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Knowledge gaps in our perceptual model of Great Britain's hydrology

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Abstract

There is a no lack of significant open questions in the field of hydrology. How will hydrological connectivity between freshwater bodies be altered by future human alterations to the hydrological cycle? Where does water go when it rains? Or what is the future space–time variability of flood and drought events? However, the answers to these questions will vary with location due to the specific and often poorly understood local boundary conditions and system properties that control the functional behaviour of a catchment or any other hydrologic control volume. We suggest that an open, shared and evolving perceptual model of a region's hydrology is critical to tailor our science questions, as it would be for any other study domain from the plot

All our knowledge has its origins in our perception.
Leonardo da Vinci (1452-1519).

to the continental scale. In this opinion piece, we begin to discuss the elements of and point out some knowledge gaps in the perceptual model of the terrestrial water cycle of Great Britain. We discuss six major knowledge gaps and propose four key ways to reduce them. While the specific knowledge gaps in our perceptual model do not necessarily transfer to other places, we believe that the development of such perceptual models should be at the core of the debate for all hydrologic communities, and we encourage others to have a similar debate for their hydrologic domain.

KEYWORDS
catchments, hydrology, knowledge gaps, perceptual model, science questions

1 | INTRODUCTION

There is no lack of significant open questions in the field of hydrology, regardless of whether we are trying to understand catchments, groundwater aquifers, hillslopes or any other possible control volume (an incomplete list of examples is: Beven, 2019a, 2019b; Beven et al., 2019; Bishop et al., 2008; Blöschl et al., 2019; Brown et al., 2010; Fan, 2019; Fenicia et al., 2013; Lavers et al., 2020; McDonnell, 2003; McDonnell et al., 2010; Milly et al., 2008; Montanari et al., 2013; Seneviratne et al., 2010; Sivapalan, 2009; Tetzlaff et al., 2009; Van Loon, 2015; Wagener et al., 2010, 2021). Example questions from these papers include: What is the spatial and temporal variability of flood and drought events, is this variability changing, and how could it be altered by land management and climate change? What is the importance of preferential flow for groundwater recharge? How do vegetation and soils interact and evolve with climate to control evapotranspiration? Where does water go when it rains? How will hydrological connectivity between freshwater bodies (rivers, floodplains, lakes, groundwater) be altered by future human alterations to the hydrological cycle? How do changes in hydrological systems interact with, and feedback to social systems? What is the total subsurface storage at scales useful for defining some “process response unit”? What are the controls on fluxes of water and solutes in different layers in relation to subsurface hydrological functioning and land management? And so forth.

However, most of these questions do not have one general definitive answer, even though we usually understand the basic physics underlying the problem. Rather, the answer will vary with the location we study, as well as with the space–time scale or time period we analyse. The search for a unique and general answer is elusive unless we focus on basic process mechanisms due to the dominant control of widely varying local boundary conditions and system properties (McDonnell et al., 2007). The main question for hydrology is rather how its processes manifest themself at the chosen scale of interest given the specific boundary conditions and physical system properties present. Our hydrologic world shows tremendous space–time variability of environmental conditions, further modified by varying degrees of human activity, including in Great Britain (consisting of Scotland, Wales and England) where the landscape has been managed intensively for hundreds of years (Crane, 2017). Therefore, for a particular location, such as a catchment, we must assess the above questions in the context and the history of co-evolving climate, geology, land cover, topography, soils, water management and so forth (see Bloomfield et al., 2011, for an example in the Thames River basin). Studying a specific hydrologic question for a particular location and time period at a particular space–time scale is as much a problem of understanding the influence of local boundary conditions and system properties (Beven, 2019a) as it is a question of understanding some fundamental laws and mechanisms (Dooge, 1986). Here, we will use Great Britain (GB) as our target region for this discussion. GB provides significant variability in hydrologically relevant characteristics as discussed below but does not contain any transboundary basins. GB is particularly diverse in terms of its hydrogeology with units varying in age from Pre-Cambrian to Recent, resulting in significant diversity in aquifer types, while its climate is predominantly temperate oceanic in the Köppen-Geiger climate classification, though with some upland sub-arctic oceanic areas and highly varying rainfall patterns (Darwish et al., 2018).

We propose that an open, shared and evolving perceptual model of GB's hydrology is critical to tailor our science questions, as it would be for any other study domain from the plot to the continental scale. The accumulated knowledge about the hydrology of a particular place—obtained through a multitude of activities including direct observations, experimentation or modelling—forms a hydrologist's perceptual model of that place. A perceptual model is the summary of our current understanding and knowledge of a particular system (e.g. a catchment) presented in qualitative or quantitative ways (Beven, 1987, 2009, 2012; Gupta et al., 2008; Wagener et al., 2007; Westerberg et al., 2017). We assume here that a perceptual model is a (at least partially qualitative) conceptualization of a hydrologic system, thus similar to conceptual models used in hydrogeology where such conceptualizations have played a more important role than in other sub-domains of hydrology so far (Enemark et al., 2019). At some level, such perceptual models are specific to an individual person because experience and knowledge levels vary between us, and we have been taught to access new information in different learning frameworks – thus enabling us to escape Plato's cave with varying degrees of success (https://en.wikipedia.org/wiki/Allegory_of_the_cave).

