Gnann, S. J., McMillan, H., Woods, R. A., & Howden, N. J. K. (2021). Including Regional Knowledge Improves Baseflow Signature Predictions in Large Sample Hydrology. *Water Resources Research*, *57*(2), [e2020WR028354]. https://doi.org/10.1029/2020wr028354

Including Regional Knowledge Improves Baseflow Signature Predictions in Large Sample Hydrology

Sebastian J. Gnann[1], Hilary McMillan[2], Ross A. Woods[1], Nicholas J. K. Howden[1]

[1]Department of Civil Engineering, University of Bristol, Bristol, UK
[2]Department of Geography, San Diego State University, San Diego, California, USA

Key Points:

- Region-specific hydro(-geo)logical knowledge is underutilized in large sample hydrology
- Multiple baseflow signatures are needed to better distinguish between different baseflow sources
- We propose and apply a framework based on standardized perceptual models to organize findings from hydrologically diverse regions

---

Corresponding author: Sebastian J. Gnann, `sebastian.gnann@bristol.ac.uk`

Abstract

A catchment's hydrological response is controlled by climatic forcing and by the landscape through which water moves. Yet when we compare large samples of catchments, we often find climate to be the only good predictor of the hydrological response and a lot of variability is left unexplained. This contradicts extensive evidence from field and regional studies which shows the importance of catchment form (e.g. geology) on catchment hydrological processes, particularly on baseflow processes. We hypothesize that this is due to limitations in (a) the catchment attributes we use to inform our analyses and (b) the hydrological signatures we use to describe the hydrological response. To test these hypotheses we use a large sample of catchment data across the contiguous United States. By reviewing literature from several U.S. regions, we show that region-specific knowledge is underutilized in large sample studies. To organize the findings from these regions we propose and apply a framework based on standardized perceptual models. Informed by these perceptual models, we use both available and newly calculated catchment attributes to show that baseflow signature predictions can be improved regionally. Multiple baseflow signatures are needed to better distinguish between different baseflow sources, such as the subsurface, surface water bodies, and snow. We conclude with pointing at potential future directions and argue that we should aim at a more systematic and hydrologically motivated selection of catchment attributes and hydrological signatures.

Plain Language Summary

River flow dynamics are influenced by climate and by the landscape through which a river flows. However, when we investigate many river catchments using large scale datasets such as global maps, we often cannot find a link between river flow dynamics and landscape characteristics (e.g. geology). We show (a) that such maps are often too general and do not describe aspects relevant for river flow dynamics, and (b) that we need to pay more attention to the metrics we use to quantify river dynamics. There is a wealth of information contained in articles and datasets focusing on the regional scale which we can and should make use of. Since such information is often very specific to a certain region, we propose a conceptual framework that facilitates the use of regional knowledge for comparison between different river catchments.

1 Introduction

A stream reflects the catchment it drains. Its mean discharge is mostly controlled by climatic forcing (Budyko, 1974), and so are many response characteristics at shorter time scales (Berghuijs et al., 2014; Knoben et al., 2018). Yet we see striking differences in the hydrological response from catchments forced by a very similar climate (Farvolden, 1963; Tague & Grant, 2004; Pfister et al., 2017). These differences are typically attributed to differences in a catchment's form, such as the underlying geology (e.g. Price, 2011). Especially the slow response of a catchment (e.g. baseflow, recessions) is thought to carry the signature of the subsurface in which water is stored and from which it is eventually released.

Many studies could relate baseflow signatures to catchment attributes, such as soils (Boorman et al., 1995; Schneider et al., 2007; Santhi et al., 2008), geology (Farvolden, 1963; Tague & Grant, 2004; Bloomfield et al., 2009; Pfister et al., 2017; Kuentz et al., 2017; Carlier et al., 2018), geology-vegetation groups (Lacey & Grayson, 1998), land use (Y. K. Zhang & Schilling, 2006), or topography (Santhi et al., 2008). A lot of that knowledge is, however, fragmented and place-specific (Beck et al., 2013). This is reflected in results from recent large sample studies (Beck et al., 2013, 2015; Addor et al., 2018); while climate indices were the dominant predictors of most hydrological signatures, baseflow signatures were harder to predict, and non-climatic catchment attributes (e.g. geology attributes) could not significantly improve these predictions.

So, why is it so difficult to link catchment attributes (catchment form) to hydrological response (catchment function), despite extensive evidence that these attributes are important? We might argue that every place is unique (Beven, 2000) and that synthesizing the diversity of catchments around the globe is impossible. There are, however, examples of hydrological similarity (e.g. Budyko, 1974; Berghuijs et al., 2014) which suggest that we can transfer knowledge across places through a comparative hydrology approach (Falkenmark & Chapman, 1989). When we compare many catchments, it is important to balance "depth with breadth" (Gupta et al., 2014), and to acknowledge place-specific processes (uniqueness) within general theories (similarity). Bridging this gap between the local and global scale is not just important for the advancement of our scientific understanding, but also for practical applications that require knowledge at regional scales (e.g. water resources management; Wagener et al., 2010).

The main aim of this paper is to investigate the following question. Why have non-climatic catchment attributes shown limited explanatory power in recent large sample studies, even for hydrological signatures that are generally thought to be controlled by these catchment attributes (e.g. baseflow index; see Beck et al., 2013, 2015; Addor et al., 2018)? We hypothesize that this is due to limitations in:

(a) the catchment attributes we use to inform our analyses, and
(b) the hydrological signatures we use to describe the hydrological response.

The input data (a), in particular non-climatic catchment attributes, might not reflect the catchment characteristics that are regionally important, thus limiting their explanatory power. This might be because the resolution of the data is too coarse to capture the relevant spatial variability, or because of imperfect upscaling methods (Addor et al., 2018). While some catchment attributes nominally represent soils or geology, they might not represent the relevant hydrological aspects of soils or geology (Beck et al., 2013). As discussed by Addor et al. (2018), sometimes catchment attributes are simply not (yet) available, even though they have shown to be important. Lastly, data uncertainty might complicate a linkage to the hydrological response even if an attribute is theoretically relevant (Beck et al., 2013, 2015; Addor et al., 2018, 2020).

Hydrological signatures (b) that have limited discriminatory power (McMillan et al., 2017), or are highly uncertain (Westerberg et al., 2016), will be difficult to link to catchment attributes and hydrological processes (see also McMillan, 2020). For example, the baseflow index is not only associated with methodological uncertainty, but also with conceptual uncertainty as it lumps together various processes, such as lake outflow, snowmelt, and groundwater discharge (e.g. Parry et al., 2016; Stoelzle et al., 2020). Therefore, it is possible that catchment attributes, even if they were hydrologically relevant, will not be good predictors of such a signature.

To address hypotheses (a) and (b) we review regionally relevant literature which we contrast with information contained in a large sample dataset. We use the CAMELS dataset (Newman et al., 2015; Addor et al., 2017) in our analysis, which consists of several hundred catchments in the contiguous U.S. (for a brief description see Section 2.3). The CAMELS dataset has been used in many recent studies (e.g. Addor et al., 2018; Kratzert et al., 2019; Jehn et al., 2020) and we deem it representative of many large sample datasets (for a recent review see Addor et al., 2020).

As a way to better synthesize regionally relevant knowledge, we propose the use of standardized perceptual models of catchment function (see Black, 1997; Wagener et al., 2007). Standardized perceptual models offer a qualitative yet systematic way to communicate our understanding of hydrological systems. We view these perceptual models as a first step to formalize the relationship between catchment attributes and hydrological signatures. Developing a perceptual model of a region might point at datasets worth collecting and allows us to synthesize and communicate soft information (e.g. expert knowl-

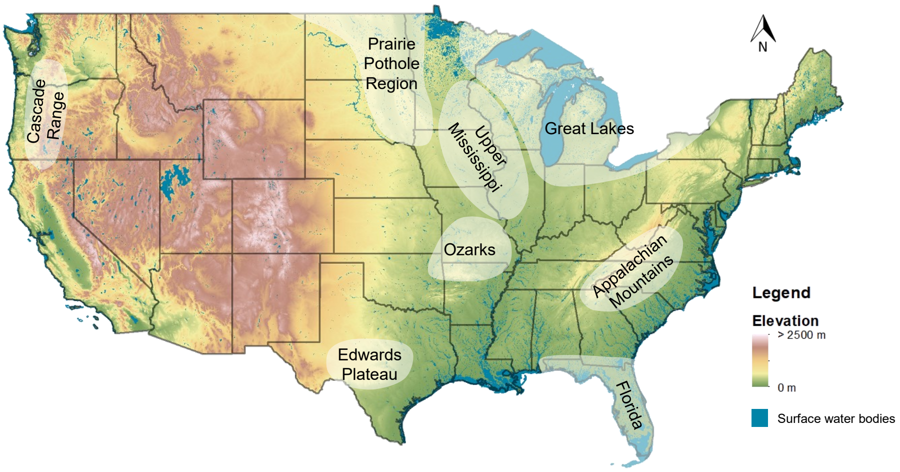

Figure 1. Map of the contiguous U.S. indicating the approximate regions of the case studies. Note that some regions might be different to the whole region of the same name (e.g. Appalachian Mountains). The map shows elevations and surface water bodies (data sources are described in Section 2.3).

edge) in a more systematic way. These perceptual models will evolve continuously and may be updated (or rejected) as we learn about processes and places (see e.g.] McGlynn et al., 2002; Shanley et al., 2015). The perceptual model framework is introduced in more detail in Section 2.2.

In summary, the aim of this paper is to demonstrate how limitations in input data and hydrological signatures can obscure relationships between catchment attributes and hydrological signatures. To organize the findings from different regions, we propose a framework based on perceptual models that enables a systematic comparison of attribute-signature relationships.

2 Methods and Datasets

2.1 Literature Review and Case Study Regions

We argue that large scale datasets of catchment attributes must reflect deep, region-specific knowledge. Therefore, we selected eight contrasting U.S. regions where an initial literature review has indicated that non-climatic catchment attributes influence the streamflow response (Neff et al., 2005; Zimmer & Gannon, 2018; Tague & Grant, 2004; Adamski et al., 1995; B. M. Woodruff & Abbott, 1979; Winter, 1999), shown in Figure 1. In each region we explore regionally relevant literature, field knowledge and availability of datasets that characterize this knowledge but that have not previously been used in U.S.-wide approaches such as the CAMELS dataset.

The literature review will be the basis of both our perceptual models (described in Section 2.2) and the catchment attributes (described in Section 2.3) that are used to better understand several baseflow signatures (described in Section 2.4). We found many references that have – to our knowledge – rarely been considered in this context; possibly due to their local or regional scope, because they do not directly stem from hydrology (but from related fields such as geomorphology), or because they are scientific reports rather than journal papers. In particular, reports and datasets from the United

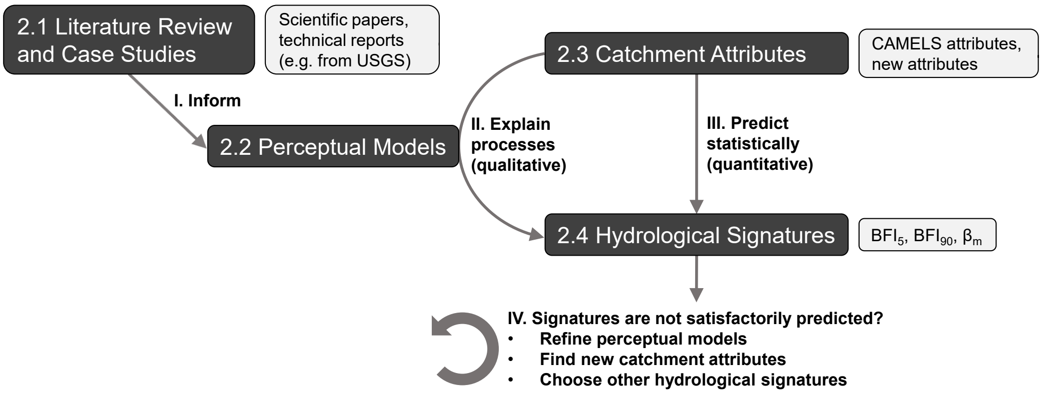

Figure 2. Overview of our methodological approach. The boxes correspond to Sections 2.1-2.4, where the notations are defined. The Roman numerals indicate the order in which the steps are carried out.

States Geological Survey (USGS) or State Agencies contain useful information about the places we investigate here. Figure 2 outlines our methodological approach, which is described in more detail in the upcoming sections.

2.2 Perceptual Models

As a way to formalize the relationship between catchment attributes and hydrological signatures we propose to use standardized perceptual models based on the framework of Wagener et al. (2007). Wagener et al. (2007) distinguish between forcing (incoming water and energy), catchment form (e.g. soils and geology), and catchment function (the actions of the catchment on the incoming water and energy). Catchment functions are further divided into partition, storage, and release. As water is partitioned into different stores, and these stores release water in different ways, partition, storage, and release depend upon each other and cannot be viewed in isolation. Nevertheless, they provide a useful framework to organize our knowledge of catchment hydrological processes. Figure 3 shows a general perceptual model that gives an overview of the catchment functions we explore in this paper. This serves as a standard model that is adapted for each of the case studies shown in Figure 1) – an approach similar to the concept of hydrological landscapes (Winter, 2001). Drawing from the diagrammatic concepts of Falkenmark and Chapman (1989), we also try to approximately quantify the relative magnitude of the fluxes associated with the different catchment functions (e.g. release in the form of baseflow).

