S. (2015). Understanding ENSO Diversity. *Bulletin of the American Meteorological Society*, 96, 921-938, https://doi.org/10.1175/BAMS-D-13-00117.1

Chifflard, P., Blume, T., Maerker, K., Hopp, L., van Meerveld, I., Graeff, T., … Achleitner, S. (2019). How can we model subsurface stormflow at the catchment scale if we cannot measure it? *Hydrological Processes*. 33, 1378-1385. doi:10.1002/hyp.13407

Cuthbert, M.O., Gleeson, T., Moosdorf, N., Befus, K.M., Schneider, A. & Hartmann, J. (2019). Global patterns and dynamics of climate – groundwater interactions. *Nature Climate Change*, 9, 137-141. doi:10.1038/s41558-018-0386-4

de Graaf, I. E. M., Gleeson, T., (Rens) van Beek, L. P. H., Sutanudjaja, E. H. & Bierkens, M. F. P. (2019). Environmental flow limits to global groundwater pumping. *Nature*, 574, 90–94. doi:10.1038/s41586-019-1594-4

Deser, C., Alexander, M. A., Xie, S. P., Phillips, A. S. (2010) Sea surface temperature variability: patterns and mechanisms. *Annual Review of Marine Science*, 2, 115-143.

Deser, C., Phillips, A., Bourdette, V. & Teng, H. (2012). Uncertainty in climate change projections: the role of internal variability. *Climate Dynamics*, 38, 527–546. http://dx.doi.org/10.1007/s00382-010-0977-x.

Devers, A., Vidal, J.- P., Lauvernet, C., Graff, B. & Vannier, O. (2019). A framework for high-resolution meteorological surface reanalysis through offline data assimilation in an ensemble of downscaled reconstructions. *Quarterly Journal of the Royal Meteorological Society*, Accepted Author Manuscript. doi:https://doi.org/10.1002/qj.3663

Dieppois, B., Durand, A., Fournier, M. & Massei, N. (2013). Links between multidecadal and interdecadal climatic oscillations in the North Atlantic and regional climate variability of northern France and England since the 17th Century. *Journal of Geophysical Research*: Atmospheres, 118, 4359–4372.

Dieppois, B., Pohl, B., Crétat, J., Eden, J., Sidibe, M., New, M., … Lawler, D. M. (2019). Southern African summer-rainfall variability, and its teleconnections, on interannual to interdecadal timescales in CMIP5 models. *Climate Dynamics*, 53: 3505–3527. https://doi.org/10.1007/s00382-019-04720-5

Fan, Y. (2019). Are catchments leaky? *WIREs Water*, 6, e1386. doi:10.1002/wat2.1386

Giuntoli, I., Renard, B., Vidal, J.-P. & Bard, A. (2013). Low flows in France and their relationship to large-scale climate indices. *Journal of Hydrology*, 482, 105–118.

Haddeland, I., Clark, D. B., Franssen, W., Ludwig, F., Voß, F., Arnell, N.W., … Yeh, P. (2011). Multimodel Estimate of the Global Terrestrial Water Balance: Setup and First Results. *Journal of Hydrometeorology*, 12, 869–884, https://doi.org/10.1175/2011JHM1324.1

Hanel, M., Rakovec, O., Markonis, Y., Maca, P., Samaniego, L., Kysely, J. & Kumar, R. (2018). Revisiting the recent European droughts from a long-term perspective. *Scientific Reports*, 8, 9499. https://doi.org/10.1038/s41598-018-27464-4

Hannah, D. M., Demuth, S., van Lanen, H. A. J., Looser, U., Prudhomme, C., Rees, G., … Tallaksen, L. M. (2011). Large-scale river flow archives: importance, current status and future needs. *Hydrological Processes*, 25, 1191–1200.

Hannah, D. M., Fleig, A. K., Kingston, D. G., Stagge, J. H., & Wilson, D. (2014). Connecting streamflow and atmospheric conditions in Europe: State-of-the-art review and future directions. In T. M. Daniell (Ed.), *Proceedings of Flow Regime from International Experimental and Network Data (FRIEND)-Water Conference: Hydrology in a Changing World: Environmental and Human Dimensions*. 363, 401-406.