In this opinion piece, we start to discuss the elements of and point out some knowledge gaps in the perceptual model of the terrestrial water cycle of Great Britain (GB). We further provide some ideas about how one might fill these gaps and thus advance our knowledge and understanding as a community. In a previous related commentary, we already discussed the current need for observational advancements (Beven et al., 2019). Here we provide the more detailed context, partially driving the need for this advancement. We propose that attempting to develop a shared perceptual model of the hydrology of GB (or of elements of its hydrology) is the right vehicle to galvanize the hydrologic community in this region to share what we know and what we do not know. This discussion should reveal how widespread our questions are (Is a question limited to a small domain?), and how transferrable newly gained knowledge is if we were able to answer a specific question (Does the answer transfer to other places, maybe with a few additional measurements, or would we have to investigate each location in the same way?). How similar or dissimilar perceptual models are for different locations, and therefore how transferable, is part of the question. It also forces us to argue why and how new understanding gained in one location might be helpful in a different location and to assess the trade-off between information gained and effort made to collect this information.

2 | TOWARDS A PERCEPTUAL MODEL OF GREAT BRITAIN'S HYDROLOGY

Currently, an open and shared perceptual model for GB's hydrology does not exist, which is why we make a start here. Figure 1 provides a simple generic perceptual model of catchment hydrology with typical processes one might find in regions with temperate oceanic climate while ignoring spatial variability of processes for now. The model contains the main catchment functions that we might aim to define through the perceptual model (Black, 1997; Wagener et al., 2007). These catchment functions include how and where water/energy is partitioned inside a catchment (through interception, infiltration, percolation, recharge etc.), how and where water is stored (canopy, depression, channel, groundwater, soil moisture, etc.) and how and where water is released from our control volume, that is, the catchment (actual evapotranspiration, streamflow, inter-catchment groundwater, deep percolation, interception loss etc.). Topographically delineated catchments will often not be closed in terms of their subsurface fluxes (e.g. Fan, 2019; Liu et al., 2020; Toth, 1963). Catchments will further vary in the sense that different stores and fluxes will dominate depending on the specific physical and climatic setting. For example, variability in precipitation and energy across GB is a first order control on differences in the long-term water balance, separated further by geological differences, which can lead to climatically similar regions being hydrologically different (Gnann et al., 2020; Laizé & Hannah, 2010; Wilson et al., 2013). A perceptual model for a particular place is also unlikely to be constant in time, but rather will evolve with changing climatic boundary conditions (e.g. increasing or decreasing the release through atmospheric losses); with land-use or water management alterations (e.g. changing partitioning at the land surface, reservoir storage and abstractions); with geomorphological change at the coast or inland after flood events; or with the availability of new types of observations. Perceptual models will also differ in their level of granularity, depending on the information available, the

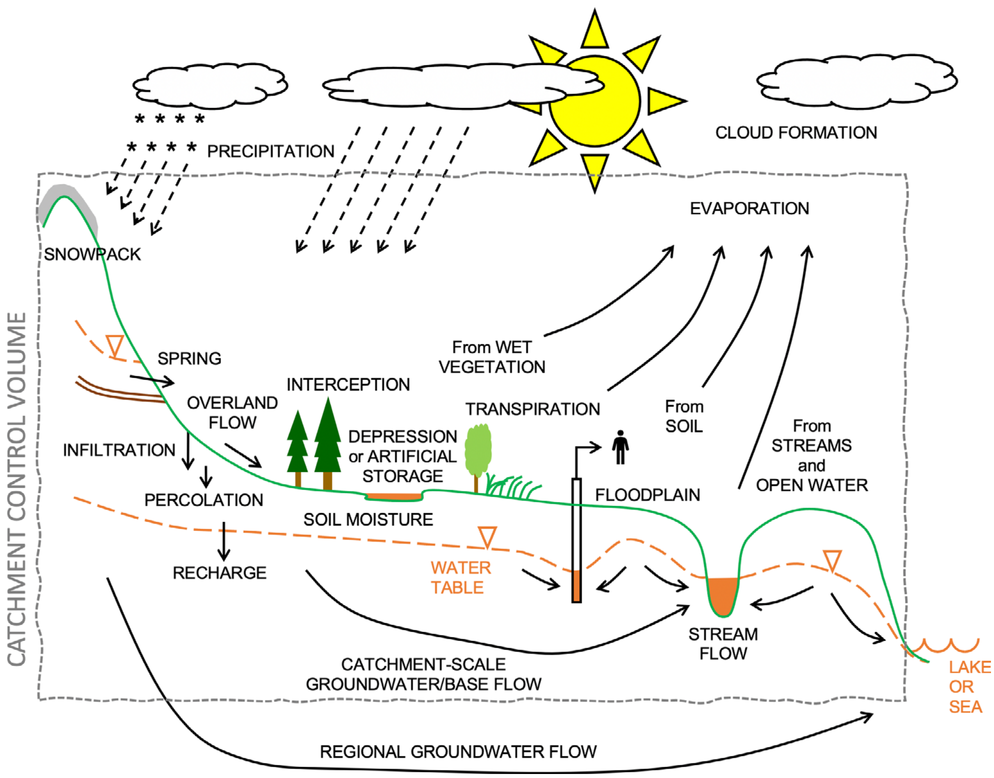

FIGURE 1 The image shows a simple perceptual model (term as defined in Beven, 2012) of generic terrestrial hydrological processes potentially occurring in a typical GB catchment (image is building on Brutsaert, 2005 and Toth, 1963). The perceptual model should visualize main catchment functions related to water and energy, including partition (interception, infiltration, percolation, etc), storage (canopy, depression, channel, groundwater, soil moisture, etc.) and release (actual evapotranspiration, streamflow, groundwater, interception loss etc.) (as defined in Black, 1997 and Wagener et al., 2007). Additional functions such as incatchment transmission of fluxes could also be part of the perceptual model

subsequent purpose of the model (e.g. to build a simulation model or to define an experiment), or the preferences of the hydrologist who created it (Beven & Chappell, 2021; Wagener et al., 2021).