2.3 Datasets

2.3.1 CAMELS

Hydro-meteorological data, catchment shapefiles, and catchment attributes are obtained from the CAMELS dataset (Newman et al., 2015; Addor et al., 2017). CAMELS includes daily precipitation P, potential evapotranspiration E_p (catchment-averaged forcing data are based on the Daymet dataset, one of three gridded precipitation products used in CAMELS; see Newman et al., 2015) and streamflow data Q, a wide range of catchment attributes, and catchment shapefiles for 671 mostly natural catchments (i.e. minimal land use changes or disturbances, minimal human water withdrawals; Newman et al., 2015) in the contiguous United States. The catchment attributes from CAMELS that are used in this paper are summarized in Table 1.

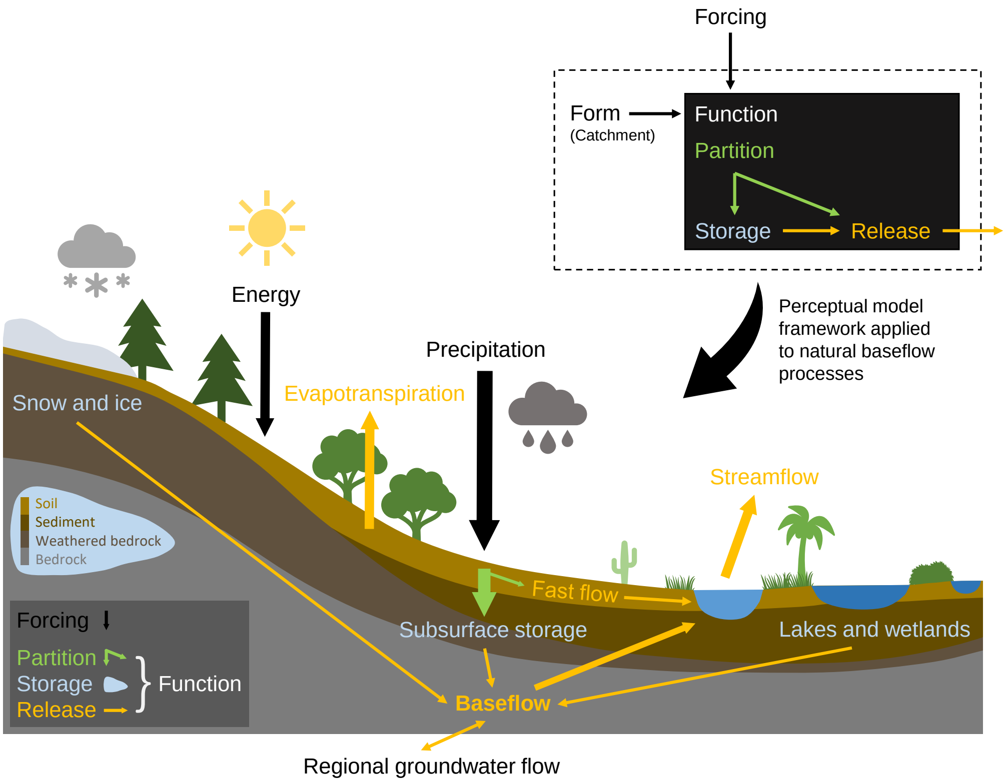

Figure 3. Perceptual model framework following Wagener et al. (2007) applied to natural baseflow processes, illustrating the catchment functions that control baseflow generation. The width of the arrows indicates the amount of water partitioned into and released from different stores. Note that this is not intended to represent any real catchment, but to serve as a general overview. We show refined perceptual models for each of the case studies in Section 3.

Table 1. Datasets used in this paper, both for visualization and analysis. "Datasets in CAMELS" refers to datasets in CAMELS that we use or refer to in this paper. Links to the datasets are provided in the Supporting Information.

Dataset name	Attributes	Reference
CAMELS	Hydro-meteorological data Catchment shapefiles Catchment attributes	Newman et al. (2015); Addor et al. (2017)
Datasets in CAMELS		
STATSGO	Soil texture, soil depth	Miller and White (1998)
GLiM	Geological classes	J. Hartmann and Moosdorf (2012)
GLHYMPS	Geological permeability, porosity	Gleeson et al. (2014)
Additional datasets		
HydroSHEDS	Digital elevation model	Lehner et al. (2008)
Generalized Glacial Limit Lines	Glacial areas	National Atlas of the United States (2005)
Physiographic Divisions of the U.S.	Physiographic provinces	Fenneman and Johnson (1946)
USGS Geological Map	Geological classes, age	Horton et al. (2017)
Principal Aquifers of the U.S.	Aquifer extents	U.S. Geological Survey (2003)
MGS Sinkhole Points	Sinkhole locations	Missouri Geological Survey (2018)
TWDB Major Aquifers	Major aquifer extents	Texas Water Development Board (2020)
National Wetlands Inventory	Surface water bodies	U.S. Fish and Wildlife Service (2020)

2.3.2 Additional Catchment Attributes

We use several datasets that are not (yet) contained in CAMELS. They are summarized in Table 1. We use these datasets to calculate new catchment attributes which are provided with this paper. Details on the calculation of catchment attributes can be found in the Supporting Information.

2.4 Baseflow Signatures

We use three baseflow signatures to characterize the slow response of a catchment: two different baseflow indices (BFIs), and the median recession exponent β_m. These three signatures are correlated, but do provide independent information (see Supporting Information for details).

2.4.1 Baseflow Indices

Baseflow Q_b is defined as the portion of streamflow Q that is derived from groundwater and other delayed sources (Hall, 1968; Smakhtin, 2001). Baseflow is typically quantified by the baseflow index (BFI), the ratio between mean baseflow $\bar{Q_b}$ and mean total streamflow $\bar{Q}$.

$$\mathrm{BFI} = \frac{\bar{Q_b}}{\bar{Q}} \tag{1}$$

We estimate baseflow with the help of the smoothed minima method (UKIH method; Institute of Hydrology, 1980). The method is particularly sensitive to one parameter, the time window N over which the streamflow minima are calculated (default: $N = 5$ days). To address this problem, Stoelzle et al. (2020) calculated the BFI for a continuous range of time window values. They then used the obtained range of BFIs (which they termed Delayed Flow Index; DFI) to distinguish between different baseflow sources. We follow this idea and calculate two BFIs. A "standard" BFI_5 using a baseflow estimate $Q_{b,5}$ obtained with a time window of 5 days; and a BFI_{90} using a baseflow estimate $Q_{b,90}$ obtained with a time window of 90 days. BFI_5 aims at separating events from inter-event baseflow and BFI_{90} aims at separating seasonal variations from more stable (multi-annual) baseflow. Increasing the value beyond 90 days has relatively little effect on the resulting BFI for most of the catchments analyzed here. Note that BFI_{90} is strongly correlated with the normalized 5% flow quantile $Q_5/\bar{Q}$ (Spearman rank correlation $\rho_s = 0.95$).

2.4.2 Recession Exponent

Recession analysis has been used extensively to quantify the drainage behavior of catchments (Brutsaert & Nieber, 1977; Roques et al., 2017; Jachens et al., 2020; Tashie et al., 2020). It is often assumed that the relationship between the rate of change of streamflow and streamflow follows a power law.

$$-\frac{dQ}{dt} = \alpha Q^{\beta} \tag{2}$$

where α and β_m are parameters that can be obtained by fitting Eq. (2) to recession data. There are numerous methodological choices that can impact the resulting parameter values (e.g. Stoelzle et al., 2013; Dralle et al., 2017; Jachens et al., 2020). We extract recession segments that are strictly decreasing ($\frac{dQ}{dt} < 0$), remove the first day, and only keep recession segments of 5 days or longer (Jachens et al., 2020). We calculate the derivative $\frac{dQ}{dt}$ by using the exponential time stepping scheme proposed by Roques et al. (2017). We then use a weighted least square regression approach to fit a line in log-log space to individual recession segments (for details see Roques et al., 2017). We use the median exponent β_m to describe a catchment's average recession behavior. We do not use the parameter α as it is strongly influenced by seasonal variations in catchment wetness and evapotranspiration (e.g. Dralle et al., 2015; Tashie et al., 2020).

2.4.3 Visual Inspection of Hydrographs

For each region, we show hydrographs to contrast catchments with a different hydrological response. We use the two baseflow estimates $Q_{b,5}$ and $Q_{b,90}$ to divide the hydrograph into fast flow and two baseflow components. Note that while we divide the hydrograph into three parts, the value of BFI_5 "contains" BFI_{90}, i.e. it resembles the commonly used BFI (Institute of Hydrology, 1980). These two baseflow components do not necessarily relate to any single baseflow source (or hydrological process), but they are rather meant to emphasize differences in baseflow response between catchments. These hydrographs are complemented by perceptual models, as outlined in Section 2.2.

3 Results

In Section 2.2 we have introduced three catchment functions: partition, storage, and release. In the next sections, we explore the processes that control these functions in the regions shown in Figure 1. A summary is given in Table 2.

3.1 Partition

3.1.1 Soil and Sediment Texture Control Partitioning: Regions Covered by Glacial Deposits

Extensive parts of the north and north eastern U.S. were covered by ice during past glaciations. Glacial erosion and deposition have resulted in thick (tens to hundreds of meters) sediment layers covering the underlying bedrock (e.g. Larson & Schaetzl, 2001). We can distinguish between areas glaciated during the most recent glaciation (Wisconsin) and areas glaciated during earlier glaciations (Pre-Wisconsin; see Figure 4a). The border between these two areas (Wisconsin and Pre-Wisconsin) roughly aligns with the border between the Great Lakes Region and the Upper Mississippi Valley (see Figure 1). Comparing these two regions shows that soil and sediment texture – rather than bedrock properties – control baseflow generation in glacial regions.

Table 2. Overview of catchment functions, corresponding regions, key catchment characteristics, associated hydrological processes, and relevant datasets (see Table 1 for details on the datasets). N/A indicates that we did not find suitable datasets. *Datasets contained in CAMELS.

Function	Regions	Catchment characteristics	Hydrological Processes	Datasets
Partition	Great Lakes Region, Upper Mississippi Valley	Soil and sediment texture, glacial history	Infiltration, groundwater discharge	STATSGO*, Generalized Glacial Limit Lines
	Appalachian Mountains	Soil stratigraphy	Infiltration	N/A
Storage	Oregon Cascades	Subsurface maturity (volcanic rock)	Groundwater storage	USGS Geological Map
	Ozarks Plateau	Subsurface maturity (carbonate rock)	Groundwater storage	USGS Geological Map, MGS Sinkhole Points
	Edwards Plateau	Weathering characteristics	Groundwater storage	TWDB Major Aquifers
Release	Ozarks Plateau, Edwards Plateau	Losing/gaining streams	Regional groundwater flow	N/A
	Prairie Pothole Region, Florida	Lakes and wetlands	Discharge from surface water bodies	National Wetlands Inventory
	The contiguous U.S.	Baseflow source (e.g. snow)	Snowmelt, discharge from surface water bodies	Snow fraction*, National Wetlands Inventory

The U.S. part of the Great Lakes Region is dominated by glacial deposits such as till and unconsolidated sediments which often mask the underlying geology (Larson & Schaetzl, 2001). The hydrology of the region is strongly influenced by the composition of soils and sediments (i.e. the soil parent material; Neff et al., 2005; Y. Zhang et al., 2013; Naylor et al., 2016). Soils and sediments in the Great Lakes Region tend to be coarse, particularly in the regions that were located deep within the glaciated area (e.g. Michigan).

While most parts of the Upper Mississippi Valley were glaciated in the past, they were not glaciated during the Wisconsin glaciation (see Figure 4a). During this ice-free period, meltwater and precipitation draining via the Upper Mississippi created a fluvial landscape (Bettis et al., 2008) with a more developed surface drainage network than in the Great Lakes Region. Soils and sediments in the Upper Mississippi Valley are finer than in the Great Lakes Region, with larger clay and silt contents and less sand.

Soil and sediment texture are a key control on the hydraulic properties of the subsurface, and thus affect recharge (Naylor et al., 2016) and baseflow (Neff et al., 2005). Sandy soils enable high infiltration rates and thus allow for a lot of recharge. Sandy aquifers provide a lot of groundwater discharge which can sustain continuous baseflow, but also allows for continuous recharge as subsurface saturation is less likely to occur. A sand-rich catchment is illustrated in Figure 4d,f which shows a perceptual model and a hydrograph of a typical Great Lakes catchment. Finer soils with higher clay content limit infiltration as well as groundwater discharge, leading to a flashier response. A clay-rich catchment is illustrated in Figure 4c,e which shows a perceptual model and a hydrograph of a typical Upper Mississippi Valley catchment. Figure 4b shows that clay and sand fraction (STATSGO data contained in CAMELS) are a strong control on the hydrological response in catchments that were glaciated in the past. Since soils are strongly related to their parent material (Naylor et al., 2016), the soil classification will also reflect sediment texture and thus also characterizes deeper layers in these regions. Therefore, to predict baseflow signatures across the U.S., we should include catchment attributes that delineate previous glacial extents. If we want to characterize or model catchments in glacial areas, we should include information about soils and sediments rather than bedrock.

