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Linking hydrologic signatures to hydrologic processes: A review

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Abstract

Hydrologic signatures are metrics that quantify aspects of streamflow response. Linking signatures to underlying processes enables multiple applications, such as selecting hydrologic model structure, analysing hydrologic change, making predictions in ungauged basins, and classifying watershed function. However, many lists of hydrologic signatures are not process-based, and knowledge about signature-process links has been scattered among studies from experimental watersheds and model selection experiments. This review brings together those studies to catalogue more than 50 signatures representing evapotranspiration, snow storage and melt, permafrost, infiltration excess, saturation excess, groundwater, baseflow, connectivity, channel processes, partitioning, and human alteration. The review shows substantial variability in the number, type, and timescale of signatures available to represent each process. Many signatures provide information about groundwater storage, partitioning, and connectivity, whereas snow processes and human alteration are under-represented. More signatures are related to the seasonal scale than the event timescale, and land surface processes (ET, snow, and overland flow) have no signatures at the event scale. There are limitations in some signatures that test for occurrence but cannot quantify processes, or are related to multiple processes, making automated analysis more difficult. This review will be valuable as a reference for hydrologists seeking to use streamflow records to investigate a particular hydrologic process or to conduct large-sample analyses of patterns in hydrologic processes.

KEYWORDS
Hydrological Signatures, Flow Metrics, Processes, Flow Indices, Streamflow

1 | INTRODUCTION

1.1 | Hydrologic signatures and their link to hydrologic processes

For water resource management and forecasting, hydrologists develop theories of watershed behaviour and encode these as computer simulation models. To evaluate whether theories and models accurately represent watershed behaviour, an emerging method is to use hydrologic signatures. These are metrics that quantify individual aspects of behaviour (e.g., "average time for a flood to reach its peak") and are used to compare theory or model predictions to observed flow data. Using signatures to evaluate model realism enables us to treat models as testable hypotheses about catchment behaviour (Beven, 2001; Clark, Kavetski, & Fenicia, 2011). Hydrologic signatures were demonstrated by Gupta, Wagener, and Liu (2008) to improve parameterization strategies in hydrologic modelling. By linking signatures of hydrologic response to individual model parameters, the dimensionality of the parameterization problem was reduced, and more realistic parameter values were obtained.

Hydrologic signatures are widely used, with applications including assessing ecological habitat based on hydrologic conditions (Olden &

Poff, 2003), selecting hydrologic model structure (Hrachowitz et al., 2014) and parameters (Pokhrel, Yilmaz, & Gupta, 2012), analysing hydrologic change (Archer & Newson, 2002), and making predictions in ungauged basins (Yadav, Wagener, & Gupta, 2007). Many applications use signatures as a proxy for the hydrologic processes in the watershed, for example, using signatures to classify functional types of watershed (Berghuijs, Sivapalan, Woods, & Savenije, 2014; Sivapalan, Yaeger, Harman, Xu, & Troch, 2011), define similarity between watersheds (Wagener, Sivapalan, Troch, & Woods, 2007), or to map hydrologic processes across a landscape (McMillan et al., 2014). Sawicz, Wagener, Sivapalan, Troch, and Carrillo (2011) find that signatures should have a direct link to watershed function in order to be useful for catchment classification.

However, many lists of hydrologic signatures are not process-based (e.g., Olden & Poff, 2003). Instead, it is common for hydrologic signature frameworks to focus on capturing elements of the flow regime that are relevant to ecological or other applications (Clausen & Biggs, 2000). For example, the indicators of hydrologic alteration method uses 32 signatures in five categories covering magnitude, extremes, timing, duration, and frequency of flow conditions (Richter, Baumgartner, Powell, & Braun, 1996). Similarly, signatures are used for model calibration, to evaluate how well this model simulates different aspects of the flow response, without any explicit link being made between signatures and watershed processes (Euser et al., 2013; Shafii & Tolson, 2015).

An early attempt to make a link between processes and signatures was by Boyle, Gupta, and Sorooshian (2000), who divided hydrographs into time slices representing “driven” (rainfall), “nondriven” (interflow), and “nondriven slow” (baseflow) processes, which were then used within a multiobjective optimization. These concepts have some similarities to older ideas of annual streamflow regimes and their link to underlying processes, for example, the variety of cold region regimes described by Woo (1986). McDonnell et al. (2007) borrow from ecology to suggest that patterns of streamflow (and the underlying patterns of landscapes and processes) should be described in terms of “functional traits” that embody the evolution and development of the watershed function. Many experimental studies show how streamflow signatures can provide valuable insights into processes. As just one example, Peters, Freer, and Aulenbach (2003) showed that streamflow, particularly stormflow, is a good proxy for hillslope processes at the experimental Panola watershed. They showed that maximum stormflow implied maximum soil moisture and water table levels on the hillslope and that storm flow was linearly related to soil moisture during wet periods.

The multitude of signatures reviewed in this paper shows how signatures enable hydrologists to make the most out of the extensive collections of streamflow data available across the globe. Without requiring additional and less widely available data (such as soil moisture or groundwater time series), signatures provide an extensive toolbox to carry out process-based analyses of streamflow dynamics and identify the occurrence and strength of hydrologic processes. These methods remind us of the value of streamflow data beyond standard model calibration methods.