We could start with a common initial perceptual model for a type of catchment or a larger domain which is subsequently tailored when more specific locations are considered (see the models of everywhere concept by Beven, 2007, and Blair et al., 2019; or a specific example for groundwater recharge by Hartmann et al., 2015). Perceptual models of some places have been published and discussed in great detail. McGlynn et al. (2002) discussed the evolution of the perceptual model of hillslope flowpaths in the Maimai catchment, New Zealand. Wrede et al. (2015) and Lischeid (2008) discussed how competing hypotheses about potential perceptual models might be tested using a multitude of activities, including experimentation and modelling. Kaandorp et al. (2018) took a relatively sophisticated pre-existing perceptual framework and tailored it to four catchments across Europe (including the Thames, GB), with necessary simplifications to account for different types of information available in the different basins. The authors subsequently used the perceptual models within a DPSIR (Drivers, Pressures, State, Impact and Response model of intervention) framework to assess the implications for groundwater-surface water interactions under multiple (resource and quality) stressors. This perceptual framework grew out of a detailed typology of groundwater-surface water interactions previously established by Dahl et al. (2007), guided by common considerations of catchment scale, geomorphology and aquifer lithology.

Different hydrologists will likely start with somewhat dissimilar perceptual models when analysing the same location, though we hope that these perceptual models would converge with time as our knowledge increases and as that knowledge is shared and debated—at least regarding a system's dominant characteristics and functions. If our perceptual models do not converge and remain significantly different, even if we have access to the same information, that is, maybe because multiple hypotheses about how the system might work are consistent with available data, then this suggests that additional information is still required through new measurements, detailed modelling or other means to resolve the differences—thus guiding future research. If our scientific world was perfect and we could measure and characterize everything we wanted, then our perceptual models would just be based on physical principles (our hydrologic laws) without the need for subjective interpretations, though this would appear to be currently unachievable in most cases due to our persistent inability to measure all system properties, states and boundary conditions at relevant resolutions (Beven et al., 2019; Savenije, 2009).

Various strategies to build perceptual models have been proposed (Buttle, 2006; Wagener et al., 2007). For example, in the US, the hydrologic landscapes idea of Winter (2007) assumes basic controls of climate, topography and geology, and has been applied across scales (Wolock et al., 2004). In the United Kingdom, the Hydrology of Soil Types (HOST) framework, which is driven by conceptualizations and characterisations of shallow subsurface properties and hydrogeology (Boorman et al., 1995), might be the closest available strategy developed specifically for our study domain. However, internal inconsistences and a level of complexity beyond our knowledge have been highlighted as problems with the current framework (e.g. Chappell & Ternan, 1992). Though the system might still be a good starting point for further development. HOST is one of the foundations of the Flood Estimation Handbook (Centre for Ecology and Hydrology, 1999), the UK industry-standard approach to estimate design floods. However, adding further controls in a perceptually more consistent way could be done in a top-down fashion using a comparative hydrology approach (Falkenmark & Chapman, 1989) or machine learning strategies (e.g. Nearing et al., 2021) to identify patterns of likely similarity in catchment function. Starting with climate and working downwards (Bower et al., 2004; Sawicz et al., 2011), one could add or replace controlling processes across space scales (e.g. Addor et al., 2018) and time scales (Sivapalan et al., 2003). Alternatively, one could attempt a bottom-up strategy using process-models if a high-granularity is considered from the beginning (e.g. Troch et al., 2013).

Key hydrologically relevant characteristics of GB's landscape that would form the basis for a national perceptual model are organized in Figure 2 (left column) – grouped into relatively coarse classes to simplify discussion (derived from Coxon et al., 2020). GB's landcover is dominated by grassland with arable agricultural regions being more prominent in the east, while patches of forest and urban centres characterize smaller areas. The topography of GB is characterized by rolling hills, having led to approaches such as the topographic index (Beven & Kirkby, 1979), which quantifies the hydrologic relevance of this feature on saturated areas and the wider hydrologic response. Higher topographic variability is found in the north and in the west. Peat cover and soils developed from glacial till influence infiltration capacity, leading to faster responding catchments in areas with higher clay content in southern GB and upland peat covered areas in southwest England, Wales, the Pennine chain and large parts of Scotland. In southern England, hydrology is strongly influenced by highly permeable geology within and across catchments, leading to significant groundwater recharge rates and inter-catchment groundwater exchange.