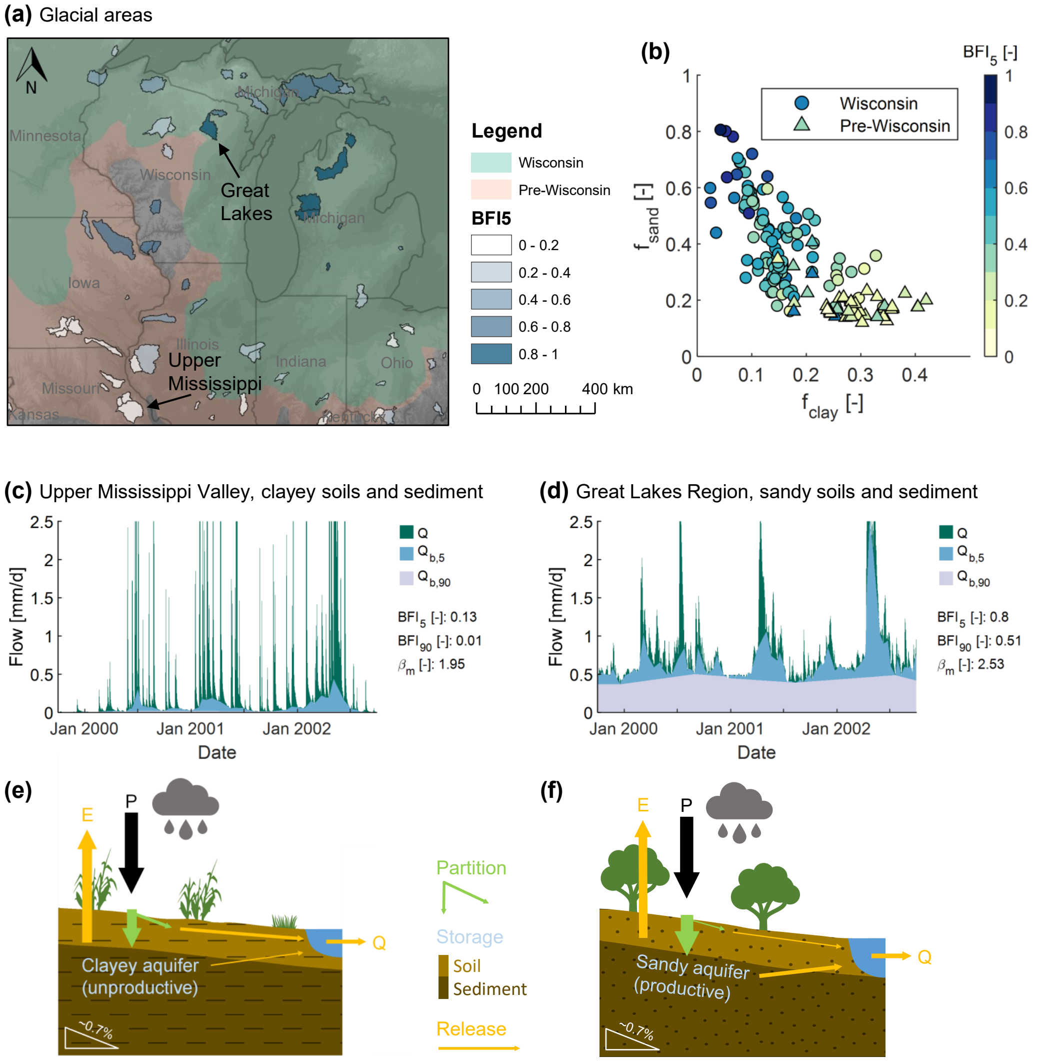

Figure 4. **(a)** Map of the glacial areas showing CAMELS catchments colored according to BFI_5 and two example catchments. **(b)** Scatter plot showing BFI_5 as a function of clay and sand fraction ($\rho_s(\text{BFI}_5, f_{\text{clay}}) = -0.70$; $\rho_s(\text{BFI}_5, f_{\text{sand}}) = 0.68$). Hydrographs of the two example catchments with estimated baseflow components for **(c)** Cuivre River near Troy (Upper Mississippi Valley; HU 5514500) and **(d)** Wolf River at Langlade, WI (Great Lakes Region; HU 4074950). Note that the y-axis is capped. Perceptual models for **(e)** catchments with high clay fractions and **(f)** catchments with high sand fractions. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

3.1.2 Soil Stratigraphy Controls Partitioning: The Appalachian Mountains in North Carolina

The Appalachian Mountains in North Carolina consist of the Blue Ridge Mountains in the west, which transition into the lower Piedmont in the east (see Figure 5a). Both regions are underlain by a relatively old, complex mixture of different lithologies (predominantly metamorphic and classified accordingly in GLiM and thus CAMELS). Soils and bedrock are deep and highly weathered (Zimmer & Gannon, 2018). As the topography transitions from steep (Blue Ridge) to shallow (Piedmont), soils and unconsolidated sediments become thicker. Yet despite having a deeper critical zone, Piedmont catchments generate less baseflow and Zimmer and Gannon (2018) hypothesized that this is due to continuous shallow impeding layers.

In the Piedmont, continuous clay-rich impeding layers can lead to perched water tables and thus to a more flashy response. In the Blue Ridge Mountains, these impeding layers are less continuous and thus allow for more recharge. This is illustrated in Figure 5d,f which shows perceptual models for both regions (following Zimmer & Gannon, 2018). The corresponding hydrographs (Figure 5b,c) show a similar seasonal $Q_{b,5}$ for both catchments, but the more stable baseflow component $Q_{b,90}$ is almost absent in the Piedmont catchment, indicating a lack of or disconnection from deeper storage. This agrees with Zimmer and Gannon (2018) who found that baseflow amounts in the Blue Ridge are larger and seasonally more stable. The hypothesized dominance of soil stratigraphy over soil texture in this region is supported by the fact that none of the soil textural attributes in CAMELS are strongly correlated with any of the baseflow signatures ($\rho_s(\mathrm{BFI}_5, f_{\mathrm{clay}}) = -0.18$; $\rho_s(\mathrm{BFI}_5, f_{\mathrm{sand}}) = 0.15$).

In-depth regional studies such as Zimmer and Gannon (2018) can help to bridge the gap between the local and continental scale, and they can point out potentially useful datasets such as datasets that describe soil stratigraphy. The importance of soil stratigraphy (e.g. impeding layers) and soil structure (e.g. macropores) has also been highlighted elsewhere (e.g. Price, 2011; Naylor et al., 2016; Fatichi et al., 2020), but there are currently no readily available large scale datasets describing soil stratigraphy.

3.2 Storage

3.2.1 Subsurface Maturity of Volcanic Rock: The Oregon Cascades

The western slopes of the Oregon Cascades can be divided into two main geological units, the Western Cascades and the High Cascades (Tague & Grant, 2004). While both are underlain primarily by volcanic rock, and classified accordingly in CAMELS, they differ markedly in their appearance and hydrology. The High Cascades consist of young and highly permeable volcanic rock. They have a poorly developed surface drainage system and drain primarily via the subsurface and springs. The Western Cascades are much older and deeply weathered. The landscape is steep, dissected, and there is an extensive surface drainage network fed by shallow subsurface stormflow (Tague & Grant, 2004; Jefferson et al., 2010). The general lithological category (volcanic igneous rock) is therefore not enough to understand the regional hydrology, and we need to understand the geomorphological evolution of the region and the maturity of the subsurface.

The differences between Western and High Cascades are reflected in the hydrology of the streams draining them, with a flashier response in Western Cascade streams and a more damped response with sustained summer low flows in High Cascade streams (Tague & Grant, 2004; Tague et al., 2008; Jefferson et al., 2010). This can be seen in Figure 6c-f, which shows perceptual models and hydrographs for two catchments primarily located in either the Western or the High Cascades. Note that both streams show two annual peaks, one in winter when precipitation is highest, and one in late spring due to snowmelt.

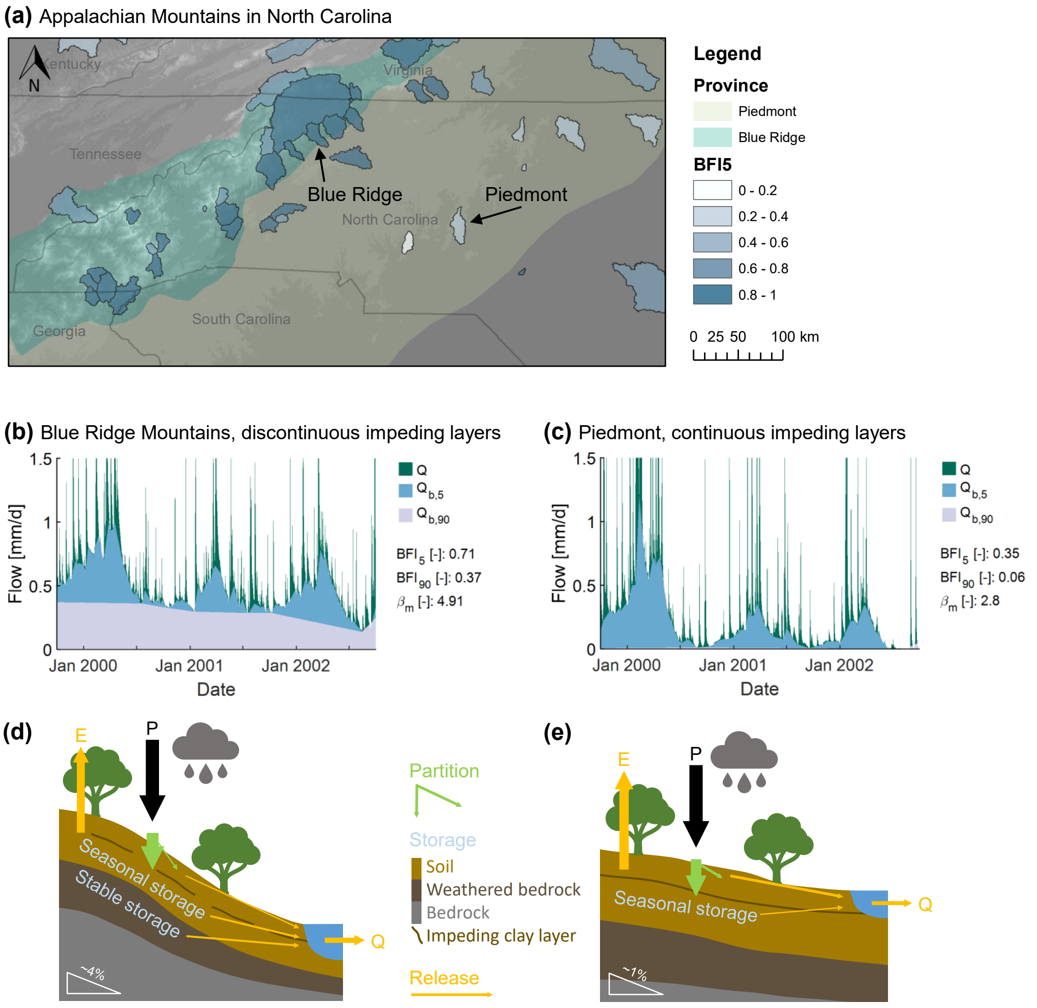

Figure 5. **(a)** Map of the Appalachian Mountains in North Carolina divided into physiographic provinces showing CAMELS catchments colored according to BFI_5 and two example catchments. Hydrographs of the two example catchments with estimated baseflow components for **(b)** Reddies River at North Wilkesboro (Blue Ridge; HU 2111500) and **(c)** Little River near Star (Piedmont; HU 2128000). Note that the y-axis is capped. Perceptual models for **(d)** Blue Ridge catchments and **(e)** Piedmont catchments. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

We can classify the Oregon Cascades similar to Tague and Grant (2004) by using geological age data contained in the USGS geology map (more details can be found in the Supporting Information). We classify volcanic (igneous) rocks younger than 2 Ma (million years) as High Cascades, volcanic rocks older than 8 Ma as Western Cascades, and volcanic rocks between 2 Ma and 8 Ma as mixed. The resulting map is shown in Figure 6a. Catchments in the High Cascades show higher BFI_{90} values, indicating sustained low flows. To show quantitatively how geologic age influences low flows, we extracted the mean age of each catchment's geology from the USGS geology map, which is plotted against BFI_{90} in Figure 6b. We also show the corresponding snow fractions to point out that they do not cause the differences in BFI_{90}. While the overall sample size is small ($n = 12$), particularly for the High Cascades, our results agree with many other studies (e.g. Tague & Grant, 2004; Tague et al., 2008; Jefferson et al., 2010; Safeeq et al., 2013). This shows that a simple classification as volcanic rock is insufficient to characterize these catchments, but that accounting for the maturity of the landscape by means of geological age data can help to better link catchment geologic attributes to baseflow signatures.

3.2.2 Subsurface Maturity of Carbonate Rock: The Ozarks

The Ozarks are located primarily in Missouri, with smaller parts in Arkansas, Kansas, and Oklahoma. The Ozarks are underlain by different types of carbonate and other sedimentary rock (Adamski et al., 1995), and they are classified primarily as carbonate rock in CAMELS. Literature about the Ozarks shows, however, that the region consists of different carbonatic units which differ in their age, composition, and degree of karstification, and thus their hydrology (Harvey, 1981; Adamski et al., 1995; Hays et al., 2016). To differentiate between the different aquifer units we make again use of the geological age data from the USGS geology map. We can divide the Ozark Plateaus aquifer system (delineated from the USGS Aquifer Map) into two units, one being older than 360 Ma (the end of the Devonian, roughly resembling the Ozark aquifer) and one being younger than 360 Ma (roughly resembling the Springfield Plateau aquifer; Adamski et al., 1995; Hays et al., 2016), shown in Figure 7a.

Catchments inside the aquifer system (colored area in Figure 7a) generate more baseflow than catchments outside the aquifer system. Within the aquifer system, catchments underlain by the Ozark aquifer (the dark brown area in Figure 7a) generate the highest amounts of baseflow. This agrees with other studies which state that the dissolution of rocks and hence the degree of karstification is greater in the Ozark aquifer than in the Springfield Plateau aquifer (Harvey, 1981; Adamski et al., 1995; Hays et al., 2016). This difference is illustrated in Figure 7c-f, which shows hydrographs and perceptual models for two catchments underlain by the Springfield Plateau aquifer and the Ozark aquifer, respectively. The catchment underlain by the Ozark aquifer (Figure 7d,f) has a more stable baseflow component stemming from an extensive subsurface flow network. Figure 7f indicates another typical karst feature, namely groundwater flow between (surface) catchments. This is also common in the Ozarks (Kleeschulte, 2000; Mugel et al., 2009) and will be discussed in Section 3.3.1.