1.2 | The importance of context

It is not always straightforward to determine which signatures are related to which processes, as one feature of the flow response can be caused by multiple hydrologic processes (Klemeš, 1983). For example, Ali et al. (2013) describe how multiple interacting processes contribute to the presence of thresholds. To mitigate this problem, signatures are often used in a more narrow context, after potential causative processes have already been identified. For example, signatures can be used to distinguish between two competing hypotheses, such as by Graeff et al. (2009) for hypotheses on the cause of double peaks in streamflow. Or they can be used to determine when a specific process occurs, such as identifying a change in overland flow response with soil cracking (Zehe, Elsenbeer, Lindenmaier, Schulz, & Blöschl, 2007). In this way, some common signatures, such as runoff ratio, can be used to gain knowledge about multiple different processes.

Additional data can sometimes be brought in to identify the process responsible for a signature behaviour. For example, fast response of streamflow could be due to several different causes, but Blume, Zehe, Reusser, Iroumé, and Bronstert (2008) also knew that groundwater response lagged streamflow response in their watershed, indicating lateral flow as the most likely underlying process. The same authors used prior knowledge of typical processes given the type of catchment, for example, fast streamflow response and fast recessions, together with a known likelihood of preferential flow in forests, provide strong evidence for macropore flow. Including expert knowledge in signature interpretation can however bring conflicting ideas, such as Becker and McDonnell (1998) who instead interpreted a higher baseflow percentage in forested areas as evidence for macropore flow along roots providing a pathway to deeper subsurface stores. Safeeq and Hunsaker (2016) describe the necessity of bringing in expert knowledge in a small catchment that has significantly higher base flow and slower recessions than its neighbours; this transpires to be due to an old dam site turned meadow that has delayed the stream in cutting down to bedrock. This example demonstrates how the “uniqueness of place” in hydrology applies to the interpretation of signatures.

Signatures might be specifically chosen according to the geology or other watershed characteristics, such as by Allen et al. (2005) when working in clay shale terrain. Signatures may change in more nuanced ways that give clues about the underlying process, for example, runoff flashiness could be due to storage characteristics or human impacts, but an increase in flashiness overtime would suggest the latter.

Despite the strategies outlined above, it is not always possible to describe a causative link between hydrologic processes and signatures. Signatures can still be useful to constrain model function in this case, for example, Schaefli (2016) who test a model in snow-dominated watersheds to determine whether it can reproduce the time variability of signatures calculated on observed data. We may have sufficient knowledge to recommend particular signatures to constrain model parameters representing a specific process, without a direct explanation of why those signatures relate to that process. An example comes from Bulygina, McIntyre, and Wheater (2009) who find that baseflow index (BFI) can be successfully used to constrain slow flow response time, despite no proven physical link between the two. Several authors investigate clustering of signatures as a method to split signatures into process-related groups, even when the processes are not yet known. Examples include Hughes and James (1989), who cluster streamflow as a precursor to finding distinct ecological niches, and Hannah, Smith, Gurnell, and McGregor (2000), who cluster daily snowmelt hydrographs to identify different driving processes. These methods may offer a strategy for uncovering the processes underlying popular but nonprocess-based signatures.

1.3 | Strengthening the link between signatures and processes

Fenicia et al. (2014) describe the importance of using experimental evidence to back up the link between processes and signatures, for example, understanding the dominant geologies and connections between stores in the watershed. We rely heavily on this approach in our review, by using the results from studies in experimental watersheds where hydrologists have drawn from their field knowledge to understand the physical causes of flow signatures.

Several other methods can help strengthen the link between signatures and processes. One technique is to look at the signature changes that occur in response to known changes in the watershed. For example, Guzha et al. (2015) reported that low flows in the Amazon decreased following ecosystem degradation, therefore linking low flow signatures with landscape change. Yilmaz, Gupta, and Wagener (2008) and McDonnell et al. (2007) look more generally for spatial–temporal patterns in the data that could be explained by differences in processes. Large-scale techniques, such as machine learning, random forests, and stepwise regressions, can elucidate the relationship of signature values with climatic and physical characteristics of watersheds, for example, Addor et al. (2018) for the United States, Kuentz, Arheimer, Hundecha, and Wagener (2017) in Europe, and Trancoso, Phinn, McVicar, Larsen, and McAlpine (2017) in Australia. These studies found that climate was a dominant control on signatures, with Kuentz et al. (2017) also finding that geology (for base flow) and land cover were important characteristics.

The aim of this review is to provide the reader with a summary of which signatures (based on streamflow and precipitation) can be used to investigate common hydrologic processes. This information will be useful for hydrologists seeking to evaluate the ability of hydrologic models to correctly reproduce specific processes and to understand how processes change overtime and space.

2 | REVIEW METHODS

The review will be structured using hydrologic process classes (Anderson & McDonnell, 2005). For each process class, we searched literature sources to find hydrologic signatures that previous authors had used to investigate the process. Often, those authors did not use the terminology of hydrologic signatures but instead referred to their analysis of features of the streamflow response. Literature sources included analyses from experimental watersheds, catalogued by the Experimental Hydrology Wiki (Blume & Tromp-van Meerveld, 2009). These included papers about how dominant processes were determined from runoff or rainfall and runoff data and papers that used ancillary data sources to back up their interpretation of streamflow response (e.g., Tetzlaff, Birkel, Dick, Geris, & Soulsby, 2014). We searched the literature for papers that referred to hydrologic signatures, hydrologic indices, or hydrologic metrics, where they also refer to interpretation of these signatures in terms of processes. Additionally, we searched studies on hydrologic model selection and model differences between watersheds, to find cases where model choices were made according to determination of dominant hydrologic processes.