This landscape has partially evolved in response to climatic and human impacts (e.g., landscape cover change), and will continue to do so in the future (Figure 2, right column). It is important to consider that this is a process of feedbacks and interactions (and not a one-way impact chain). For example, the distribution of different rock types has resulted in the current topography (higher land in the west associated with more durable formations), thus in turn affecting the distribution of orographic precipitation in GB. In many areas, landscape and hydrology still reflect what was left by glacial and periglacial processes at the end of the last glaciation. Similarly, topography and landscape (for example the location of exploitable natural resources, such as coal) have affected where urbanization, and hence human impact, has developed. Due to anthropogenic climate change the intensity of extreme rainfall events is particularly projected to increase in the east and the south of GB (Kendon et al., 2014). This expected change goes along with projections of increasing numbers of hot days—defined as days with a temperature above 25°C—in the southern parts of GB, especially around London (Kennedy-Asser

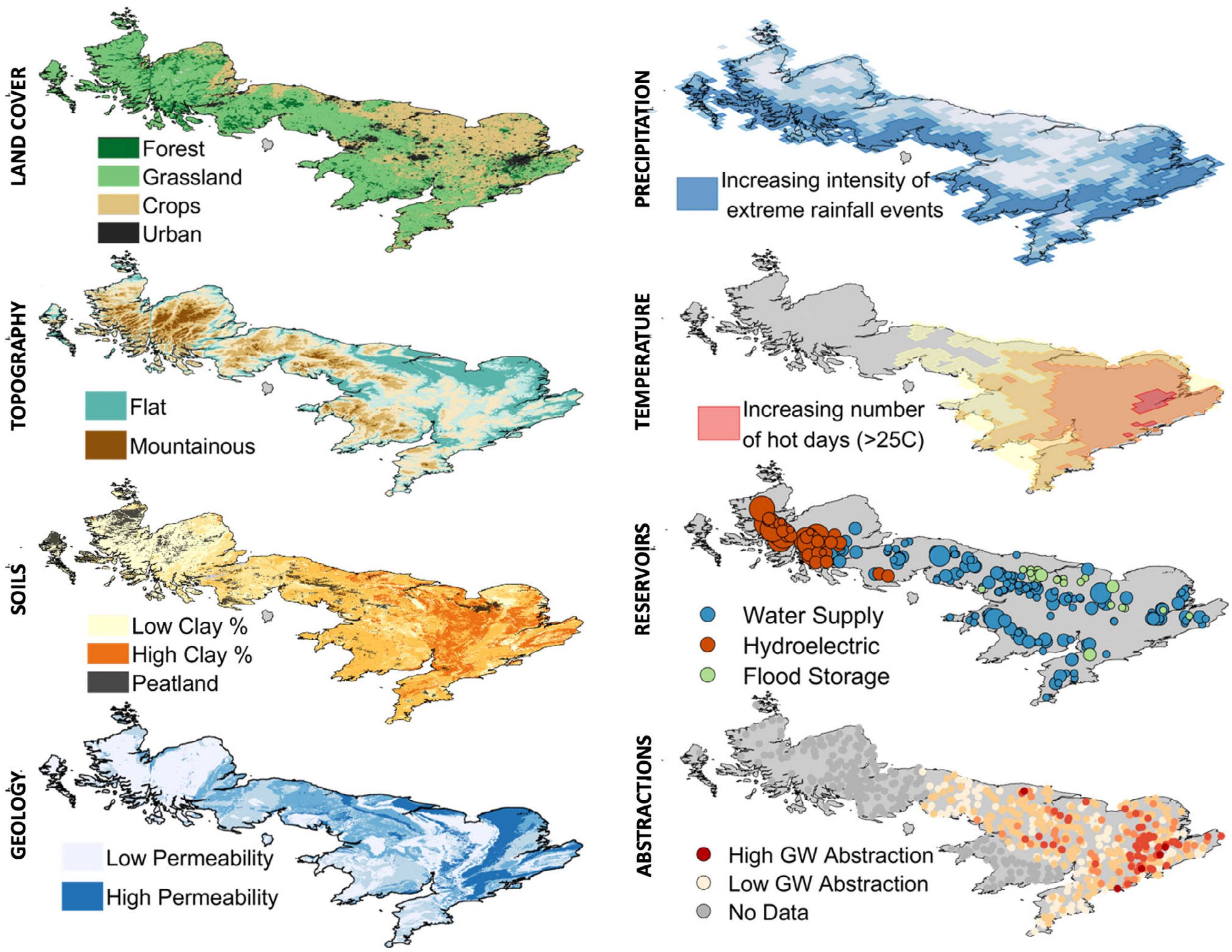

FIGURE 2 Data layers for a perceptual model of GB's hydrology separated into landscape characteristics (left column) and climate change as well as human activities (right column). The organization of each layer is relatively simple on purpose to enable subsequent discussion. Left column from top to bottom: Land cover from CEH land cover map 2015 and grouped into four broad classes. Topography is 50 m NextMap DEM classified into four classes - 500 m. Soils – Percentage clay obtained from soils data from Cranfield and James Hutton institute. Some minor gap filling was applied. Classes are 30% for 'high clay'. Peat cover is also included given its role in controlling water flow paths and its widespread cover in GB (Xu et al., 2018). Geology - permeability map is taken from the BGS (www.bgs.ac.uk/datasets/permeability/). Dark blue is 'very high', light blue is 'very low' class. Right column from top to bottom: Precipitation projections taken from UKCP18 12 km regional climate projections – Averaged across all ensemble members. Precipitation is not bias corrected (though we found spatial patterns to be consistent with bias corrected products). Calculated average 5-day annual maximum for a baseline period (1980–2000) and far future (2060–2080) – These periods match those used by the met office. Calculated percentage change in the 5-day annual maximum. Light blue is 20% change. Temperature projections taken from UKCP18 12 km regional climate projections – Average taken from all ensemble members. Calculated average number of 'hot days' > 25°C per year for baseline period (1980–2000) and far future (2060–2080) – These periods match those used by the met Office. Calculated change in number of days exceeding this threshold. Light yellow is 1–3 additional days per year of >25°C, red is >14 additional days per year of >25°C. reservoir data taken from Coxon et al. (2020) – Organized by type (colours) and storage capacity. Groundwater abstractions data taken from Coxon et al. (2020)

et al., 2021). More direct influences on the terrestrial hydrologic cycle come from human activities such as reservoir building and groundwater abstractions. Reservoirs for water supply and flood storage are widely distributed across England and Wales (though less common in the more groundwater dominated east), while reservoirs in Scotland largely focus on hydroelectric power production in line with the higher topographic gradient found there. Regions of high groundwater abstractions can especially be found around urban centres and where aquifers are more productive.