Distinguishing between the different aquifer units allows us to better explain the hydrological response in this area. But we can go a step further by looking at typical features of mature karst landscapes such as springs and sinkholes (Harvey, 1981; Adamski et al., 1995). To assess the degree of karstification we extracted the number of sinkholes per catchment from a map of the Missouri Geological Survey. Figure 7b shows that sinkhole density strongly correlates with BFI_5 for catchments in the Ozarks in Missouri. Sinkholes are therefore a useful and measurable surface feature that indicate subsurface maturity, which might be particularly useful in ungauged catchments. However, while other sinkhole datasets exist (e.g. for Florida), limited availability of good quality sinkhole data might limit this approach to certain regions (here Missouri).

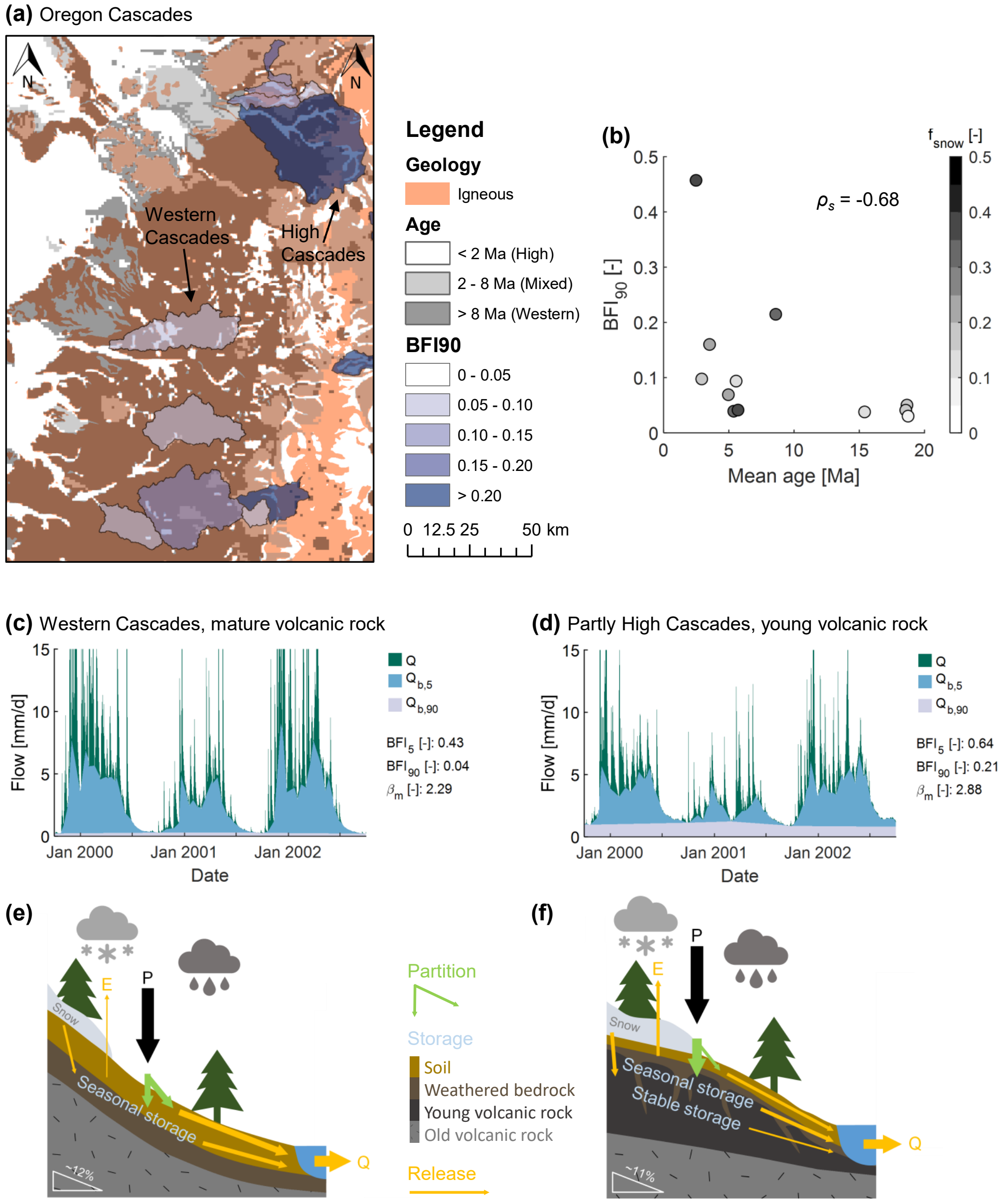

Figure 6. **(a)** Map of the Oregon Cascades showing CAMELS catchments colored according to BFI_{90} and two example catchments. Areas composed of igneous rock are overlain by shades of gray indicating geological age. **(b)** Scatter plot showing BFI_{90} vs. mean geological age ($\rho_s = -0.68$) with dots colored according to the snow fraction f_{snow}. Hydrographs of the two example catchments with estimated baseflow components for **(c)** Quartzville Creek near Cascadia (HU 14185900) and **(d)** Sandy River near Marmot (HU 14137000). Note that the y-axis is capped. Perceptual models for **(e)** Western Cascade catchments and **(f)** High Cascades catchments. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

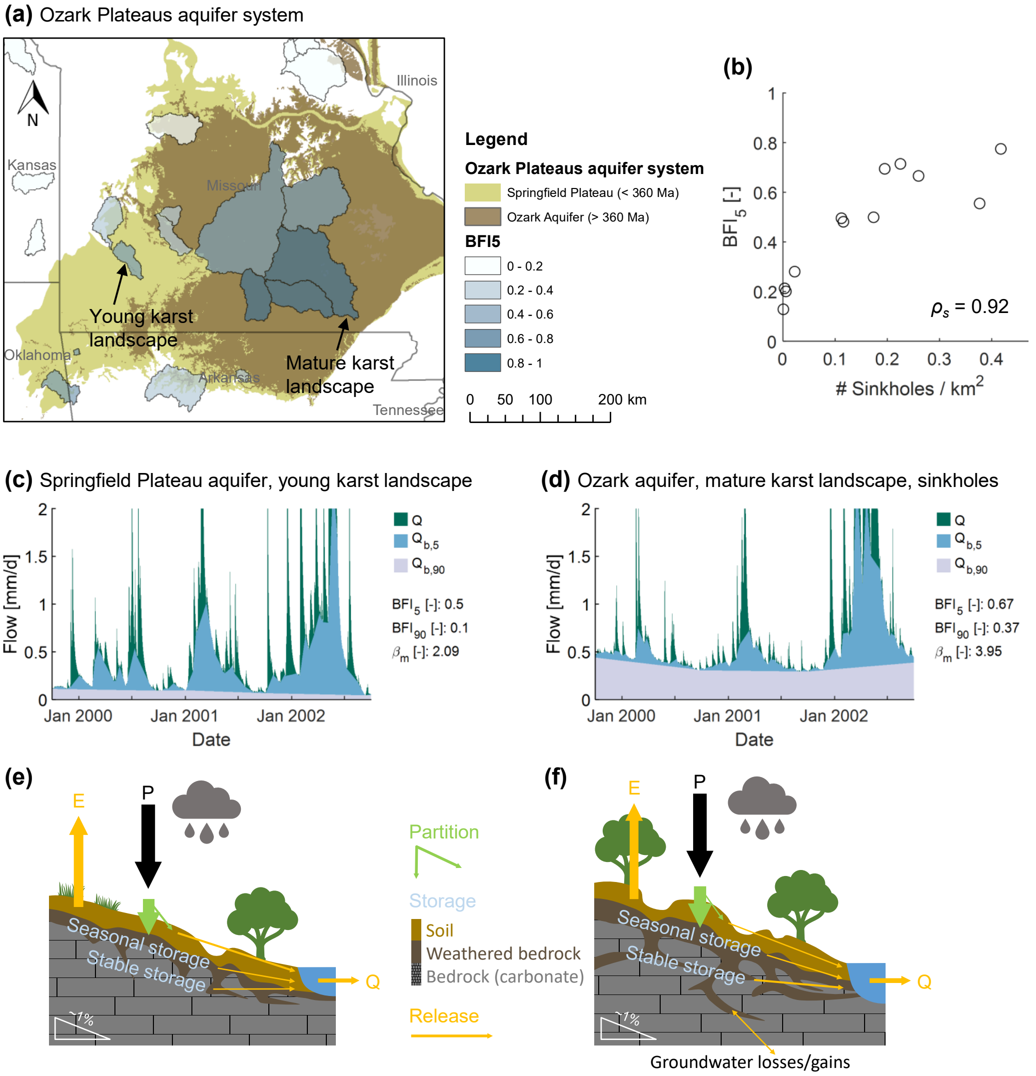

Figure 7. **(a)** Map of the Ozarks showing CAMELS catchments colored according to BFI$_5$ and two example catchments. **(b)** Scatter plot showing BFI$_5$ vs. sinkhole density ($\rho_s = 0.92$). Hydrographs of the two example catchments with estimated baseflow components for **(c)** Turnback Creek above Greenfield (HU 6918460) and **(d)** Current River at Van Buren (HU 7067000). Note that the y-axis is capped. Perceptual models for **(e)** Springfield Plateau catchments and **(f)** Ozark aquifer catchments. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

3.2.3 Erosion of Rocks with Different Weathering Characteristics: The Edwards Plateau

The Edwards Plateau region in central Texas can be divided into the Edwards Plateau proper and the Texas Hill Country (Wilcox et al., 2007). They are bounded to the southeast by the Balcones Fault Zone which gave rise to high relief and has resulted in a complex geological structure. These regions roughly align with the aquifers of the Edwards-Trinity aquifer system obtained from the Texas Water Development Board, which are shown in Figure 8a. The Edwards-Trinity aquifer is the principal aquifer in the Edwards Plateau, the Trinity aquifer is the principal aquifer in the Hill Country, and the Edwards aquifer is the principal aquifer in the Balcones Fault Zone (Barker & Ardis, 1996). The regional climatic gradient (more humid in the east), differences in relief (higher in the east), as well as regional groundwater flows towards the east, have led to increased erosion towards the east, resulting in the dissected landscape of the Texas Hill country (B. M. Woodruff & Abbott, 1979; Barker & Ardis, 1996), shown in Figure 8a. This hydrogeological diversity is not reflected in CAMELS, which classifies the whole region primarily as carbonate rock.

The Edwards-Trinity aquifer provides baseflow even during periods with little rainfall. This is illustrated in Figure 8c,e which shows a hydrograph and a perceptual model for a catchment in the Edwards Plateau proper. In the Texas Hill country, the upper parts of the Edwards-Trinity aquifer have been eroded, exposing the Glen Rose formation which consists of a sequence of limestone and dolomitic beds with varying weathering potentials (Wilcox et al., 2007; C. M. Woodruff & Wilding, 2008). This leads to a stepped topography consisting of steep risers and flat treads. Wilcox et al. (2007) and C. M. Woodruff and Wilding (2008) have shown that the steep risers have deeper soils and weathered regolith and thus act as stores and zones of subsurface flow, whereas the treads create more fast flow. This is illustrated in Figure 8d,f which shows a hydrograph and a perceptual model for a catchment in the Texas Hill Country. Storage in the steep risers only provides intermittent baseflow, leading to an ephemeral flow regime.

The difference between the Edwards Plateau proper and the Texas Hill country can be shown more quantitatively when the catchment fraction underlain by the Edwards-Trinity aquifer (delineated from the TWDB aquifer map) is plotted against BFI_{90} (Figure 8b). Catchments outside the Edwards-Trinity aquifer have low to zero BFI_{90}, whereas most catchments underlain by the Edwards-Trinity aquifer have a high BFI_{90}. A few catchments that have a very low BFI_{90} also have a particularly low runoff ratio (indicated by light colors in Figure 8b), likely because they lose water in the Balcones Fault Zone. The Balcones Fault Zone acts as a major recharge zone for the confined aquifer in the south (B. M. Woodruff & Abbott, 1979; Schaller & Fan, 2009), which might explain the low BFI_{90} values of some catchments that extend into it (see Figure 8a). We therefore also need to account for groundwater losses and gains, which is discussed in Section 3.3.1. While the aquifer map of Texas contains useful information, it is also unique to the region and needs to be interpreted with the help of regional knowledge. A next step would therefore be the integration of this knowledge into a more widely applicable classification (see discussion in Section 4.4).