This review is restricted to hydrologic signatures that can be derived using only streamflow and rainfall data. Streamflow data are the primary target of the signatures, with rainfall data added if necessary to interpret the signatures (e.g., to identify storm events) but not used by itself. We selected these datatypes as most commonly available to hydrologists. Some previous papers addressed additional signatures that can be calculated when snow (Schaefli, 2016), soil moisture (Branger & McMillan, 2019), or groundwater (Heudorfer, Haaf, Stahl, & Barthel, 2019) data are available. We recognize that many more complex findings can be derived from experimental catchments with detailed data sets, including tracers, storage, soil moisture, and others. In certain landscape types, additional data may be highly valuable for inferring dominant processes, such as water quality data in karst systems (Hartmann et al., 2013). However, such data are not typically available for large samples of catchments and were therefore determined to be outside the scope of this study.

Within each process section, signatures are organized from long to short timescales. We include narrative information about signature concepts, use of the signatures, and interpretation of the processes behind the signatures, including uncertainties about which processes are involved. We do not include equations to calculate numeric signatures as these are not typically provided in the studies we cite. At the end of the review, we provide a summary table that lists each signature, grouped by hydrologic process, and includes the signature description, hydrologic process description, and literature reference.

3 | REVIEW RESULTS

3.1 | Evapotranspiration

At a multi-year, watershed scale, total runoff ratio can be used as a signature to evaluate the volume of water that bypasses the flow gauge, that is, evaporation and groundwater fluxes (McMillan et al., 2014; Safeeq & Hunsaker, 2016), although it is not usually possible to separate these two. At seasonal to annual scales, for watersheds where precipitation is similar year-round, the seasonality of streamflow is used as a signature of variability in evapotranspiration

(ET; Wrede et al., 2015). Seasonality can be defined based on seasonal changes in flow duration curve midsection slope (Estrany, Garcia, & Batalla, 2010).

At a daily timescale, daily fluctuations in streamflow provide multiple opportunities to create signatures representing ET processes (Figure 1). As noted by Schwab, Klaus, Pfister, and Weiler (2016), the timing of the diel cycle determines the driving process: maxima in the morning signify ET, maxima in the afternoon signify snowmelt (apart from tropical watersheds with consistent rainfall in the early afternoon), whereas minima in the afternoon coupled with a losing stream can be a result of fluctuations in the viscosity of water. An asymmetric diel cycle with a sharp fall and gradual rise in flow is a further signature of an ET mechanism (Lundquist & Cayan, 2002), although this pattern may also be due to variable infiltration into the stream bed. Lundquist and Cayan (2002) use a signature based on the power spectrum of the flow time series to determine whether diel cycles occur. They specify that the daily timescale should have power at least 30% greater than neighbouring frequencies. For a signature of cycle magnitude, the same authors use the ratio of diel amplitude (half the difference between the daily maximum and minimum flow) to average daily flow. This measures the fraction of streamwater removed by ET. For downstream locations, diel fluctuations are stronger in rivers with higher water velocity, because the signal is better preserved (Wondzell, Gooseff, & McGlynn, 2007).

Even where streamflow maxima do occur in the morning, the exact ET process related to this signature is not settled. Diel fluctuations are typically related to riparian ET (Wondzell et al., 2007), but observations that the amplitude of the diel cycle increases during the summer show that an additional process must be in play, perhaps that ET is preferentially or partly met from the unsaturated zone in early summer (Wondzell, Gooseff, & McGlynn, 2010). Graham, Barnard, Kavanagh, and McNamara (2013) draw on previous work to lay out

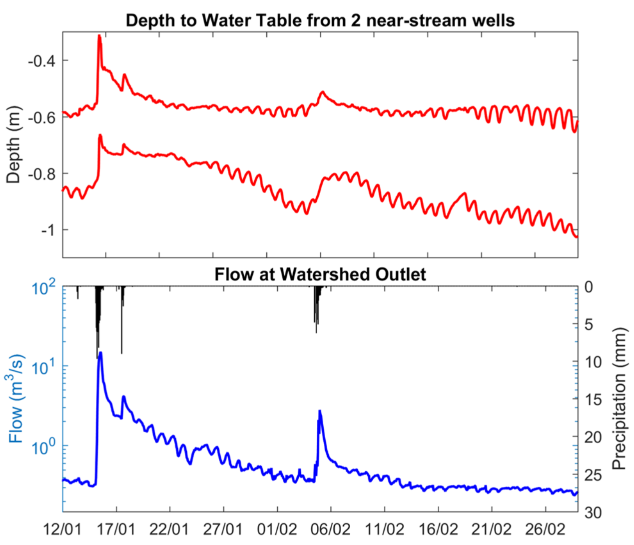

FIGURE 1 Diel cycles in streamflow and groundwater in the Waipara catchment, New Zealand. The magnitude and timing of the cycles provide signatures for evapotranspiration processes at the daily timescale

three hypotheses about how ET results in diel cycles. These are (a) the saturated wedge hypothesis: evaporation of hillslope soil moisture reduces the hydraulic gradient towards the stream and thus reduces flow (Burt, 1979); (b) the riparian interception hypothesis: riparian vegetation uses water coming from hillslopes that would otherwise reach the stream (Bren, 1997); (c) the flow path migration hypothesis: evaporation of near-surface soil water means that lateral flow only occurs in deeper, less permeable soil, so reducing flow velocities (Bond et al., 2002). Despite uncertainties in the detail of the process, signatures derived from the timing and shape of diel fluctuations provide useful information on ET and other processes that interact with channel flow.