3 | SOME KEY KNOWLEDGE GAPS IN OUR PERCEPTUAL MODEL OF GREAT BRITAIN'S HYDROLOGY

So, what are some of the gaps that we currently see in our perceptual model of GB's hydrology? Below, we discuss—and visualize in Figure 3— some of the existing knowledge gaps that need to be overcome. These gaps limit our ability to quantify the catchment functions discussed above, and they restrict our predictive understanding regarding how these functions might be altered by climate change or direct human activity, that is, what is the elasticity of the hydrologic system?

1. Accounting for groundwater fluxes to close *open water balances*: GB contains large regions of highly permeable aquifers, where catchments are regularly connected to a wider regional groundwater system (Allen et al., 1997), resulting in losses or gains of water through subsurface flowpaths (Ameli et al., 2018). In the wetter regions of the world, like GB, where subsurface flow dominates riverflow and most rivers are perennial, this subsurface-surface exchange is likely dominated by subsurface permeability and location of the catchment within the wider landscape (Allen et al., 2010; Fan, 2019) – which can be an issue even in small headwater catchments (Muñoz et al., 2016). While the presence of such losing or gaining catchments is widely acknowledged, we lack a GB wide quantification of this problem, thus leading for example to unresolved problems in modelling these basins (Lane et al., 2019). The differences between the surface (topographic) and groundwater basin (and its seasonal and inter-annual variability) are unquantified for all but a few case study catchments (Hughes et al., 2011).
Quantification of this groundwater exchange will also require a more precise quantification of other related fluxes and an attribution of uncertainties in the water balance to its components, e.g. precipitation (Liu et al., 2020). We require a nationally consistent perceptual understanding of catchment and aquifer controls on spatio-temporal variation in recharge and groundwater discharge to rivers. Mansour et al. (2018) produced the first national long term average model of recharge but is it consistent with existing perceptual models of the wider terrestrial hydrosphere? Similarly, there is no equivalent national perceptual model of the variability of GW discharge or of GW-SW interaction along the river network.
2. *Coastal catchments*: River gauges will typically be located at some distance from the coast, which leaves a potentially significant area in between gauged catchments and the coast for islands such as GB. Even though catchment water balances are influenced by distance to the coast (e.g. Fan, 2019; Luijendijk et al., 2020), these influences are generally poorly quantified, e.g. due to a lack of tidal gauges in case of GB. Currently submarine groundwater discharge is poorly constrained in GB although it plays a significant role in regulating seawater intrusion (particularly along the eastern coast) as well as the flux of nutrients and other diffuse pollution to the near costal marine environment (Slomp & Van Cappellen, 2004; Werner et al., 2013). Better quantification of this coastal exchange through rivers and sub-marine groundwater is needed to understand potential future changes to coastal ecosystems, including the potential for future compound flood events (Moftakhari et al., 2019; Speight et al., 2015). Coastal flooding and erosion are significant challenges around GB (Climate Change Committee, 2018), with sea level rise set to increase the importance of interactions between storm surges, wave overtopping and hydrological systems (rivers, urban drainage and agricultural drainage). Complex dependencies between these systems exist over multiple scales (Svensson & Jones, 2002, 2004), although progress has been made in developing integrated frameworks for combined risk assessments of inland and coastal flooding (Lamb et al., 2010).
3. *Data uncertainty*: It is not just scientific questions regarding the importance and character of hydrologic processes that require tailoring to specific places. It is highly likely that assessments of uncertainties in the measurements of all hydrological variables are