3.3 Release

3.3.1 Losing and Gaining Catchments: The Ozarks and the Edwards Plateau

Catchments are often regarded as closed systems, where incoming water leaves either via evapotranspiration or stream discharge. Groundwater discharge from or to neighboring (topographic) catchments is, however, common (Schaller & Fan, 2009; Fan, 2019). This is especially true for karst landscapes, such as the Ozarks Plateau (Kleeschulte, 2000; Mugel et al., 2009) or the Edwards Plateau (B. M. Woodruff & Abbott, 1979; Schaller

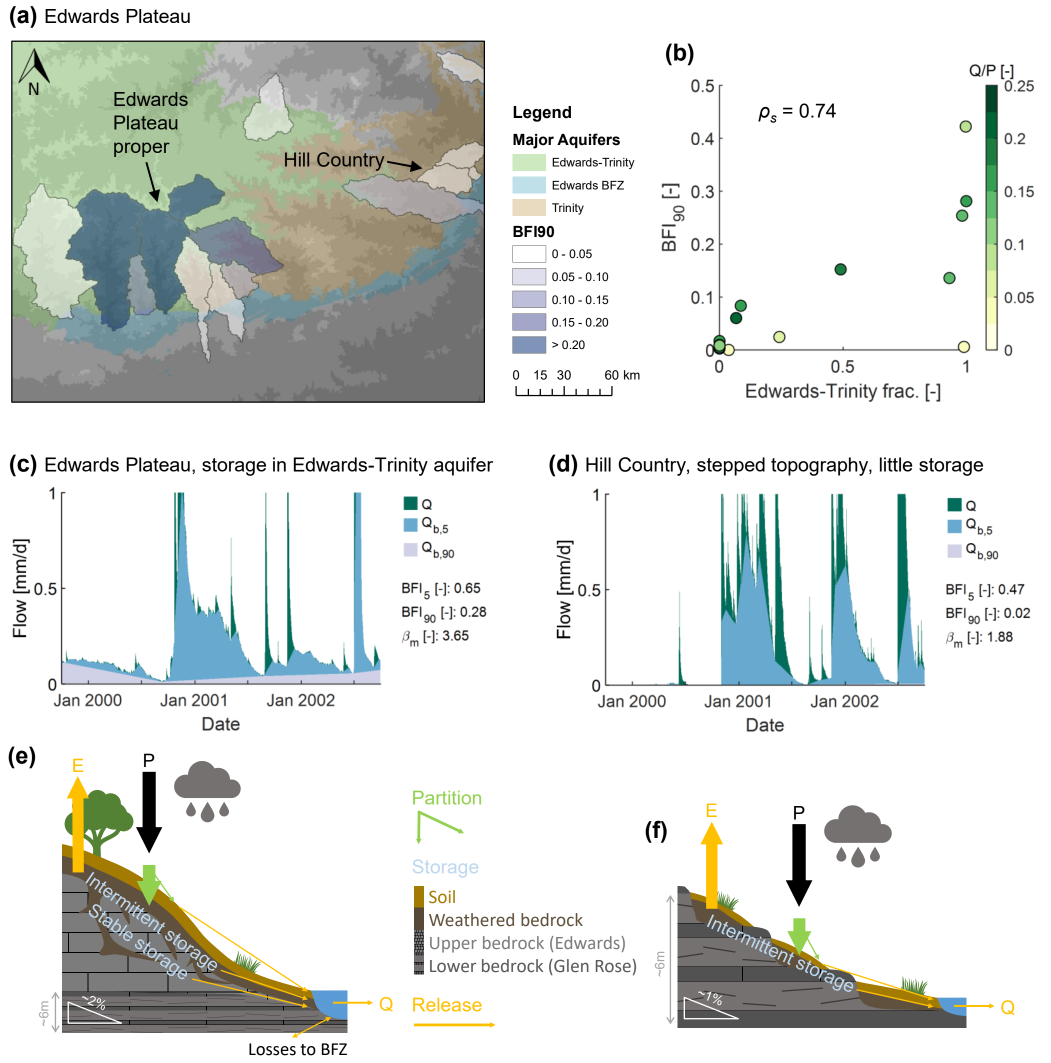

Figure 8. **(a)** Map of outcrop areas of the Edwards-Trinity aquifer system showing CAMELS catchments colored according to BFI_{90} and two example catchments. **(b)** Scatter plot showing BFI_{90} vs. Edwards-Trinity fraction (the green area in **(a)**; $\rho_s = 0.74$) with dots colored according to the runoff ratio Q/P. Hydrographs of the two example catchments with estimated baseflow components for **(c)** Frio River at Concan (HU 8195000) and **(d)** Onion Creek near Driftwood (HU 8158700). Note that the y-axis is capped. Perceptual models for **(e)** Edwards Plateau catchments and **(f)** Texas Hill Country catchments. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

& Fan, 2009). Since groundwater losses and gains can affect baseflow signatures (see Figure 8b), we tried to estimate regional groundwater flows via the water balance (see Schaller & Fan, 2009) using actual evapotranspiration estimates from two different products: MODIS (Mu et al., 2011) and GLEAM (Miralles et al., 2011; Martens et al., 2017); details can be found in the Supporting Information. We did not use the resulting estimates as they do not conclusively agree with information on losing and gaining catchments we found in the literature (e.g. Kleeschulte, 2000; Mugel et al., 2009, for the Ozarks), likely due to uncertainty in all water balance components (see e.g. Khan et al., 2018, for actual evapotranspiration). Instead we note that it will be important to obtain reliable estimates of regional groundwater flow to better understand baseflow signatures.

3.3.2 Lakes and Wetlands: The Prairie Pothole Region and Florida

Lakes and wetlands are important functional units of hydrological systems. There is currently no dataset that explicitly describes surface water bodies in CAMELS (there is only a soil attribute named ”water fraction”). If baseflow originates from surface water bodies, subsurface characteristics alone cannot explain the baseflow response. We explore two regions, the Prairie Pothole Region and the state of Florida, both shaped by their surface water bodies yet located in different climate zones. Both regions show a similar and distinct combination of baseflow signatures which reflect wetland connectivity.

The Prairie Pothole Region was formed by the last glaciation and the region (shown in Figure 1) aligns well with the boundaries of the Wisconsin glaciation (shown in Figure 4). Potholes provide storage that buffers against floods and provides baseflow, usually in connection with the shallow groundwater system (Winter, 1999; McLaughlin et al., 2014; Cohen et al., 2016; Ameli & Creed, 2017; Neff & Rosenberry, 2018). Fast surface connections occur only during large events and originate from wetlands near the stream. Slow subsurface connections originate from wetlands throughout the catchment, including geographically isolated ones (McLaughlin et al., 2014; Ameli & Creed, 2017). A perceptual model depicting the hydrology of the Prairie Pothole Region is shown in Figure 9c. The corresponding hydrograph shown in Figure 9a lacks a very fast response, illustrating the flood buffering effect of potholes. Baseflow is substantial but intermittent, which is indicated by a moderate BFI_5 and very low BFI_{90}. Recession exponents β_m close to 1 – the lowest of all CAMELS catchments – indicate fast late recessions, reaffirming the intermittent nature of baseflow in this region. Wetland connectivity decreases during drying (both due to evapotranspiration and discharge), as deeper layers tend to be less permeable (Cohen et al., 2016), and hence the flow ceases once the water levels have dropped below permeable layers (fill and spill; Cohen et al., 2016).

Florida is underlain by the Floridan aquifer system, a carbonate rock aquifer system that is confined by a clay rich layer in most places (Schiffer, 1998). This confining layer is overlain by unconsolidated sediments which make up the surficial aquifer system. Many lakes have developed from sinkholes, which mostly occur in places where thin or discontinuous sediment and clay layers expose the underlying carbonate rock. If the confining clay layer is intact, the Floridan aquifer system has limited influence on streams. This is the case for most of the CAMELS catchments in Florida, which lie almost exclusively in areas with thick sediment cover. In these catchments, hydrological connectivity is closely linked to the shallow aquifer system and depends on the thickness and hydraulic properties of soils and sediments (Schiffer, 1998; Winter, 1999). A perceptual model of such a catchment is shown in Figure 9d. Similar to the Prairie Pothole Regions, the corresponding hydrograph (Figure 9b) lacks a very fast response and baseflow is substantial but intermittent.

As lakes can have a strong impact on the hydrological response of a catchment, we need to include information on surface water bodies in large sample datasets (see also Beck et al., 2013). In the next Section 3.3.3, we show that the fraction covered by sur-

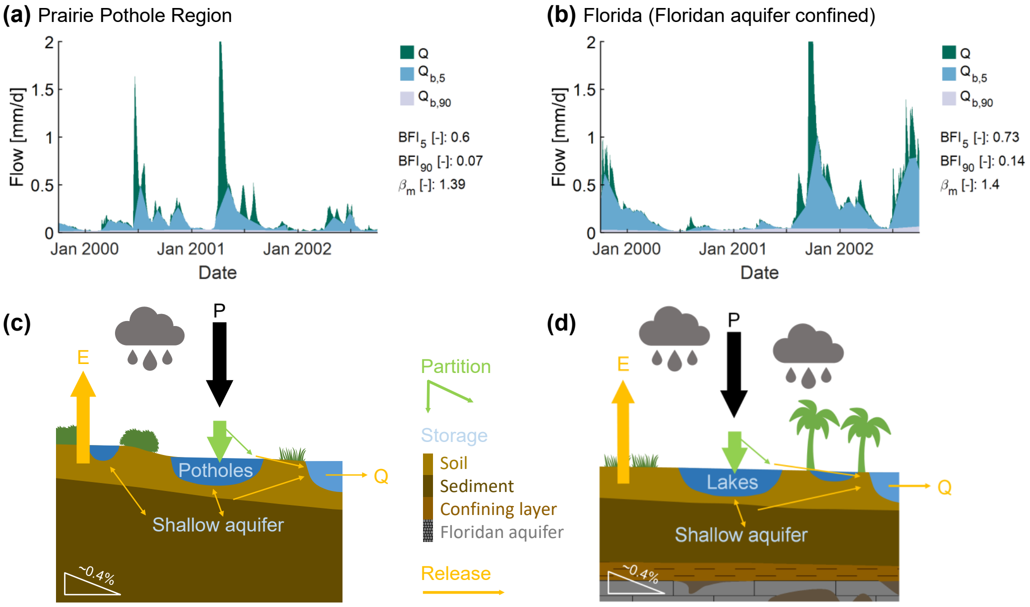

Figure 9. Hydrographs with estimated baseflow components for **(a)** Sheyenne River near Cooperstown, North Dakota (HU 5057000), and **(b)** Blackwater Creek near Cassia, Florida (HU 2235200). Note that the y-axis is capped. Perceptual models for **(c)** Prairie Pothole catchments and **(d)** catchments in Florida. The width of the arrows indicates the amount of water relative to a normalized precipitation input.

face water bodies (derived from the National Wetlands Inventory; U.S. Fish and Wildlife Service, 2020) can be used to distinguish between hydrologically different catchment groups (e.g. surface water dominated). But it is likely that more detailed information about wetland type and wetland geographic distribution will help to better understand baseflow signatures in catchments influenced by surface water bodies.

3.3.3 Release Characteristics of Different Baseflow Sources: Surface Water Bodies, Snow, and the Subsurface

Baseflow can originate from different sources, but a single signature such as BFI$_5$ often cannot distinguish between these different sources. For example, substantial amounts of baseflow indicated by a moderate BFI$_5$ can be found in many regions (e.g. Oregon Cascades, Edwards Plateau, Prairie Pothole Region, Florida). But a moderate BFI$_5$ in conjunction with fast release dynamics indicated by a very low β_m is very typical for the surface water dominated catchments of the Prairie Pothole Region and Florida (see Section 3.3.2). If a catchment attribute (e.g. rock type) is important for one but unimportant for another baseflow source (e.g. groundwater storage and wetland storage), it might be difficult to link that attribute to a single signature such as BFI$_5$. We therefore explored the relationship between two signatures, BFI$_5$ and β_m, for different baseflow sources. We can divide the CAMELS catchments into three groups (McDonnell & Woods, 2004); catchments where water is primarily stored (a) in surface water bodies, (b) as snow, and (c) in the subsurface. To visualize how baseflow release dynamics are related to the amount of baseflow released, we plot the median recession exponent β_m against BFI$_5$, shown in Figure 10.

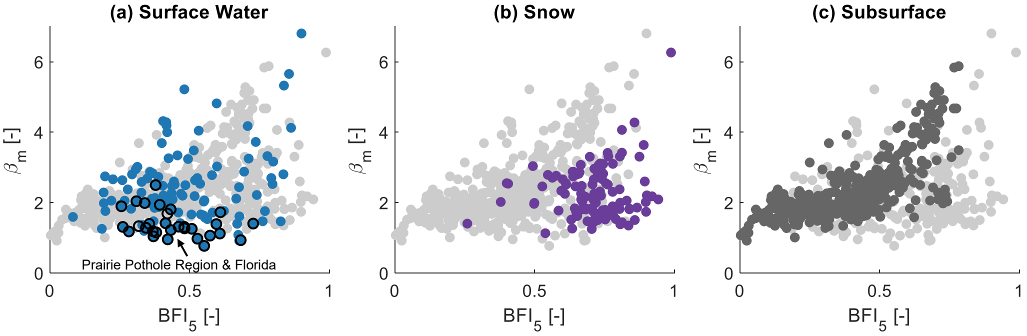

Figure 10. Scatter plots of median recession exponent β_m vs. BFI$_5$ ($\rho_s = 0.42$ for all catchments). Subplots show catchments where water is primarily stored in **(a)** in surface water bodies (>1% of area classified as lake or wetland delineated from the National Wetlands Inventory; $\rho_s = 0.15$ for the subgroup); **(b)** as snow (>30% precipitation falling as snow; $\rho_s = 0.07$); and **(c)** in the subsurface ($\rho_s = 0.72$). Note that each catchment only belongs to one class, with surface water bodies being the first criterion and snow being the second criterion. Note that the y-axis is capped. Similar plots for other signature combinations are shown in the Supporting Information.

While many catchments in the Prairie Pothole Region and Florida show a similar combination of BFI$_5$ and β_m, there is no clear pattern for surface water dominated catchments in general (Figure 10a). The fact that BFI$_5$ and β_m form an uncorrelated point cloud shows that similar amounts of baseflow can be associated with very different baseflow dynamics and hence with different hydrological processes. Lakes and wetlands interact with local groundwater systems and are strongly influenced by seasonal climate and vegetation dynamics (Winter, 1999). Therefore, we will need to better understand these complex, typically regional processes to understand the relationship between surface water bodies and baseflow beyond the case studies shown here.