3.2 | Snow storage, melt, and permafrost processes

Schaefli (2016) is one of few authors who develop signatures to evaluate hydrologic models ability to simulate snow processes and describes a signature for total annual snow storage in a catchment, by using a mass curve to calculate the winter precipitation excess over streamflow. See the same paper for additional seasonal-scale snowmelt signatures if temperature data are available to calculate slopes of the temperature discharge curve. Cortés, Vargas, and McPhee (2011) use the water year hydrograph centre of timing to study annual changes in the streamflow regime related to snowmelt timing and the dominance of snowmelt. On a daily timescale, Lundquist, Dettinger, and Cayan (2005) use the timing of diel fluctuation maxima as a signature for the time taken for afternoon snowmelt to propagate to the river.

Safeeq and Hunsaker (2016) use a variety of signatures to quantify hydrologic response in snow-affected watersheds, although not all their signatures directly target the snowpack. They use a high flow duration curve (FDC) slope to signify a catchment with a flashy hydrograph that suggests lack of storage, including snow storage and groundwater storage. Midsection (10th–50th percentile) FDC slope is also used by Kelleher, Wagener, and McGlynn (2015) to capture flow behaviour during the snowmelt/wetting-up period and summer drying period. For experimental watersheds with snowpack data, signatures can be based directly on the snow water equivalent time series (e.g., Kelleher et al., 2015, and in the SNOWMIP2 model intercomparison studies reported by Essery et al., 2009).

Streamflow characteristics related to permafrost processes are described by Woo (1986) and Woo, Kane, Carey, and Yang (2008), who review studies of basins with varying degrees of permafrost. The authors note the difficulty of calculating average flow patterns with short, sparse records in permafrost locations, where it is particularly hard to measure the high flows that occur during ice breakup. Instead, these signatures target event to seasonal timescales. Basins with a flashy streamflow regimes and high runoff yield, for example, runoff ratios of 0.7—0.8, correspond to those with a large percentage area of permafrost. These relationships are hypothesized to be due to low infiltration into groundwater in the permafrost regimes. Both indicators are confirmed by McNamara, Kane, and Hinzman (1998) in their study in Arctic Alaska, who credit the flashy response to "water tracks," that is, downslope pathways that remain saturated for most of the summer. High quickflow ratios that show large reductions during the melt season, (e.g., decreasing from 0.8 to 0.2; Yamazaki, Kubota, Ohata, Vuglinsky, & Mizuyama, 2006) are a further indicator of permafrost; McNamara et al. (1998) compared quickflow ratios of 0.33–0.37 in their study of permafrost basins with averages of 0.08–0.1 elsewhere in the United States. Very long characteristic recession times by area (approximately 10 times longer than the US average) provide a signature of the characteristic permafrost process of infiltration into a highly absorptive surface layer which then slowly releases the water (McNamara et al., 1998).

3.3 | Infiltration excess

To investigate infiltration excess overland flow, the event-scale relationship between rainfall intensity and streamflow is examined (Figure 2). Infiltration excess is indicated where flow is related to intensity but not to catchment storage. In general, if a threshold intensity is required before flow is produced, infiltration excess processes are occurring in the watershed (Ali et al., 2013). See McMillan et al. (2014) for a method to measure the occurrence, location, and strength of hydrologic thresholds. In the extreme case where high-intensity storms in summer do not produce flow, infiltration excess cannot be a significant mechanism (Wrede et al., 2015). To compare the influence of rainfall intensity with the influence of catchment storage, Estrany et al. (2010) regress peak flow magnitude and flow volume against a variety of predictors, including precipitation-based antecedent condition metrics, event rainfall volume, and rainfall intensity metrics. Positive coefficients for antecedent condition metrics and negative coefficients for intensity metrics showed that saturation excess was dominant in the watershed, with infiltration excess being less important.

3.4 | Saturation excess overland flow

For saturation excess overland flow, different signatures are used for permanently saturated versus transiently saturated areas. Signatures for saturation excess are typically event-timescale descriptors, including analyses of changes in dynamics between events. Watersheds with no (or very low, e.g., <3 mm) threshold of precipitation depth required before runoff is produced indicate saturation excess flow from permanently saturated areas, assumed to be in riparian zones (Tani, 1997). This interpretation is backed up by experimental evidence from water table dynamics (Tetzlaff et al., 2014), helping to distinguish between permanently saturated and impermeable areas.

The presence of a storage threshold in the watershed response (i.e., flow is only generated above a certain watershed storage) is a possible signature of saturation excess overland flow, although it may also be caused by subsurface flow processes (Ali et al., 2013; McGrath, Hinz, & Sivapalan, 2007). Experimentation with flexible model structures in addition to experimental knowledge attributes a short time-to-peak in runoff and a strong threshold in the storage-discharge relationship to saturation excess overland flow (Fenicia et al., 2014). The watershed storage can be approximated using several methods, some using only rainfall and streamflow (such as an antecedent precipitation index or storm rainfall total, optionally adjusted by streamflow as a proxy for storage) but others requiring additional data, such as antecedent soil moisture (Detty & McGuire, 2010; McMillan & Srinivasan, 2015).