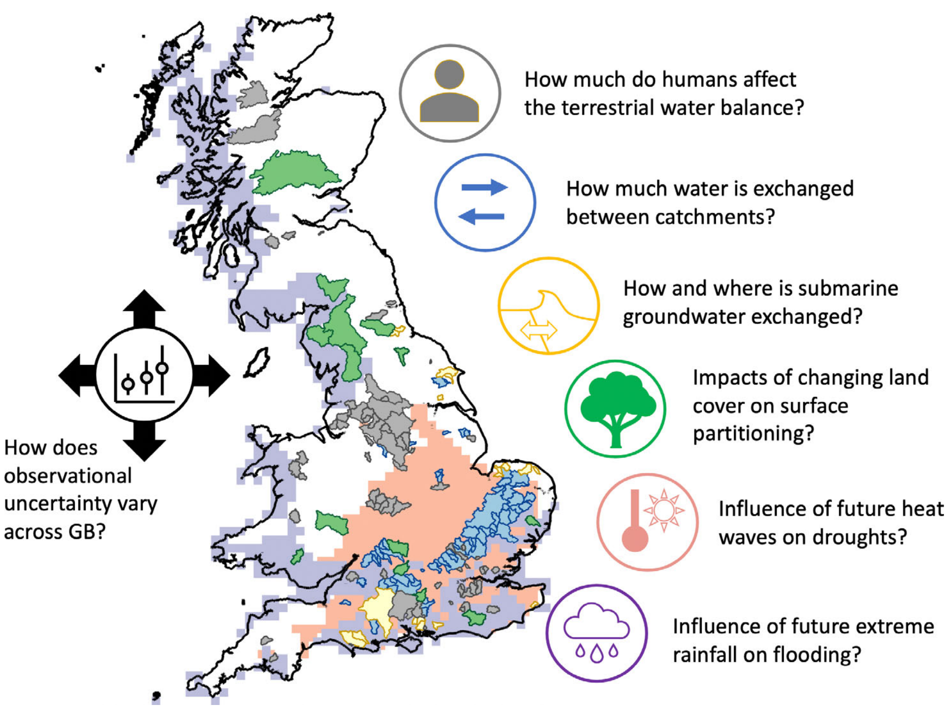

FIGURE 3 Key knowledge gaps in our perceptual model of GB hydrology. Human influences–grey catchments with 'high' human influences from either urbanization (>25% coverage), high surface water or groundwater abstractions (>0.5 mm/day) or high reservoir capacity relative to mean flow. Groundwater exchange–blue and yellow catchments underlain by >50% 'very high' permeability aquifers (www.bgs.ac.uk/datasets/permeability/), with yellow catchments also being within 10 km of the coast. Land cover changes– green catchments are priority catchments on the 'Woodland for Water' scheme that aims to create woodland to reduce flood risk. Climate change – Light red shaded area is >7 additional days >25°C from UKCP18 data (see Figure 2 caption), while purple shaded area is >20% increase in the 5-day annual maximum from UKCP18 data (see Figure 2 caption)

place and time specific and variable across GB. An assessment of stage-discharge rating curves by Coxon et al. (2015) for 500 UK gauging stations showed that the uncertainty in these curves varied significantly across catchments and across flow ranges, thus showing that the assumption of a single generic degree of expected uncertainty across a wide range of catchments would be misleading. Hence, we have to consider that the insight gained from such observations is associated with uncertainties that vary across locations as well as in time. This will also apply to the post-processing of hydrological variables (Herschy, 1999) as well as their use in modelling and forecasting (Flack et al., 2019). There are also widely acknowledged uncertainties in both catchment-wide estimates of precipitation and evapotranspiration, making it difficult to close the water balance without allowing for that uncertainty. Though use of new sensors might help to reduce such uncertainties (e.g. Wallbank et al., 2021). This problem is for example reflected in the apparent wide variations in runoff coefficients, even in fast responding catchments (e.g. Beven, 2019b).

4. *Climate change impacts on GB hydrology*: Climate change projections suggest that atmospheric circulation patterns across GB will change, though the extent of this change is highly uncertain (Shepherd, 2014). How climate and weather patterns (especially with regard to extremes) will be altered is thus unclear, but some trends are more likely than others (Garner et al., 2017; Watts et al., 2015). Within currently available historical observations, air temperatures have risen, and winter rainfalls have become more intense, while projections suggest reduced summer flows and larger and more frequent flooding, although with large uncertainties (Cloke et al., 2013; Kay et al., 2021; Watts et al., 2015). Probabilistic event attribution studies have shown that historical greenhouse gas emissions have already contributed to increased risk of flooding within the context of specific extreme events (quantified for the floods in winter 2013–14, which affected large parts of GB, by Schaller et al., 2016 and Kay et al., 2018). Future GB precipitation and temperature extremes are expected to change in both magnitude and frequency, and even in the type of event (De Luca et al., 2019; Kendon et al., 2014). An increasing frequency of localized summer storms is projected to go hand in hand with more frequent and more widespread droughts (Guillod et al., 2018). Which catchments are more sensitive to changing atmospheric boundary conditions and drivers, as well as land cover change (Bower et al., 2004; Prudhomme et al., 2009a, 2009b)? Where will changing summer storm intensities lead to increased flooding, how might this affect spatial changes in recharge, and where will the response of extreme rainfall be more dampened (Gnann et al., 2020)? Across drought affected domains, which catchments will see the drought signal move through soil moisture and groundwater stores more quickly than others, and which catchments will recover first when the drought subsides (Wendt et al., 2020)? For example, there is evidence of increased frequency and magnitude of groundwater droughts over the 20th century based on an analysis of long-term GW level records in the GB chalk – driven by increased evapotranspiration due to global warming (Bloomfield et al., 2019). How these questions are addressed should depend on how the hydrological perceptual model varies across GB.
5. *Human activity*: Society is increasingly modifying terrestrial fluxes of water through land-use change, abstractions/returns, damming and other activities, leaving very few GB catchments with a 'natural' flow regime (Harrigan et al., 2018). Jones et al. (2019) suggest that 97% of GB's river network is fragmented through artificial barriers, with barrier density estimates of 0.48 barriers/km in Scotland to 0.63 barriers/km in Wales, and 0.75 barriers/km in England. Further large-scale infrastructure to buffer future hydrological extremes has already been recommended by the National Infrastructure Commission (NIC, 2018a, 2018b, 2018c), while policy changes are expected to reform water abstraction management. In recent years, the impacts of human activity on river flows has been studied, e.g. using paired catchment analyses (Van Loon et al., 2019). However, many human impacts are poorly quantified or even unquantified since abstraction estimates and operational reservoir rules are held by private companies who perceive it as a disadvantage to release such information. Attributing and disentangling the influence of large scale (e.g. climatic) and local scale (e.g. abstractions) influences of hydrologic regimes is therefore problematic (Wendt et al., 2020). For example, natural recharge to groundwater aquifers is complemented by leakage from almost half a million kilometres of water pipes running through the UK's subsurface, which, across England and Wales alone, lose just under 3 billion litres of water every day due to leaks (WaterUK, 2020). These interactions are further complicated by the co-evolution of society and climate. For example, future changes in temperature will likely lead to changes in agricultural practices and a need for more irrigated agriculture, thus exacerbating pressures on water supplies. A key question is therefore how strongly our perceptual models are defined by anthropogenic activities (Westerberg et al., 2017)?
6. *Land cover changes*: Climatic changes such as those to precipitation and atmospheric evaporative demand explain significant fractions of the larger-scale trends in observed streamflow patterns in the United Kingdom (Vicente-Serrano et al., 2019). However, land-use change can have significant local/regional impacts on catchment functions including recharge or evapotranspiration in relation to floods and droughts (Dadson et al., 2017). English water companies have recently committed to planting 11 million trees by 2030 as part of their commitment to achieving 'net zero' carbon emissions, (WaterUK, 2021) and the United Kingdom government has committed to protecting an additional 4000km^2 of land across the United Kingdom while increasing woodland to 12% of the total land cover by 2060 (DEFRA, 2019). Will these changes—that will alter the partitioning of moisture and energy at the land surface—have a measurable impact on river flows and groundwater recharge? This effort is unlikely to impact GB hydrology as a whole, but it might matter locally depending on where trees are planted. It ties in with a shift in management interventions towards more natural solutions that can reduce the frequency and severity