Snow dominated catchments (Figure 10b) form a relatively distinct point cloud with high BFI$_5$ values and comparatively low β_m values. This is probably a consequence of the seasonal nature of snowmelt, which only provides baseflow for a few months in spring and summer. For example, catchments in the High Cascades (Figure 6d) show lower β_m values than catchments in regions with similarly significant subsurface storage such as the Ozarks (Figure 7d). As the partitioning of snowmelt will also depend on the subsurface, understanding baseflow processes in snow dominated regions requires the inclusion of both snow and groundwater processes (e.g. Tague & Grant, 2004; Safeeq et al., 2013).

In catchments where water is primarily stored in the subsurface, BFI$_5$ and β_m are strongly correlated (Figure 10c). High baseflow amounts (high BFI$_5$) are mostly associated with slow late recessions (high β_m), i.e. stable low flows. This can be seen in many of our case studies, such as the Great Lakes Region (Figure 4d), the Appalachian Mountains (Figure 5c), or the Ozarks (Figure 7d). The remaining variability indicates that also for this subgroup, similar amounts of baseflow can be associated with different baseflow release dynamics, possibly related to different geological settings.

4 Discussion

4.1 Region-Specific Knowledge is Underutilized in Large Sample Studies

Large scale catchment attributes often do not reflect region-specific hydro(geo-)logical knowledge. But a wealth of – currently underutilized – region-specific qualitative and quantitative information exists and it can help us to better understand the link between catchment attributes and baseflow processes. The case studies shown here are not limited to single catchments, but often describe states or larger regions. This suggests that a better characterization of both surface and subsurface properties will also improve our understanding at the continental and global scale. Finding this information requires a creative and open search, including journal articles from related fields (e.g. geomorphology), articles from regional journals, grey literature such as technical reports from agencies (e.g. USGS), as well as communication with experts. While these additional information sources come with limitations such as a lack of external review, they proved very useful and – based on our judgment – are often of similar quality as externally reviewed academic literature. Synthesizing and sharing this information requires a systematic approach, and here we have proposed and applied a framework based on standardized perceptual models.

Standardized perceptual models offer a means to formalize the relationship between catchment attributes and hydrological signatures. They have the advantage that they allow us to share qualitative or place-specific information in a systematic way (see Wagener et al., 2020). We can use perceptual models to state explicitly how we think a system works, and this can then be developed into a testable hypothesis (c.f. Winter, 2001). If a postulated relationship between a hydrological signature and a catchment attribute is not supported by data, we can either reject (or revise) our perceptual model, or try to find other, more relevant data or updated, potentially improved datasets (see Figure 2). Of course, perceptual models are (by definition) subjective and some disagreement will be inevitable. But disagreement can be a useful starting point for progress, and the continuous refinement (or rejection) of these models should be seen as a learning process about processes and places (c.f. Beven, 2007).

4.2 Multiple Baseflow Signatures Are Needed to Distinguish Between Different Baseflow Sources

Baseflow is typically defined as the portion of streamflow that is derived from groundwater and other delayed sources (Hall, 1968; Smakhtin, 2001). But baseflow signatures such as the BFI are often used without explicitly linking them to different baseflow sources. This is problematic as transferring information in both space and time requires knowledge about the processes that generate baseflow. For example, if we want to assess the impact of warmer temperatures on baseflow, we need to understand how that affects both snow and groundwater processes (e.g. Safeeq et al., 2013). Figure 10 shows how different sources of baseflow can lead to very different dynamics, even if the estimated amount of baseflow (quantified by BFI_5) is the same. In many catchments, the stable baseflow component BFI_{90} shows a much clearer link to geological characteristics than BFI_5 (e.g. in the Oregon Cascades, see Figure 6). The combination of different signatures as well as meaningful subgroups can help us to explicitly link baseflow signatures to hydrological processes. This might also help us to identify relationships between baseflow signatures and geology that are otherwise hidden.

4.3 Limitations: Data Uncertainty and Hydrological Signature Selection

An advantage of large sample hydrology is that regional patterns make it less likely to draw wrong conclusions based on a few anomalous catchments (Gupta et al., 2014). At the same time, data errors can hide patterns if a hydrological signature is sensitive to these errors (Westerberg & McMillan, 2015). This applies both to catchment attributes (Addor et al., 2018, 2020) and hydro-meteorological data (Westerberg & McMillan, 2015). For example, regional groundwater flow can affect hydrological signatures (e.g. Figure 8b). But uncertainty in all hydro-meteorological data, particularly in actual evapotranspiration, makes it very difficult to quantify this effect. This substantiates the need for uncertainty estimates which large sample datasets often lack (c.f. Addor et al., 2020).

We have limited our analysis to three signatures: BFI_5, BFI_{90} and β_m. This is just one possible set of signatures and they will not capture the whole range of baseflow processes. For example, a wider range of BFI values as suggested by Stoelzle et al. (2020) might lead to a more refined characterisation of the slow response of different catchments. Furthermore, analyzing seasonal differences in both baseflow and recession behavior might reveal more about the influence of climatic and topographic boundary conditions on the storage-discharge relationship (e.g. Zimmer & Gannon, 2018; Tashie et al., 2019). The baseflow estimation and the recession analysis are also associated with methodological uncertainty (e.g. Stoelzle et al., 2013; Dralle et al., 2017). We did not perform an extensive comparison of different signature calculation methods, but we compared the signature calculation methods used here with a few alternative methods (Lyne & Hollick, 1979; Brutsaert & Nieber, 1977); details can be found in the Supporting Information.

4.4 Next Steps

4.4.1 Viewing Catchments as Systems with a History

We have seen many examples where the geomorphological history of a region does not just give us a glimpse into why a place is like it is, but also provides useful information that is hard to observe directly. The volcanic Cascades evolve from being almost entirely groundwater dominated towards having an efficient surface drainage network (Jefferson et al., 2010). The carbonatic Ozarks evolve in the other direction, as the self-perpetuating dissolution of carbonate rock leads to an increasingly efficient subsurface drainage network (Adamski et al., 1995; A. Hartmann et al., 2014). The Edwards Plateau might be placed somewhere in between. There is an extensive karst network below the ground, yet at the same time surface erosion has carved an extensive surface drainage network into the landscape (B. M. Woodruff & Abbott, 1979). In glacial areas, we can see the imprint of the glacial history in form of sediment composition, but also in form of fluvial erosion induced by glacial meltwater (e.g. Upper Mississippi). The hydrology of the Appalachian Mountains can be better understood by understanding the evolution and thus the architecture of their critical zone (Zimmer & Gannon, 2018). Whether these results are transferable remains to be explored. But we renew the argument that by viewing catchments as systems with a history we might be able to learn more about their present state, and perhaps about how they will evolve in the future (Harman & Troch, 2014; Troch et al., 2015). This does not necessarily imply a long history of co-evolution, as the history of a catchment can be shaped by events (faulting, glaciation; see e.g. Beven, 2015) and more recently increasingly by humans (Wagener et al., 2010)

4.4.2 Challenges for a Geological Classification at the Continental Scale

We have shown examples where a better characterization of geological characteristics allows us to better explain the hydrological response at the regional scale. When extending this approach to larger scales, we will face several challenges. First, we need to merge the diverse regional classifications into a coherent framework that reflects this diversity while being general enough to be useful. Second, we need to translate qualitative information such as rock type into quantitative hydrological properties or indices. Third, we need to account more explicitly for different climatic conditions as both long-term and short-term climatic conditions vary. For example, seasonal variability can affect baseflow (Zimmer & Gannon, 2018) and recessions (Tashie et al., 2019), and thus complicate the linkage between static catchment attributes and hydrological signatures. Similarly, differences in topography can affect recharge and hydraulic gradients, and this can alter the hydrological response even if the hydraulic properties of the subsurface stay the same (Carlier et al., 2019). At the same time, topography is related to hydrologically relevant properties of the subsurface itself (e.g. fractures; St. Clair et al., 2015; Prancevic & Kirchner, 2019). Disentangling these different, potentially co-varying processes is challenging (Price, 2011), but we will have to explicitly address them if we aim at a geological classification at the continental scale.

4.4.3 How Much Regional Information Do We Need to Predict Baseflow Response at the Continental Scale?

Our results suggest that the amount of regional information required to arrive at acceptable continental scale predictions depends both on the spatial scale and on the regions covered. We started by delineating different regions which typically covered large fractions of a state and sometimes multiple states ($\approx 10^4$–10^5 km^2). In some regions, a single attribute that characterizes the subsurface could explain most of the variability in baseflow response (e.g. sinkhole density in the Ozarks, see Figure 7b). In other regions, more information is required, especially if baseflow originates from multiple sources (e.g. wetlands and groundwater, see Section 3.3.3). Continental scale predictions will require attributes that characterize all sub-regions (even though some of the attributes might only be used for some regions).

One way to approximately specify the necessary level of detail for each region would be a simple classification of the main components of our hydrological system, i.e. an initial perceptual model. We might start with the three groups presented in Section 3.3.3 and distinguish between water that is stored in surface water bodies, as snow, and in the subsurface (McDonnell & Woods, 2004). If water is primarily stored in the subsurface, we might then further distinguish between storage in soils, sediment layers, weathered bedrock, etc. Such a classification could be informed by using previous glacial extents (see Section 3.1.1) or by a geomorphological classification (e.g. an upland vs. lowland classification, see Pelletier et al., 2016).

4.4.4 How Can Our Results Help to Understand and Predict Change?

In this paper we have focused on understanding current baseflow response in mostly natural catchments. This is a crucial first step, but ultimately we are also interested in understanding and predicting the hydrological response under change. If we better understand the drivers of baseflow generation, we can use this understanding to assess how these individual drivers and the corresponding attributes respond to change, e.g. when forced by a different climate. Some attributes will be directly impacted by change (e.g. wetland extent, snow cover). Other attributes are mostly static themselves (e.g. geological attributes), but their interaction with climatic forcing controls key hydrological processes (e.g. groundwater storage). Human impacts can be an additional driver of baseflow response and might be assessed by including attributes that characterize human interventions (e.g. land use changes; Y. K. Zhang & Schilling, 2006).

Models that credibly predict change need to adequately represent the dominant hydrological processes and ideally both model structure and model parameters should be informed by process understanding rather than calibration (Sivapalan, 2005; Kirchner, 2006; Clark et al., 2017). By linking baseflow response to catchment attributes via perceptual models, our results could provide guidance on model building and a means to appraise model realism (c.f. Fenicia et al., 2014). By showing that CAMELS catchment attributes do not contain all hydrologically relevant information, we also show that we need better attributes if we want to identify model structures or parameter values based on catchment attributes. This is reinforced by a recent model intercomparison study using the same dataset which did not find a relation between model structures and static catchment attributes (Knoben et al., 2020).

5 Concluding Remarks

In the introduction, we asked why non-climatic catchment attributes have shown limited explanatory power in recent large sample studies. We hypothesized that this is due to limitations in (a) the input data we use to inform our analyses, and (b) the hydrological signatures we use to describe the hydrological response. So what have we learned?

(a) We have found that region-specific knowledge is underutilized in large sample studies. There are many sources of information that can help us to better understand regional hydrological processes, and a key challenge will be to synthesize this information in a useful way. We suggest that this is best done through a common framework underpinned by perceptual models (i.e. "perceptual models of everywhere", cf. Beven, 2007).

(b) It is important to pay attention to the hydrological signatures we use, and we should try to explicitly link them to hydrological processes. We have shown that the use of multiple baseflow signatures – instead of a single BFI – and meaningful catchment subgroups allows us to better distinguish between different baseflow sources. A thoughtful choice of signatures will be crucial to meaningfully assess whether a catchment attribute is hydrologically relevant.

We conclude that we will be able to better link hydrological signatures to catchment attributes if we aim at a more systematic and hydrologically motivated selection of catchment attributes and hydrological signatures.

Acknowledgments

This work is funded as part of the Water Informatics Science and Engineering Centre for Doctoral Training (WISE CDT) under a grant from the Engineering and Physical Sciences Research Council (EPSRC), grant number EP/L016214/1. Parts of this project were undertaken during a research visit of the first author to San Diego State University. Data sources can be found in Table 1. New catchment attributes and baseflow signatures are available from: `https://doi.org/10.5281/zenodo.4071983`. Code used for this study is available from `https://github.com/SebastianGnann/Baseflow_signatures`. Thanks to Ryoko Araki for many discussions and thanks to Gemma Coxon for help with the extraction of catchment attributes. We also thank the Editor, one anonymous reviewer, and Michael Stoelzle for their thoughtful comments which helped to improve this manuscript.

References

Adamski, J. C., Petersen, J. C., Freiwald, D. A., & Davis, J. V. (1995). Environmental and hydrologic setting of the Ozark Plateaus study unit, Arkansas, Kansas, Missouri, and Oklahoma. *U.S. Geological Survey Water-Resources Investigations Report*, *94-4022*, 69. Retrieved from `http://pubs.usgs.gov/wri/wri944022/`

Addor, N., Do, H. X., Alvarez-Garreton, C., Coxon, G., Fowler, K., & Mendoza, P. A. (2020). Large-sample hydrology: recent progress, guidelines for new datasets and grand challenges. *Hydrological Sciences Journal*, *65*(5), 712–725. Retrieved from `https://doi.org/10.1080/02626667.2019.1683182` doi: 10.1080/02626667.2019.1683182

Addor, N., Nearing, G., Prieto, C., Newman, A. J., Le Vine, N., & Clark, M. P. (2018). A Ranking of Hydrological Signatures Based on Their Predictability in Space. *Water Resources Research*, *54*(11), 8792–8812. Retrieved from `http://doi.wiley.com/10.1029/2018WR022606https://onlinelibrary.wiley.com/doi/abs/10.1029/2018WR022606` doi: 10.1029/2018WR022606

Addor, N., Newman, A. J., Mizukami, N., & Clark, M. P. (2017). The CAMELS data set: Catchment attributes and meteorology for large-sample studies. *Hydrology and Earth System Sciences*, *21*(10), 5293–5313. Retrieved from `https://www.hydrol-earth-syst-sci.net/21/5293/2017/` doi: 10.5194/hess-21-5293-2017

Ameli, A. A., & Creed, I. F. (2017). Quantifying hydrologic connectivity of wetlands to surface water systems. *Hydrology and Earth System Sciences*, *21*(3), 1791–1808. doi: 10.5194/hess-21-1791-2017

Barker, R. A., & Ardis, A. F. (1996). Hydrogeologic framework of the Edwards-Trinity aquifer system, west-central Texas. *U.S. Geological Survey Professional Paper*(1421 B).