To determine the rate at which saturated areas expand with additional rainfall, runoff is plotted against precipitation depth on a per-storm basis. The slope of the runoff increase above the threshold at which runoff begins shows the expansion of the saturated area (Tani, 1997). Some authors perform a hydrograph separation prior to this analysis, considering quickflow volume in place of total flow volume, then more simply use quickflow as a percentage of precipitation as an indicator of saturated area expansion (Becker & McDonnell, 1998). The minimum observed percentage quickflow indicates the impermeable or permanently saturated area contribution that is stable between events.

3.5 | Groundwater

Due to the large number of studies describing signatures related to groundwater, we have split this section by signature type.

3.5.1 | Double peaks in streamflow at the event scale

The presence of a significant groundwater flow mechanism is strongly linked to the saturation excess process, caused by groundwater rising to the land surface. This mechanism can cause a telling signature: a

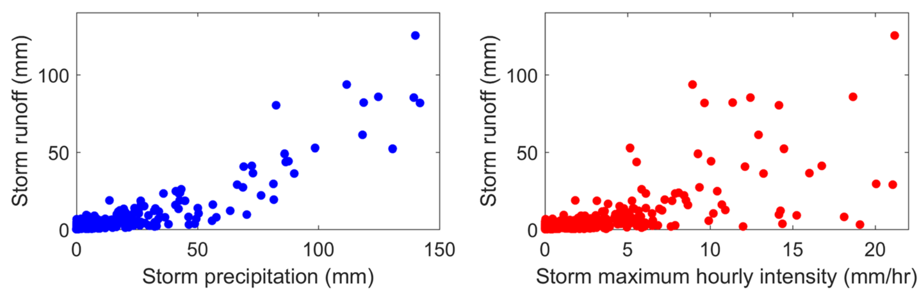

FIGURE 2 Threshold behaviour in the Mahurangi catchment, New Zealand. The left plot shows a strong threshold between storm precipitation and storm runoff, whereas the right plot shows a weak threshold between maximum rainfall intensity and storm runoff. This combination is a signature of saturation excess rather than infiltration excess runoff generation mechanisms

double peak in streamflow resulting from a single precipitation event, a feature noted in multiple watersheds with the second peak occurring hours to days after the first (Figure 3). The first peak is typically attributed to saturation excess and riparian processes, whereas the second, more prolonged peak is attributed to subsurface flow.

The subsurface flow mechanism causing the second peak may be either fast displacement of shallow groundwater, or subsurface storm flow as saturated areas within the hillslope becomes connected. To distinguish between the two, Graeff et al. (2009) propose analysing the best predictors of bimodality in a logistic regression, using various predictors, including metrics based on precipitation, antecedent precipitation index, and flow prior to the event. In their study, the best predictors were total precipitation and antecedent flow (a proxy for groundwater level), suggesting that displacement of groundwater that was already connected to the stream is the cause of the second peak. If subsurface storm flow had been occurring, then antecedent precipitation index would have been expected as a strong predictor. Further evidence was provided against the storm flow hypothesis due to the long duration of the second peak.

In experimental watersheds, authors have used additional knowledge to distinguish between the two potential processes, providing valuable knowledge that can be used in watersheds without such additional data. Martínez-Carreras et al. (2016) used storage measurements to show that a storage threshold must be met before the double peak occurs. Their measurements of storage showed that the maximum storage in the watershed occurs between the two peaks. Fenicia et al. (2014) found a double peak response that occurred only in winter and used knowledge of the watershed geology to attribute this to a fill-and-spill process (as described by Tromp-van Meerveld & McDonnell, 2006) that occurs when winter rains fill depression storage at the surface of the impermeable schist bedrock, creating subsurface flow. Overall, double peaks resulting from one event are an easily identified signature of groundwater response, but further data or analysis are needed to identify the process more exactly.

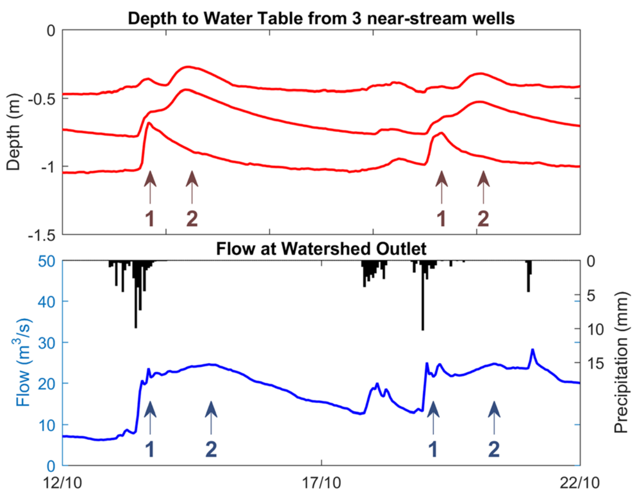

FIGURE 3 Double peaks in groundwater and flow shown in data from Waipara catchment, New Zealand. This signature indicates riparian runoff generation (Peak 1) followed by subsurface runoff generation (Peak 2). Discussed further in McMillan and Srinivasan (2015)