of flooding, though questions about the overall benefit and possible negative side-effects of such measures remain (Cooper et al., 2021; Page et al., 2020). Open questions also remain regarding the efficacy of such approaches and the sensitivity of runoff extremes or low flows to land cover change for catchments across space and time scales, as well as their wider (possibly unintended) impact on ecosystem services. Most observations on the effects of land cover on flooding originate from a very limited number of small catchments such as the Plynlimon catchment experiments (see Marc & Robinson, 2007), with large-scale impacts still unclear – that is, most studies to date suggest you cannot see land-use change impacts on floods in catchments >50km^2 (Dadson et al., 2017; Rogger et al., 2017). Nonetheless flooding in larger catchments can be mitigated through the use of off-channel storage areas and by reconnecting rivers with natural floodplains. While land cover changes are accelerating, their detailed consequences are thus complex and not easy to determine (Levia et al., 2020).

4 | WHAT IS NEEDED TO FILL THESE AND SIMILAR GAPS?

Hydrology so far largely lacks a wider discussion of gaps or inconsistencies in our perceptual models across larger domains (Beven & Chappell, 2021; Wagener et al., 2021). Few examples of such discussions are available (Kingston et al., 2020). While the number of discussions at the catchment scale are slowly increasing, they are far from being the norm and the inclusion of perceptual models—summarizing the hydrologist's system understanding—is still surprisingly rare in hydrologic publications. While detailed discussions about the hydrology of individual catchments is important, we need to understand how our perception of catchment functions differs (at least in relative terms) from each other across larger domains if we want to create generalizable and transferrable knowledge, including our ability to make prediction.

Understanding relative difference (rather than absolute) in catchment behaviour is often a good start to improve our expectations about catchment responses—potentially even beyond observed historical variability (Rogger et al., 2012). Also, in hydrology, it is easy to get lost in detail, thus a first order assessment of even simple perceptual models in a top-down fashion might be a meaningful start for a discussion of regional hydrology and a way to galvanize (regional) hydrological communities (this could start with few relatively simple perceptual models tailored in a top-down fashion, e.g., Hartmann et al., 2015). Integrating what we have learned from both empirical regionalization approaches for breadth (e.g., Addor et al., 2018) and from model-based analyses in fewer places for depth (e.g. Bloomfield et al., 2011) might be the best strategy to build up robust understanding for regional hydrology and predictions (Beven, 2007; Gupta et al., 2014; Wagener & Montanari, 2011). Such an approach has two important consequences: (1) It precludes us from using a single model structure everywhere because it demands tailoring of any simulation model to local/regional perceptual models including consideration of the uncertainties in the perceptual model. Hence, we would move further away from applying single model structures across large domains. (2) While modular modelling frameworks have been postulated as the answer to the need for variable computational model structures, such frameworks can ultimately only be meaningful for scientific advancement if the computational model structures considered to represent a catchment are selected based on their consistency with the underlying perceptual model for this location—rather than because they produce reasonable values of some statistical performance metric.

We close with a few suggestions on how we might tackle our knowledge gaps. These suggestions should be seen as complementary to the previously discussed need for additional and new observational methods to reduce the uncertainty in the hydrological observations we obtain (Beven et al., 2019).