Beck, H. E., de Roo, A., & van Dijk, A. I. J. M. (2015). Global maps of streamflow characteristics based on observations from several thousand catchments. *Journal of Hydrometeorology*, *16*(4), 1478–1501. Retrieved from `http://journals.ametsoc.org/doi/10.1175/JHM-D-14-0155.1` doi: 10.1175/JHM-D-14-0155.1

Beck, H. E., van Dijk, A. I. J. M., Miralles, D. G., De Jeu, R. A., Bruijnzeel, L. A., McVicar, T. R., & Schellekens, J. (2013). Global patterns in base flow index and recession based on streamflow observations from 3394 catchments. *Water Resources Research*, *49*(12), 7843–7863. doi: 10.1002/2013WR013918

Berghuijs, W. R., Sivapalan, M., Woods, R. A., & Savenije, H. H. G. (2014). Patterns of similarity of seasonal water balances: A window into streamflow variability over a range of time scales. *Water Resources Research*, *50*(7), 5638–5661. Retrieved from `http://doi.wiley.com/10.1002/2014WR015692` doi: 10.1002/2014WR015692

Bettis, E. A., Benn, D. W., & Hajic, E. R. (2008). Landscape evolution, alluvial architecture, environmental history, and the archaeological record of the Upper Mississippi River Valley. *Geomorphology*, *101*(1-2), 362–377. doi: 10.1016/j.geomorph.2008.05.030

Beven, K. (2000). Uniqueness of place and process representations in hydrological modelling. *Hydrology and Earth System Sciences*, *4*(2), 203–213. doi: 10.5194/hess-4-203-2000

Beven, K. (2007). Towards integrated environmental models of everywhere: Uncertainty, data and modelling as a learning process. *Hydrology and Earth System Sciences*, *11*(1), 460–467. doi: 10.5194/hess-11-460-2007

Beven, K. (2015). What we see now: Event-persistence and the predictability of hydro-eco-geomorphological systems. *Ecological Modelling*, *298*, 4–15. Retrieved from `http://dx.doi.org/10.1016/j.ecolmodel.2014.07.019` doi: 10.1016/j.ecolmodel.2014.07.019

Black, P. E. (1997). Watershed functions. *Journal of the American Water Resources Association*, *33*(1), 1–11. Retrieved from `http://doi.wiley.com/10.1111/j.1752-1688.1997.tb04077.x` doi: 10.1111/j.1752-1688.1997.tb04077.x

Bloomfield, J. P., Allen, D. J., & Griffiths, K. J. (2009). Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK. *Journal of Hydrology*, *373*(1-2), 164–176. Retrieved from `http://dx.doi.org/10.1016/j.jhydrol.2009.04.025` doi: 10.1016/j.jhydrol.2009.04.025

Boorman, D. B., Hollis, J. M., & Lilly, A. (1995). Hydrology of soil types: a hydrologically-based classification of the soils of United Kingdom. *Institute of Hydrology*, *IH Report.*(126), 137. doi: 10.1029/98GL02804

Brutsaert, W., & Nieber, J. L. (1977). Regionalized drought flow hydrographs from a mature glaciated plateau. *Water Resources Research*, *13*(3), 637–643. Retrieved from `http://doi.wiley.com/10.1029/WR013i003p00637` doi: 10.1029/WR013i003p00637

Budyko, M. I. (1974). *Climate and Life: English Ed. edited by David H. Miller.* Academic Press.

Carlier, C., Wirth, S. B., Cochand, F., Hunkeler, D., & Brunner, P. (2018). Geology controls streamflow dynamics. *Journal of Hydrology*, *566*(July), 756–769. Retrieved from `https://doi.org/10.1016/j.jhydrol.2018.08.069` doi: 10.1016/j.jhydrol.2018.08.069

Carlier, C., Wirth, S. B., Cochand, F., Hunkeler, D., & Brunner, P. (2019). Exploring geological and topographical controls on low flows with hydrogeological models. *Groundwater*, *57*(1), 48–62. doi: 10.1111/gwat.12845

Clark, M. P., Bierkens, M. F., Samaniego, L., Woods, R. A., Uijlenhoet, R., Bennett, K. E., ... Peters-Lidard, C. D. (2017). The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism. *Hydrology and Earth System Sciences*, *21*(7), 3427–3440. doi: 10.5194/hess-21-3427-2017

Cohen, M. J., Creed, I. F., Alexander, L., Basu, N. B., Calhoun, A. J., Craft, C., ... Walls, S. C. (2016). Do geographically isolated wetlands influence landscape functions? *Proceedings of the National Academy of Sciences of the United States of America*, *113*(8), 1978–1986. doi: 10.1073/pnas.1512650113

Dralle, D. N., Karst, N. J., Charalampous, K., Veenstra, A., & Thompson, S. E. (2017). Event-scale power law recession analysis: Quantifying methodological uncertainty. *Hydrology and Earth System Sciences*, *21*(1), 65–81. doi: 10.5194/hess-21-65-2017

Dralle, D. N., Karst, N. J., & Thompson, S. E. (2015). a, b careful! Consequences of scale invariance in power-law models of the streamflow recession. *Geophysical Research Letters*, *42*, 9285–9293. doi: 10.1002/2015GL066007.Received

Falkenmark, M., & Chapman, T. (1989). *Comparative hydrology: an ecological approach to land and water resources.* The Unesco Press.

Fan, Y. (2019). Are catchments leaky? *WIREs Water*, *6*(6), 1–25. doi: 10.1002/wat2.1386

Farvolden, R. (1963). Geologic controls on ground-water storage and base flow. *Journal of Hydrology*, *1*(3), 219–249.

Fatichi, S., Or, D., Walko, R., Vereecken, H., Young, M. H., Ghezzehei, T. A., ... Avissar, R. (2020). Soil structure is an important omission in Earth System Models. *Nature Communications*, *11*(1). Retrieved from `http://dx.doi.org/10.1038/s41467-020-14411-z` doi: 10.1038/s41467-020-14411-z

Fenicia, F., Kavetski, D., Savenije, H. H. G., Clark, M. P., Schoups, G., Pfister, L., & Freer, J. (2014). Catchment properties, function, and conceptual model representation: is there a correspondence? *Hydrological Processes*, *28*(4), 2451–2467. Retrieved from `http://doi.wiley.com/10.1002/hyp.9726` doi: 10.1002/hyp.9726

Fenneman, N., & Johnson, D. (1946). Physiographic divisions of the conterminous U.S. Retrieved from `https://water.usgs.gov/GIS/metadata/usgswrd/XML/physio.xml#Metadata_Reference_Information`

Gleeson, T., Moosdorf, N., Hartmann, J., & Van Beek, L. P. (2014). A glimpse beneath earth's surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity. *Geophysical Research Letters*, *41*(11), 3891–3898. Retrieved from `http://doi.wiley.com/10.1002/2014GL059856` doi: 10.1002/2014GL059856

Gupta, H. V., Perrin, C., Blöschl, G., Montanari, A., Kumar, R., Clark, M. P., & Andréassian, V. (2014). Large-sample hydrology: A need to balance depth with breadth. *Hydrology and Earth System Sciences*, *18*(2), 463–477. doi: 10.5194/hess-18-463-2014

Hall, F. R. (1968). Base-Flow Recessions-A Review. *Water Resources Research*, *4*(5), 973–983. Retrieved from `http://doi.wiley.com/10.1029/WR004i005p00973` doi: 10.1029/wr004i005p00973

Harman, C. J., & Troch, P. A. (2014). What makes Darwinian hydrology "Darwinian"? Asking a different kind of question about landscapes. *Hydrology and Earth System Sciences*, *18*(2), 417–433. doi: 10.5194/hess-18-417-2014

Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., & Weiler, M. (2014). Karst water resources in a changing world. *Review of Geophysics*, *2013*(September), 218–242. doi: 10.1002/2013RG000443.Received

Hartmann, J., & Moosdorf, N. (2012). The new global lithological map database GLiM: A representation of rock properties at the Earth surface. *Geochemistry, Geophysics, Geosystems*, *13*(12), 1–37. doi: 10.1029/2012GC004370

Harvey, E. J. (1981). *Ground water in the springfield-salem plateaus of southern missouri and northern arkansas* (Vol. 80). U.S. Geological Survey.

Hays, P. D., Knierim, K. J., Breaker, B., Westerman, D. A., & Clark, B. R. (2016). Hydrogeology and hydrologic conditions of the Ozark Plateaus aquifer system. *U.S. Geological Survey Scientific Investigations Report*(2016-5137), 61.

Horton, J., San Juan, C., & Stoeser, D. (2017). The State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States (ver. 1.1, August 2017). (1052), 46. Retrieved from `https://doi.org/10.3133/ds1052` doi: 10.3133/ds1052

Institute of Hydrology. (1980). *Low flow studies report no. 1: Research report.* Institute of Hydrology.

Jachens, E. R., Rupp, D. E., Roques, C., & Selker, J. S. (2020). Recession analysis revisited: impacts of climate on parameter estimation. *Hydrology and Earth System Sciences*, *24*(3), 1159–1170. Retrieved from `https://www.hydrol-earth-syst-sci.net/24/1159/2020/` doi: 10.5194/hess-24-1159-2020

Jefferson, A., Grant, G. E., Lewis, S. L., & Lancaster, S. T. (2010). Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA. *Earth Surface Processes and Landforms*, *35*(7), 803–816. doi: 10.1002/esp.1976

Jehn, F. U., Bestian, K., Breuer, L., Kraft, P., & Houska, T. (2020). Using hydrological and climatic catchment clusters to explore drivers of catchment behavior. *Hydrology and Earth System Sciences*, *24*(3), 1081–1100. doi: 10.5194/hess-24-1081-2020

Khan, M. S., Liaqat, U. W., Baik, J., & Choi, M. (2018). Stand-alone uncertainty characterization of GLEAM, GLDAS and MOD16 evapotranspiration products using an extended triple collocation approach. *Agricultural and Forest Meteorology*, *252*, 256–268. Retrieved from `https://doi.org/10.1016/j.agrformet.2018.01.022` doi: 10.1016/j.agrformet.2018.01.022

Kirchner, J. W. (2006). Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. *Water Resources Research*, *42*(3), 1–5. doi: 10.1029/2005WR004362

Kleeschulte, M. J. (2000). *Ground-and surface-water relations in the eleven point and current river basins, south-central missouri.* U.S. Geological Survey.

Knoben, W. J. M., Freer, J. E., Peel, M. C., Fowler, K., & Woods, R. A. (2020). A brief analysis of conceptual model structure uncertainty using 36 models and 559 catchments. *Water Resources Research*, *n/a*(n/a), e2019WR025975. Retrieved from `https://onlinelibrary.wiley.com/doi/abs/10.1029/2019WR025975{\%}0Ahttps://doi.org/10.1029/2019WR025975` doi: 10.1029/2019WR025975

Knoben, W. J. M., Woods, R. A., & Freer, J. E. (2018). A quantitative hydrological climate classification evaluated with independent streamflow data. *Water Resources Research*, *54*(7), 5088–5109. Retrieved from `http://doi.wiley.com/10.1029/2018WR022913` doi: 10.1029/2018WR022913

Kratzert, F., Klotz, D., Herrnegger, M., Sampson, A. K., Hochreiter, S., & Nearing, G. S. (2019). Toward improved predictions in ungauged basins: Exploiting the power of machine learning. *Water Resources Research*, *55*(12), 11344–11354. doi: 10.1029/2019WR026065

Kuentz, A., Arheimer, B., Hundecha, Y., & Wagener, T. (2017). Understanding hydrologic variability across Europe through catchment classification. *Hydrology and Earth System Sciences*, *21*(6), 2863–2879. Retrieved from `https://www.hydrol-earth-syst-sci.net/21/2863/2017/` doi: 10.5194/hess-21-2863-2017

Lacey, G. C., & Grayson, R. B. (1998). Relating baseflow to catchment properties in south-eastern Australia. *Journal of Hydrology*, *204*(1-4), 231–250. doi: 10.1016/S0022-1694(97)00124-8

Larson, G., & Schaetzl, R. (2001). Origin and evolution of the Great Lakes. *Journal of Great Lakes Research*, *27*(4), 518–546. Retrieved from `http://dx.doi.org/10.1016/S0380-1330(01)70665-X` doi: 10.1016/S0380-1330(01)70665-X

Lehner, B., Verdin, K., & Jarvis, A. (2008). New global hydrography derived from spaceborne elevation data. *Eos, Transactions American Geophysical Union*, *89*(10), 93–94.