3.5.2 | Runoff ratio

Runoff ratio is the fraction of precipitation that becomes runoff and can be calculated at multiannual ("total runoff ratio"), seasonal, or event scales. Total runoff ratio is used as a signature of overall water loss to deep groundwater (i.e., water that bypasses the flow gauge; Hrachowitz et al., 2014). As total runoff ratio is also influenced by ET, it is especially useful to look at differences in water losses in neighbouring watersheds, where ET could be expected to be similar (McMillan et al., 2014). At a seasonal timescale, the ratio between summer and winter runoff ratios is found by Pfister et al. (2017) to be an indicator of bedrock permeability in an analysis of 16 small catchments of varying geologies, with lower ratios indicating higher bedrock permeability. At an event timescale, low event runoff ratios are widely used as an indicator of fast drainage and large storage. McMillan, Clark, Bowden, Duncan, and Woods (2011) used event runoff ratio as a signature of rapid vertical drainage of water to a groundwater reservoir with response time of weeks or longer, with low ratios indicating more drainage. Noguchi, Nik, Yusop, Tani, and Sammori (1997) state that a steep hydrograph recession limb and therefore a low event runoff ratio show that most rain water is retained in the soil. Blume et al. (2008) use the combination of low event runoff coefficients and high yearly runoff coefficients as an indicator of large storage capacity. Similarly, Estrany et al. (2010) state that a low event runoff ratio indicates a water table well below the surface, due to good drainage. Runoff ratios are therefore widely used as signatures of drainage to groundwater, and the longer the timescale, the deeper the groundwater store.

3.5.3 | Storage fraction

A signature for the permeability of bedrock was developed by Pfister et al. (2017). They used a very simple daily water balance model to calculate daily storage deficits in 16 small catchments of varying geologies. The model was used to evaluate active storage volume (maximum storage deficit in the series) and total storage volume (extrapolation to find storage deficit at near-zero flow). The signature used was the ratio of active to total storage. This ratio was low (minimum of 13%) for catchments with permeable bedrock and higher total storage and high (maximum of 100%) for catchments with impermeable bedrock and lower total storage, for example, geology of schists and/or marls.

3.5.4 | Streamflow recessions

Analysis of streamflow recessions can help determine the size of groundwater storage reservoirs in a watershed, the extent to which storage reservoirs can be differentiated and act independently, and the relationship of groundwater storage to river discharge. Recession analysis examines the relationship between flow and the derivative of flow, either by fitting a master recession curve or by fitting relationships to a recession analysis plot of dQ/dt against Q (Figure 4). In either case, the dQ/dt versus Q relationship can be integrated to provide a relationship between storage and discharge. Various techniques are used from event to multiannual timescales, such as fitting a master recession curve to overlaid recession segments from the flow series (Lamb & Beven, 1997) or integrating the master recession curve and fitting a trend line (Fenicia, Savenije, Matgen, & Pfister, 2006). To allow for the effect of recharge on the watershed storage volume, an iterative modelling approach can be used to fit recharge parameters and then remove the effect of recharge (Fenicia et al., 2006). When using the recession analysis plot approach, a relationship can be fitted to all points, data can be binned by flow interval and then fitted (Kirchner, 2009), or the fit can be made by season and then averaged (Westerberg & McMillan, 2015). Shaw and Riha (2012) suggest that seasonal variations in recession rate themselves provide a signature of the impact of ET on watershed storage. Storage–discharge relationships can alternatively be calculated using a water balance approach, that is, by calculating storage as cumulative precipitation minus runoff during seasons when vegetation is dormant and ET is at a minimum. The resulting relationship between storage and discharge can be used to calculate average watershed storage from the average baseflow (McNamara et al., 2011; Peters & Aulenbach, 2011).

Changes of slope in the recession analysis plot (or of the master recession curve in log space) indicate the presence of multiple distinguishable storage reservoirs in the watershed, which is particularly relevant when determining the most appropriate structure for the

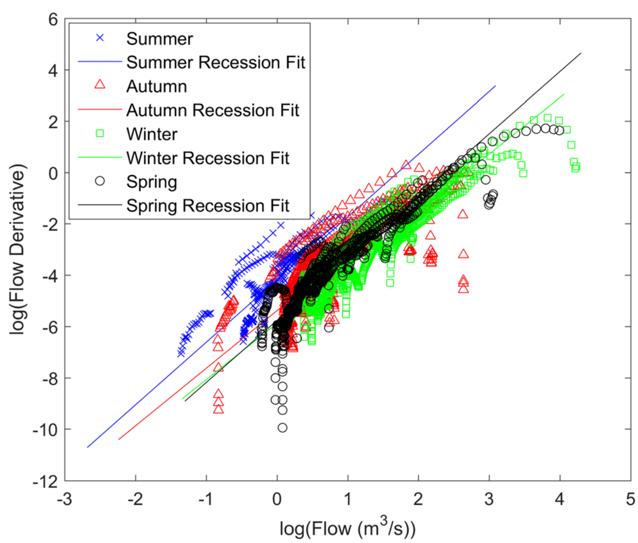

FIGURE 4 Analysis of streamflow recessions in the Mahurangi catchment, New Zealand. The plot shows the relationship of dQ/dt against Q for hourly data points and fitted with linear trend lines by season. The corresponding hydrologic signatures would be the parameters of the storage–discharge relationship in the catchment, estimated from the trend line equations

groundwater portion of a hydrologic model. Clark et al. (2009) demonstrated a case where three parallel linear reservoirs were required to fit the lower bound of a recession analysis plot. These reservoirs were related to the hillslope, ephemeral stream riparian zone and perennial stream aquifer, using field knowledge from the watershed. The first steep section of the master recession curve represents storage near the soil surface that is quickly depleted and the gradient of the mid-section of the curve to the water retention capacity of the watershed. Lower gradients are seen in watersheds with shallow topography, alongside soil texture and geological characteristics related to higher retention capacity (Estrany et al., 2010). In addition to changes in slope, nonuniqueness in the recession (and therefore storage–discharge) relationship implies the existence of multiple reservoirs (McMillan et al., 2011) and therefore a sensitivity of flow to the recharge history of the watershed (Harman, Sivapalan, & Kumar, 2009).