- First, we need a national focus to develop an open, shared and evolving perceptual model as a learning framework for the hydrologic community to help overcome some of the issues that limit our progress. Understanding the state of knowledge in a field such as hydrology is difficult, given that much of knowledge is created through a large number of (often) small-scale studies, which we do not integrate regularly and consistently (Evaristo & McDonnell, 2017). The transferability of this knowledge to other scales or locations has also been difficult – partially due to our inability to characterize hydrologically relevant catchment features that determine how processes interact (McDonnell et al., 2007). A national perceptual model would enable a stronger focus on knowledge accumulation as a community and would open up new opportunities on how we communicate the results of our studies (e.g. Garner et al., 2017; Wagener et al., 2021). We envisage an evolving national perceptual model based on principles of comparative hydrology, continuously advanced through regular revision based on dialogue and synthesis (maybe through regular workshops as part of our national meetings). The National River Flow Archive (https://nrfa.ceh.ac.uk) provides a digital starting point through its linguistic descriptions of individual catchments and their properties. This could be combined with the semi-empirical HOST methodology (or its revisions), the BGS groundwater conceptualization (BGS, 2020), further extended through other relevant properties (Kral et al., 2015) (Figure 2).
- Second, the amount of hydrologically relevant data currently accessible for research is still significantly lower than the amount of data that exists (Hannah et al., 2011). Insights into the hydrologic variability present across GB can only come from spatially diverse and temporally extensive datasets on hydrologic functions (stores and fluxes), catchment properties, human activities etc. While the amount of freely available data has grown greatly in recent years (e.g. Coxon et al., 2020), more effort is needed to make additional data accessible. Data that is often not freely available in GB include those on soils, on land cover, on groundwater and on human activities (especially abstractions and reservoir

management). This lack of access might be because the data are privately held, because the data are held by a public organization but in inaccessible form, because the data are only available under specific (and difficult to reach) individual agreements, or for other reasons. A concerted effort to itemize all available (significant) data (currently openly accessible or not) and to identify the bottlenecks that limit access (legal agreements, finance, lack of digitization, etc.), would be a tremendously beneficial investment. Most hydrological data collected in GB is done so by environmental regulators (and to a lesser extent the water companies)—not by the research community. Enabling the research community to utilize such data—even though their uncertainties might be difficult to assess as discussed above—would further expand our ability to characterize the water environment significantly, and to understand where data gaps really exist.

- Third, modelling and monitoring must be seen as a connected and integrated activity (Harrigan et al., 2020). Essentially, observations generally become hydrologically meaningful after they have been processed through some type of data-processing model (e.g., streamflow based on rating curves or spatial rainfall based on some interpolation model) and we use hydrological models to extrapolate and interpolate hydrologic dynamics to include additional processes, or to move across scales and locations. A national simulation model ensemble (necessary to avoid biasing the result to a particular model) should be connected to data assimilation and sensitivity analysis tools to quantify the potential value of new or better data for uncertainty reduction and to assess our ability to distinguish between competing hypotheses in the presence of unavoidable uncertainties. Further attributing uncertainty in the model outputs to its sources would help us to distinguish whether we need new models, better observed data or better theory (Wagener & Pianosi, 2019). Such a hydrologic observation-simulation system-experiment (OSSE) framework (e.g. Zeng et al., 2020) would enable the testing of the potential value of additional or new data in synthetic experiments prior to actually investing in new monitoring sites etc. (see discussion in Beven et al., 2019). The point here is not to suggest that operational (non-research) monitoring by regulators or private companies should be adjusted to be optimal for the research community (clearly companies and regulators have their own objectives). The point is rather that any research-focused monitoring should be built around the full existing operational monitoring so that duplication is avoided, and the value of long-term observations is realized.
- Fourth, linking our hydrological simulations explicitly to an evolving perceptual model would directly allow for the testing of competing hypotheses, and it would enable us to highlight opportunities for further measurements or even for fundamentally new measurements. There is no reason why this interaction should not also include data-based models (e.g., building on the rich tradition of hydrologic regionalization across GB). The argument developed earlier in favour of tailored models was explored by Beven (2007) as a concept of" models of everywhere" that explicitly includes the testing of local hypotheses and predictions using local data and knowledge. The technology landscape now offers great opportunities to implement and operationalize these concepts (Blair et al., 2019; Gil et al., 2019), which could be linked to regionalized hydrologic signature constraints in an uncertainty framework (Wagener & Montanari, 2011) so that statistical- and process-based hydrology are merged as well.

A national effort including an evolving perceptual model focused on dominant processes down to the small catchment scale, a national ensemble of the main hydrologic models and the accessibility of available data including metadata on their uncertainties would provide a vehicle to advance GB hydrology and its community at an unprecedented rate. Though we should further clarify this statement: (1) We propose a perceptual model (or model framework) for GB. We do not suggest that such models should in general be defined by administrative boundaries (but rather hydrologically meaningful ones), though GB has the advantage of being an island (or set of islands). It is important to stress that implementing such a perceptual model is also full of challenges since we would have to define a framework in which (spatial) qualitative and quantitative information can be combined, which allows frequent interaction by a multitude of users, and allows for the highlighting of inconsistencies or uncertainties (Gil et al., 2019). (2) A national ensemble of simulation models is required for at least two reasons. One, local simulation models need to reflect local perceptual models and consider data available for conditioning/hypothesis testing (both local or interpolated), so no single model structure is likely to be equally suitable everywhere (including the option that no suitable model structure is available). Second, hydrologists regularly disagree on how to simplify reality for model development, how to set boundary conditions, what granularity of processes is needed etc. Hence, building on the multitude of large-scale hydrologic models increasingly available will help to assess in how far these decisions matter, and, if they do, which choices are more appropriate. In the long-term, we would hope that these advancements would also influence operational methods and tools.

Here, we provided an insight into the current discussion across the GB hydrological community about where we have specific knowledge gaps, whether these gaps have widespread influence or relate to specific hydrologic settings, and what vehicles we might utilize to advance this discussion and to accumulate and advance our joint knowledge of GB hydrology. We hope that this discussion will feed into the evolving debate about how we best further our understanding of hydrology more widely by encouraging similar debates elsewhere.

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DATA AVAILABILITY STATEMENT

All our data have been previously published as discussed in the manuscript.

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