Hanson, R.T., Dettinger, M.D. & Newhouse, M.W. (2006). Relations between climatic variability and hydrologic time series from four alluvial basins across the southwestern United States. *Hydrogeology Journal*, 14, 1122–1146. doi:10.1007/s10040-006-0067-7

Harpold, A. A., Kaplan, M. L., Klos, P. Z., Link, T., McNamara, J. P., Rajagopal, S. … Steele, C. M. (2017). Rain or snow: hydrologic processes, observations, prediction, and research needs. *Hydrology and Earth System Sciences*, 21, 1–22, https://doi.org/10.5194/hess-21-1-2017.

Hartmann, A., (2016). Putting the cat in the box: why our models should consider subsurface heterogeneity at all scales. *WIREs Water*. doi:10.1002/wat2.1146

Hartmann, A., Gleeson, T., Wada, Y. & Wagener, T. (2017). Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. *Proceedings of the National Academy of Sciences*, 114, 2842-2847. DOI: 10.1073/pnas.1614941114.

Haustein, K., Otto, F. E. Venema, V. Jacobs, P. Cowtan, K. Hausfather, Z. … Schurer, A.P. (2019). A Limited Role for Unforced Internal Variability in Twentieth-Century Warming. *Journal of Climate*, 32, 4893–4917, https://doi.org/10.1175/JCLI-D-18-0555.1

Hawkins, E. & Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, 90, 1095–1108.

Hnley, B. J., Meehl, G., Power, S. B., Folland, C. K., King, A. D., Brown, J. N., … Neukom, R. (2017). Spatial and temporal agreement in climate model simulations of the Interdecadal Pacific Oscillation. *Environmental Research Letters*, 12, 044011.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., … Baillie, J. E. M. (2020). Importance and vulnerability of the world’s water towers. *Nature*, 577, 364–369. doi:10.1038/s41586-019-1822-y

Ionita, M., Lohmann, G., Rimbu, N., & Chelcea, S. (2012). Interannual Variability of Rhine River Streamflow and Its Relationship with Large-Scale Anomaly Patterns in Spring and Autumn. *Journal of Hydrometeorology*, 13, 172-188.

Kaser, G., Grosshauser M., & Marzeion, B. (2010) Contribution potential of glaciers to water availability in different climate regimes, *Proceedings of the National Academy of Sciences*, 107, 20223-20337.

Keller, V. D. J., Tanguy, M., Prosdocimi, I., Terry, J. A., Hitt, O., Cole, S. J., … Dixon, H. (2015). CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications. *Earth System Science Data*, 7, 143–155, https://doi.org/10.5194/essd-7-143-2015.

Keune, J. & Miralles, D.G. (2019). A precipitation recycling network to assess freshwater vulnerability: Challenging the watershed convention. Water Resources Research, 55, 9947-9961. doi:10.1029/2019wr025310

Kingston, D. G., Lawler, D. M., & McGregor, G. R. (2006). Linkages between atmospheric circulation, climate and streamflow in the northern North Atlantic: Research prospects. *Progress in Physical Geography*, 30, 143-174. doi: 10.1191/0309133306pp471ra

Kingston, D. G., Webster, C. S., & Sirguey, P. (2016). Atmospheric circulation drivers of lake inflow for the Waitaki River, New Zealand. *International Journal of Climatology*, 36, 1102-1113. doi: 10.1002/joc.4405

Labat, D., Godderis, Y., Probst, J.-L. & Guyot, J.-L. (2004). Evidence for global runoff increase related to climate warming. *Advances in Water Resources*, 27, 631-642.

Laize, C. & Hannah, D. M. (2010). Modification of climate–river flow associations by basin properties. *Journal of Hydrology*, 389, 186-204. https://doi.org/10.1016/j.jhydrol.2010.05.048.

Lavers, D. A., Prudhomme, C. & Hannah, D. M. (2013). European precipitation connections with large-scale mean sea-level pressure (MSLP) fields. *Hydrological Sciences Journal*, 58, 310-327, DOI: 10.1080/02626667.2012.754545

Lavers, D. A., Zsoter, E., Richardson, D. S. and Pappenberger, F. (2017). An assessment of the ECMWF extreme forecast index for water vapor transport during boreal winter. *Weather and Forecasting*, 32, 1667–1674. https://doi.org/10.1175/WAF-D-17-0073.1.