3.6 | Baseflow

3.6.1 | Visual inspection

Baseflow in a watershed is strongly related to groundwater, with Wrede et al. (2015) recommending that a visual inspection of the hydrograph should be used to establish the existence or importance of groundwater influence. In particular, stable baseflow throughout the winter and summer indicates a large groundwater storage reservoir.

3.6.2 | BFI

The long-term proportion of baseflow in a streamflow time series can be formalized using a BFI, such as the popular method of Gustard, Bullock, and Dixon (1992) shown in Figure 5. An alternative BFI is proposed by Yilmaz et al. (2008), as the volume of the flow duration curve low flow segment (>0.7 exceedance probability; taken after log transform to emphasize the lowest flows). Yilmaz et al. (2008) note that this BFI is impacted by baseflow interaction with riparian ET at low flows. BFI is an indicator of baseflow residence time (high BFI indicating high residence time), as demonstrated by Bulygina et al. (2009) who experimented with a semi-distributed model to show that constraining modelled BFI constrains the baseflow residence time parameter (as expected, baseflow proportion was also strongly constrained).

An increasingly popular method to classify the long-term baseflow proportion of streamflow is to use a digital low pass filter (Hrachowitz et al., 2014). The smoothness of the filter may be determined according to the baseflow recession constant estimated from a master recession curve (this curve is determined as a combination of overlaid recession segments from the observed flow series). The baseflow recession constant (k) itself is used as a metric of groundwater influence on stream flow by Safeeq, Grant, Lewis, and Tague (2013), whereby slower recessions (lower k) indicated subsurface properties

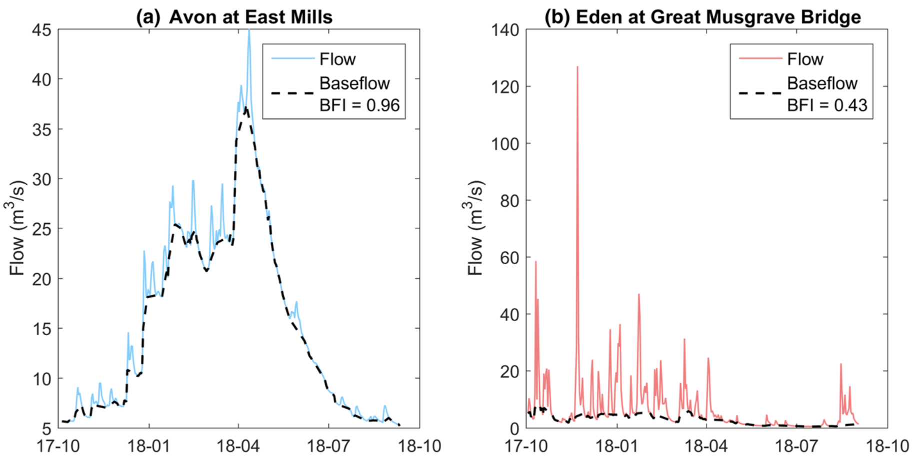

FIGURE 5 Hydrographs showing fitted baseflow and baseflow index (BFI) using the method of Gustard et al. (1992), for two UK watersheds with (a) high and (b) moderate BFI

that cause greater groundwater influence and longer subsurface flow paths. The usefulness of this metric was demonstrated by significant negative correlation between K and aquifer permeability across 58 watersheds in Oregon.

Estrany et al. (2010) further quantify baseflow influence using the "variability index," the standard deviation of the 10 to 90% percentiles at 10% intervals of the cumulative distribution function of log of flow. A low variability index is associated with more sustained flow and higher water storage, whereas a high variability index is associated with greater surface runoff and lower water storage. However, BFI methods are by far the most popular signatures to quantify the importance of baseflow processes.

3.7 | Connectivity

Connectivity has been proposed as a unifying theory that controls how watersheds produce runoff in response to rainfall (Ali et al., 2013). Hydrologic signatures can be used to determine the degree of connectivity in a watershed, that is, whether hillslopes become hydrologically connected to the stream during storm events, contributing to storm flow. Using multiyear data, a double mass curve (cumulative precipitation plotted against cumulative flow) that shows staircase behaviour indicates a highly seasonal watershed that dries out in summer with muted response to precipitation. This is a signature of lack of connectivity between hillslopes and channel, and the angle of the summer segments of the double mass curve provides a quantitative signature (Wrede et al., 2015). Where there is some quickflow in summer (which can be estimated using a digital filter to remove baseflow, see preceding section), this runoff is typically generated in the riparian zone as hillslopes are assumed to be disconnected (Hrachowitz et al., 2014).

In glacial environments where runoff is driven by meltwater and is less sensitive to precipitation variability, the year-to-year variability in flow magnitude and flow duration curve provide signatures for the magnitude and distribution of connection between meltwater sources and channels (Gooseff, Wlostowski, McKnight, & Jaros, 2017). Connectivity distribution can be quantified using a connectivity duration curve, the equivalent of the FDC (Jencso et al., 2009). The connectivity duration curve shows the frequency distribution of percentage connectivity between stream pixels and their contributing hillslopes. Jencso et al. (2009) show that the connectivity duration curve is strongly correlated to the FDC by using auxiliary groundwater data in Tenderfoot Creek Experimental Forest, Montana, providing further evidence that the FDC can be used as a signature of connectivity distribution.