Lyne, V. D., & Hollick, M. (1979). *Stochastic time-variable rainfall runoff modelling.*

Martens, B., Miralles, D. G., Lievens, H., Van Der Schalie, R., De Jeu, R. A., Fernández-Prieto, D., ... Verhoest, N. E. (2017). GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development*, *10*(5), 1903–1925. doi: 10.5194/gmd-10-1903-2017

McDonnell, J. J., & Woods, R. A. (2004). On the need for catchment classification. *Journal of Hydrology*, *299*(1-2), 2–3. doi: 10.1016/s0022-1694(04)00421-4

McGlynn, B. L., McDonnell, J. J., & Brammer, D. D. (2002). A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. *Journal of Hydrology*, *257*(1-4), 1–26. Retrieved from `http://linkinghub.elsevier.com/retrieve/pii/S0022169401005595` doi: 10.1016/S0022-1694(01)00559-5

McLaughlin, D. L., Kaplan, D. A., & Cohen, M. J. (2014). A significant nexus: Geographically isolated wetlands influence landscape hydrology. *Water Resources Research*, *50*(9), 7153–7166. doi: 10.1002/2013WR015002

McMillan, H. K. (2020). Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes*, *34*(6), 1393–1409. doi: 10.1002/hyp.13632

McMillan, H. K., Westerberg, I. K., & Branger, F. (2017). Five guidelines for selecting hydrological signatures. *Hydrological Processes*, *31*(26), 4757–4761. Retrieved from `http://doi.wiley.com/10.1002/hyp.11300` doi: 10.1002/hyp.11300

Miller, D. A., & White, R. A. (1998). A conterminous United States multilayer soil characteristics dataset for regional climate and hydrology modeling. *Earth Interactions*, *2*(1), 2–2. doi: 10.1175/1087-3562(1998)002⟨0002:cusms⟩2.0.co;2

Miralles, D. G., Holmes, T. R., De Jeu, R. A., Gash, J. H., Meesters, A. G., & Dolman, A. J. (2011). Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, *15*(2), 453–469. doi: 10.5194/hess-15-453-2011

Missouri Geological Survey. (2018). Missouri Geological Survey Geosciences Technical Resource Assessment Tool (GeoSTRAT). Retrieved from `https://apps5.mo.gov/geostrat/`

Mu, Q., Zhao, M., & Running, S. W. (2011). Improvements to a MODIS global terrestrial evapotranspiration algorithm. *Remote Sensing of Environment*, *115*(8), 1781–1800. Retrieved from `http://dx.doi.org/10.1016/j.rse.2011.02.019` doi: 10.1016/j.rse.2011.02.019

Mugel, D. N., Richards, J. M., & Schumacher, J. G. (2009). *Geohydrologic investigations and landscape characteristics of areas contributing water to springs, the current river, and jacks fork, ozark national scenic riverways, missouri.* U.S. Geological Survey.

National Atlas of the United States. (2005). Generalized Glacial Limit Lines: Geology of the Conterminous United States. Retrieved from `http://purl.stanford.edu/vz874sc7648`

Naylor, S., Letsinger, S. L., Ficklin, D. L., Ellett, K. M., & Olyphant, G. A. (2016). A hydropedological approach to quantifying groundwater recharge in various glacial settings of the mid-continental USA. *Hydrological Processes*, *30*(10), 1594–1608. doi: 10.1002/hyp.10718

Neff, B. P., Day, S., Piggott, A., & Fuller, L. (2005). Base flow in the Great Lakes Basin. *U.S. Geological Survey Scientific Investigations Report*(2005-5217), 23. Retrieved from `http://pubs.usgs.gov/sir/2005/5217/pdf/SIR2005-5217.pdf` doi: 10.3133/sir20055217

Neff, B. P., & Rosenberry, D. O. (2018). Groundwater connectivity of upland-embedded wetlands in the Prairie Pothole Region. *Wetlands*, *38*(1), 51–63. doi: 10.1007/s13157-017-0956-7

Newman, A. J., Clark, M. P., Sampson, K., Wood, A., Hay, L. E., Bock, A., … Duan, Q. (2015). Development of a large-sample watershed-scale hydrometeorological data set for the contiguous USA: data set characteristics and assessment of regional variability in hydrologic model performance. *Hydrology and Earth System Sciences*, *19*(1), 209–223. Retrieved from `http://www.hydrol-earth-syst-sci.net/19/209/2015/https://www.hydrol-earth-syst-sci.net/19/209/2015/` doi: 10.5194/hess-19-209-2015

Parry, S., Wilby, L. R., Prudhomme, C., & Wood, J. P. (2016). A systematic assessment of drought termination in the United Kingdom. *Hydrology and Earth System Sciences*, *20*(10), 4265–4281. doi: 10.5194/hess-20-4265-2016

Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G., … Gochis, D. (2016). A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling. *Journal of Advances in Modeling Earth Systems*, *8*(1), 41–65. Retrieved from `https://onlinelibrary.wiley.com/doi/abs/10.1002/2015MS000526` doi: 10.1002/2015MS000526

Pfister, L., Martínez-Carreras, N., Hissler, C., Klaus, J., Carrer, G. E., Stewart, M. K., & McDonnell, J. J. (2017). Bedrock geology controls on catchment storage, mixing, and release: A comparative analysis of 16 nested catchments. *Hydrological Processes*, *31*(10), 1828–1845. doi: 10.1002/hyp.11134

Prancevic, J. P., & Kirchner, J. W. (2019). Topographic controls on the extension and retraction of flowing streams. *Geophysical Research Letters*, *46*(4), 2084–2092. doi: 10.1029/2018GL081799

Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. *Progress in Physical Geography*, *35*(4), 465–492. Retrieved from `http://journals.sagepub.com/doi/10.1177/0309133311402714` doi: 10.1177/0309133311402714

Roques, C., Rupp, D. E., & Selker, J. S. (2017). Improved streamflow recession parameter estimation with attention to calculation of -dQ/dt. *Advances in Water Resources*, *108*, 29–43. Retrieved from `https://doi.org/10.1016/j.advwatres.2017.07.013` doi: 10.1016/j.advwatres.2017.07.013

Safeeq, M., Grant, G. E., Lewis, S. L., & Tague, C. L. (2013). Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the western United States. *Hydrological Processes*, *27*(5), 655–668. doi:

10.1002/hyp.9628

Santhi, C., Allen, P. M., Muttiah, R. S., Arnold, J. G., & Tuppad, P. (2008). Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. *Journal of Hydrology*, *351*(1-2), 139–153. Retrieved from `http://linkinghub.elsevier.com/retrieve/pii/S0022169407007433` doi: 10.1016/j.jhydrol.2007.12.018

Schaller, M. F., & Fan, Y. (2009). River basins as groundwater exporters and importers: Implications for water cycle and climate modeling. *Journal of Geophysical Research Atmospheres*, *114*(4), D04103. Retrieved from `http://doi.wiley.com/10.1029/2008JD010636` doi: 10.1029/2008JD010636

Schiffer, D. M. (1998). *Hydrology of central florida lakes: A primer* (Vol. 1137). U.S. Geological Survey.

Schneider, M. K., Brunner, F., Hollis, J. M., & Stamm, C. (2007). Towards a hydrological classification of European soils: Preliminary test of its predictive power for the base flow index using river discharge data. *Hydrology and Earth System Sciences*, *11*(4), 1501–1513. doi: 10.5194/hess-11-1501-2007

Shanley, J. B., Sebestyen, S. D., McDonnell, J. J., McGlynn, B. L., & Dunne, T. (2015). Water's Way at Sleepers River watershed - revisiting flow generation in a post-glacial landscape, Vermont USA. *Hydrological Processes*, *29*(16), 3447–3459. doi: 10.1002/hyp.10377

Sivapalan, M. (2005). Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale. In *Encyclopedia of hydrological sciences.* Chichester, UK: John Wiley & Sons, Ltd. Retrieved from `http://doi.wiley.com/10.1002/0470848944.hsa012` doi: 10.1002/0470848944.hsa012

Smakhtin, V. (2001). Low flow hydrology: a review. *Journal of Hydrology*, *240*(3-4), 147–186. Retrieved from `https://linkinghub.elsevier.com/retrieve/pii/S0022169400003401` doi: 10.1016/S0022-1694(00)00340-1

St. Clair, J., Moon, S., Holbrook, W. S., Perron, J. T., Riebe, C. S., Martel, S. J., … De Richter, D. B. (2015). Geophysical imaging reveals topographic stress control of bedrock weathering. *Science*, *350*(6260), 534–538. doi: 10.1126/science.aab2210

Stoelzle, M., Schuetz, T., Weiler, M., Stahl, K., & Tallaksen, L. M. (2020). Beyond binary baseflow separation: a delayed-flow index for multiple streamflow contributions. *Hydrology and Earth System Sciences*, *24*(2), 849–867. doi: 10.5194/hess-24-849-2020

Stoelzle, M., Stahl, K., & Weiler, M. (2013). Are streamflow recession characteristics really characteristic? *Hydrology and Earth System Sciences*, *17*(2), 817–828. doi: 10.5194/hess-17-817-2013

Tague, C. L., & Grant, G. E. (2004). A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research*, *40*(4), 1–9. doi: 10.1029/2003WR002629

Tague, C. L., Grant, G. E., Farrell, M., Choate, J., & Jefferson, A. (2008). Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change*, *86*(1-2), 189–210. doi: 10.1007/s10584-007-9294-8

Tashie, A., Pavelsky, T., & Emanuel, R. E. (2020). Spatial and temporal patterns in baseflow recession in the continental United States. *Water Resources Research*, *56*(3), 1–18. doi: 10.1029/2019WR026425

Tashie, A., Scaife, C. I., & Band, L. E. (2019). Transpiration and subsurface controls of streamflow recession characteristics. *Hydrological Processes*, *33*(19), 2561–2575. doi: 10.1002/hyp.13530

Texas Water Development Board. (2020). Major aquifers of Texas. Retrieved from `http://www.twdb.texas.gov/mapping/gisdata.asp`

Troch, P. A., Lahmers, T., Meira, A., Mukherjee, R., Pedersen, J. W., Roy, T., & Valdés-Pineda, R. (2015). Catchment coevolution: A useful framework for improving predictions of hydrological change? *Water Resources Research*, *51*(7), 4903–4922. Retrieved from `https://onlinelibrary.wiley.com/doi/abs/10.1002/2015WR017032` doi: 10.1002/2015WR017032

U.S. Fish and Wildlife Service. (2020, May). National Wetlands Inventory. Retrieved from `http://www.fws.gov/wetlands/`

U.S. Geological Survey. (2003). Principal Aquifers of the 48 Conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands. Retrieved from `https://water.usgs.gov/ogw/aquifer/map.html`

Wagener, T., Gleeson, T., Coxon, G., Hartmann, A., Howden, N., Pianosi, F., ... Woods, R. (2020). On doing large-scale hydrology with lions: Realising the value of perceptual models and knowledge accumulation.

Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., ... Wilson, J. S. (2010). The future of hydrology: An evolving science for a changing world. *Water Resources Research*, *46*(5), 1–10. Retrieved from `http://doi.wiley.com/10.1029/2009WR008906` doi: 10.1029/2009WR008906

Wagener, T., Sivapalan, M., Troch, P. A., & Woods, R. A. (2007). Catchment classification and hydrologic similarity. *Geography Compass*, *1*(4), 901–931. Retrieved from `http://doi.wiley.com/10.1111/j.1749-8198.2007.00039.x` doi: 10.1111/j.1749-8198.2007.00039.x

Westerberg, I. K., & McMillan, H. K. (2015). Uncertainty in hydrological signatures. *Hydrology and Earth System Sciences*, *19*(9), 3951–3968. Retrieved from `https://www.hydrol-earth-syst-sci.net/19/3951/2015/` doi: 10.5194/hess-19-3951-2015

Westerberg, I. K., Wagener, T., Coxon, G., McMillan, H. K., Castellarin, A., Montanari, A., & Freer, J. (2016). Uncertainty in hydrological signatures for gauged and ungauged catchments. *Water Resources Research*, *52*(3), 1847–1865. Retrieved from `http://doi.wiley.com/10.1002/2015WR017635` doi: 10.1002/2015WR017635

Wilcox, B. P., Wilding, L. P., & Woodruff, J. M. (2007). Soil and topographic controls on runoff generation from stepped landforms in the Edwards Plateau of Central Texas. *Geophysical Research Letters*, *34*(24), 1–6. doi: 10.1029/2007GL030860

Winter, T. C. (1999). Relation of streams, lakes, and wetlands to groundwater flow systems. *Hydrogeology Journal*, *7*(1), 28–45. doi: 10.1007/s100400050178

Winter, T. C. (2001). The concept of hydrologic landscapes. *Journal of the American Water Resources Association*, *37*(2), 335–349. Retrieved from `https://doi.org/10.1111/j.1752-1688.2001.tb00973.xhttp://doi.wiley.com/10.1111/j.1752-1688.2001.tb00973.x` doi: 10.1111/j.1752-1688.2001.tb00973.x

Woodruff, B. M., & Abbott, P. L. (1979). Drainage-basin evolution and aquifer development in a karstic limestone terrain south-central Texas, USA. *Earth Surface Processes*, *4*(4), 319–334. doi: 10.1002/esp.3290040403

Woodruff, C. M., & Wilding, L. P. (2008). Bedrock, soils, and hillslope hydrology in the Central Texas Hill Country, USA: Implications on environmental management in a carbonate-rock terrain. *Environmental Geology*, *55*(3), 605–618. doi: 10.1007/s00254-007-1011-4

Zhang, Y., Ahiablame, L., Engel, B., & Liu, J. (2013). Regression modeling of baseflow and baseflow index for Michigan USA. *Water (Switzerland)*, *5*(4), 1797–1815. doi: 10.3390/w5041797

Zhang, Y. K., & Schilling, K. E. (2006). Increasing streamflow and baseflow in Mississippi River since the 1940 s: Effect of land use change. *Journal of Hydrology*, *324*(1-4), 412–422. doi: 10.1016/j.jhydrol.2005.09.033

Zimmer, M. A., & Gannon, J. P. (2018). Run-off processes from mountains to foothills: The role of soil stratigraphy and structure in influencing run-off characteristics across high to low relief landscapes. *Hydrological Processes*, *32*(11), 1546–1560. doi: 10.1002/hyp.11488