Le Gros, C., Sauquet, E., Lang, M., Achard, A.-L., Leblois, E. & Biton, B. (2015). The hydrological yearbooks published by the Société Hydrotechnique de France: a valuable source of information on hydrology in France. *La Houille Blanche*, 4, 66-77 https://doi.org/10.1051/lhb/20150048

Lovejoy, S. (2015). A voyage through scales, a missing quadrillion and why the climate is not what you expect. *Climate Dynamics*, 44, 3187–3210. doi:10.1007/s00382-014-2324-0

Markonis, Y. & Koutsoyiannis, D. (2016). Scale-dependence of persistence in precipitation records, *Nature Climate Change*, 6 , 399-401.

Massei, N., Dieppois, B., Hannah ; D. M., Lavers, D. A., Fossa, M., Laignel , B. & Debret, M. (2017). Multi-time-scale hydroclimate dynamics of a regional watershed and links to large-scale atmospheric circulation: Application to the Seine river catchment, France. *Journal of Hydrology*, 546, 262-275, doi: 10.1016/j.jhydro1.2017.01.008, 2017.

Menary, M. B., Hodson, D. L. R., Robson, J. I., Sutton, R. T., Wood, R. A., and Hunt, J. A. (2015). Exploring the impact of CMIP5 model biases on the simulation of North Atlantic decadal variability, *Geophysical Research Letters*, 42, 5926– 5934, doi:10.1002/2015GL064360.

Milner A. M., Khamis K., Battin T. J., Brittain J. E, Barrand N. E., Fuereder L., … Brown L. E. (2017), Glacier shrinkage driving global changes in downstream ecosystems, *Proceedings of the National Academy of Sciences*, 114, 9770-9778 DOI: 10.1073/pnas.1619807114

Moravec, V., Markonis, Y., Rakovec, O., Kumar, R., & Hanel, M. (2019). A 250- year European drought inventory derived from ensemble hydrologic modeling. *Geophysical Research Letters*, 46, 5909– 5917. https://doi.org/10.1029/2019GL082783

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, 319, 573–574.

Prudhomme, C., Giuntoli, I., Robinson, E. L., Clark, D. B., Arnell, N.W., Dankers, R., … Wisser, D. (2014). Hydrological droughts in the 21st century: hotspots and uncertainties from a global multi-model ensemble experiment, *Proceedings of the National Academy of Sciences (PNAS)*, 111, 3262-3267. DOI: 10.1073/pnas.1222473110

Renard, B., & Thyer, M. (2019). Revealing hidden climate indices from the occurrence of hydrologic extremes. *Water Resources Research*, 55, 7662– 768 https://doi.org/10.1029/2019WR024951

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W. & Lo, m.-H. (2018). Emerging trends in global freshwater availability. *Nature,* 557, 651–659. doi:10.1038/s41586-018-0123-1

Ruhi, A., Messager, M. L. & Olden, J. D. (2018). Tracking the pulse of the Earth's fresh waters. *Nature Sustainability,* 1, 198–203. doi:10.1038/s41893-018-0047-7

Salinger, M., Renwick, J. & Mullan, A. (2001). Interdecadal Pacific Oscillation and South Pacific climate. *International Journal of Climatology,* 21, 1705-1721. doi:10.1002/joc.691

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D. B., … Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences (PNAS)*, 111, 3245-3250; https://doi.org/10.1073/pnas.1222460110

Sidibe, M., Dieppois, B., Eden, J., Mahé, G., Paturel, J. E., Amoussou, E., … Lawler, D. (2019). Interannual to Multi-decadal streamflow variability in West and Central Africa: interactions with catchment properties and large-scale climate variability. *Global and Planetary Change*, 177, 141-156. https://doi.org/10.1016/j.gloplacha.2019.04.003

Spracklen, D., Arnold, S. & Taylor, C. (2017) Observations of increased tropical rainfall preceded by air passage over forests. *Nature,* 489, 282–285. doi:10.1038/nature11390

Stagge, J. H., Kingston, D. G., Tallaksen, L. M., & Hannah, D. M. (2017). Observed drought indices show increasing divergence across Europe. *Scientific Reports*, 7, 14045. doi: 10.1038/s41598-017-14283-2

Taylor, R.G. 2009 Rethinking water scarcity: the role of storage. *Eos*, 90, 237-239

Thompson, D. W. & Wallace, J. M. (2000). Annular Modes in the Extratropical Circulation. Part I: Month-to-Month Variability. *Journal of Climate*, 13, 1000–1016, https://doi.org/10.1175/1520-0442(2000)013<1000:AMITEC>2.0.CO;2

Todd, M. C., Taylor, R. G., Osborn, T. J., Kingston, D. G., Arnell, N. W., & Gosling, S. N. (2011). Uncertainty in climate change impacts on basin-scale freshwater resources: Preface to the special issue: The QUEST-GSI methodology and synthesis of results. *Hydrology & Earth System Sciences*, 15(3), 1035-1046. doi: 10.5194/hess-15-1035-2011

Van Lanen, H. A. J., Laaha, G., Kingston, D. G., Gauster, T., Ionita, M., Vidal, J.-P., … Van Loon, A. F. (2016). Hydrology needed to manage droughts: The 2015 European case. *Hydrological Processes*, 30(17), 3097-3104. doi: 10.1002/hyp.10838

Van Loon A. F., Gleeson T., Clark J,. Van Dijk A. I. J. M, Stahl K., Hannaford J., … Van Lanen H.A.J. (2016a), Drought in a human-modified world: reframing drought definitions, understanding and analysis approaches, *Hydrology and Earth Systems Science*, 20, 3631-3650 DOI: 10.5194/hess-20-3631-2016

Van Loon A. F., Gleeson T., Clark J,. Van Dijk A. I. J. M, Stahl K., Hannaford J., … Van Lanen H.A.J. (2016b), Drought in the Anthropocene, *Nature Geosciences*, 9, 89-91 DOI: 10.1038/ngeo2646

Vernon-Kidd & Kiem, 2010, Quantifying Drought Risk in a Nonstationary Climate, *Journal of Hydrometeorology*, 11, 1119-1131

Vicente-Serrano, S. M., Beguería, S. & López-Moreno, J. I. (2010). A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1

Vicente‐Serrano, S. M., Peña‐Gallardo, M., Hannaford, J., Murphy, C., Lorenzo‐Lacruz, J., Dominguez‐Castro, F., ... Vidal, J.-P. (2019). Climate, irrigation, and land cover change explain streamflow trends in countries bordering the Northeast Atlantic. *Geophysical Research Letters*, 46, 10821– 10833. https://doi.org/10.1029/2019GL084084

Wanner, H., Bronnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B. & Xoplaki, E. (2001). North Atlantic Oscillation – concepts and studies. *Surveys in Geophysics*, 22, 321–82.

Wine, M. L. & Davison, J.H. (2019) Untangling global change impacts on hydrological processes: Resisting climatization. *Hydrological Processes*, 33, 2148– 2155. https://doi.org/10.1002/hyp.13483

WWAP (UNESCO World Water Assessment Programme). 2019. *The United Nations World Water Development Report 2019: Leaving No One Behind*. Paris, UNESCO.

Zipper, S. C., Carah, J. K., Dillis, C., Gleeson, T., Kerr, B., & Rohde, M. M., (2019). Cannabis and residential groundwater pumping impacts on streamflow and ecosystems in Northern California Cannabis and residential groundwater pumping impacts on stream fl ow and ecosystems in Northern California. *Environmental Research Communications*, 1, 125005. doi:https://doi.org/10.1088/2515-7620/ab534d

Figure captions

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).

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

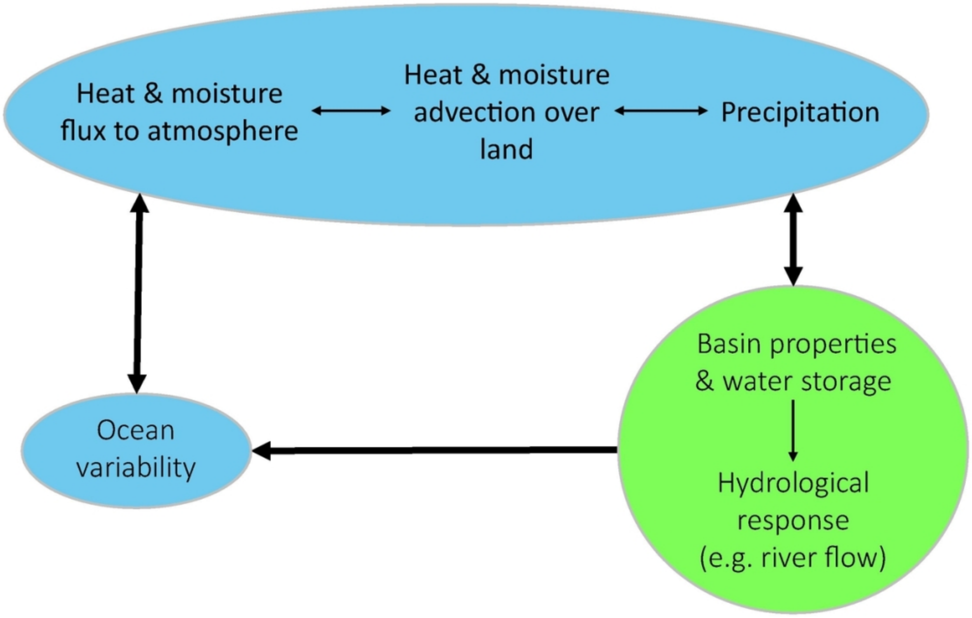
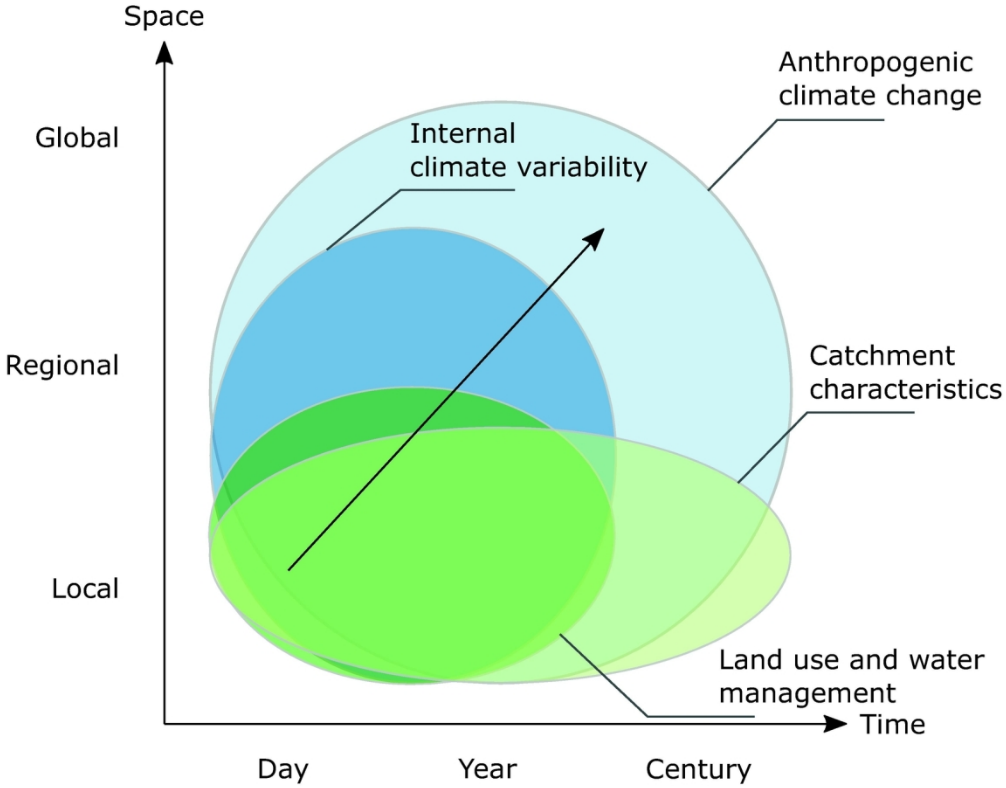


Figure 1 A conceptual model of the links between large-scale ocean-atmosphere variation and terrestrial hydrological variability, including the filtering effect of land surface conditions (adapted from Hannah, Fleig, Kingston, Stagge & Wilson, 2014).



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