Minimum event runoff ratios are used as signatures of connectivity occurrence at shorter timescales. Very low event runoff ratios (e.g., <4%) suggest runoff generation solely from the riparian zone and therefore no connectivity to hillslopes. Li, Sivapalan, and Tian (2012) showed that a sharp drop in event runoff ratios in spring is a signature of strong drying of the soil due to a large deficit in precipitation compared with potential ET; in their basin hypothesized to be due to cracking of clay soils. Detty and McGuire (2010) propose that event runoff ratios of >10% indicate hillslope connectivity, based on an estimate of the percentage of the watershed area classified as near-stream toe-slopes within 10 m of the channel. We would therefore recommend that the minimum runoff ratio deemed to indicate connectivity is adjusted according to river valley topography.

Spatial changes in hillslope connectivity are indicated by changes in overland flow response times, as response times increase when distant parts of the watershed begin to contribute to the stream (Li & Sivapalan, 2011). In densely-gauged watersheds, spatial variation in connectivity along the channel can be investigated using incremental stream gauging. Flow gains show that hillslopes and riparian zones are connected and contributing to the channel (Blume & Van Meerveld, 2015). But this technique is complicated by potential losses or gains to groundwater, and flow measurement errors, which can be substantial at low flows (McMillan, Krueger, & Freer, 2012). Such uncertainties mean that it is simpler to evaluate connectivity at the watershed scale using the mass curve and event runoff ratio signatures described above.

3.8 | Channel processes

Hydrologic signatures calculated from a flow series can give insight into the hydrologic processes occurring within the upstream channel.

At annual or long timescales, the last (lowest flow) change of slope in a recession plot of flow against its derivative shows when ephemeral streams have stopped flowing (Ghosh, Wang, & Zhu, 2016). A commonly used hydrologic signature, the rising limb density (defined as the inverse of the mean time to peak; usually calculated from a year or more of events), is correlated with the ratio of flow length to basin area (Shamir, Imam, Morin, Gupta, & Sorooshian, 2005). Small ratios imply an elongated channel such that channel processes dominate over hillslope processes; model experiments by the same authors showed that rising limb density was sensitive to routing and delay processes in the channel. Another common signature, the number of peaks over a threshold (with the threshold commonly defined as a multiple of the median flow) is related to channel roughness, with a decline in POT related to establishment of a mature forest that vegetates and blocks drainage channels (Archer & Newson, 2002). Where multiple flow gauges are available, the timing of peak flows can be examined. If peak times are coincident despite an increase of volume downstream, this implies that subsurface flow must travel downstream before intersecting the channel (McGlynn, McDonnel, & Brammer, 2002; Mosley, 1979). Therefore, hydrologic signatures can give insights into channel length, roughness, inflows, and overall importance of channel processes.

3.9 | Partitioning/percolation

Related to the watershed storage capacity is the partitioning of water between different stores and between fast and slow runoff pathways. Hydrologists use several metrics to quantify the flashiness of a watershed (a flashy watershed is one that produces steep hydrographs soon after rainfall, followed by a fast return to the pre-event state). Several authors use signatures of the speed of runoff response, such as the average lag time between the rainfall centroid (50% of event rainfall depth occurring) and runoff centroid, calculated on an event basis (Clark, McMillan, Collins, Kavetski, & Woods, 2011; McMillan et al., 2011). This metric is explained as describing partitioning between surface/near-surface flow and baseflow, notwithstanding pipeflow mechanisms that could lead to fast transmission of the flow peak through deeper pathways. Yilmaz et al. (2008) generalize this signature by using the time lag between rainfall and flow series that maximizes the cross-correlation. This method avoids the need to define events in the series but does require a flow threshold set by eye, whereby only flows above the threshold are considered. Morin, Georgakakos, Shamir, Garti, and Enzel (2002) define a more general "response timescale" based on the timescale of smoothing applied to the rainfall data that produce a filtered signal most similar to the flow data. Similarity was judged by comparing the inverse of the rising limb density of the two signals.

As an alternative to signatures based on timing, signatures based on volume are also used. McMillan et al. (2014) use the event runoff ratio (runoff as a proportion of rainfall, occurring within a set time period after rainfall) as a signature to quantify the split between fast and slow runoff processes. Yilmaz et al. (2008) use the steepness of the midsection slope of the FDC. A steep slope is related to small soil capacity and higher overland flow, whereas a flatter slope indicates more sustained groundwater response. Therefore, within a given precipitation regime, the slope is a signature of vertical redistribution in the watershed. Farmer, Sivapalan, and Jothityangkoon (2003) focus on the low-flow slope of the FDC (referred to as the persistence of the curve), finding that this signature provides a strong test for whether models provide an accurate representation of runoff from deep groundwater and the nonlinearity of this process. The volume of the high flow segment (<0.02 exceedance probability) of the FDC is used as a complementary signature of flashiness.

The interpretation of flashiness is strengthened, where it can be combined with process knowledge. For example, Blume et al. (2008) suggest that a fast streamflow response and fast recessions, together with a known likelihood of preferential flow in forests, provide strong evidence for macropore flow. An extension that provides a dynamic measure of partitioning is the elasticity of the watershed, that is, the fractional change in flow per fractional change in annual precipitation. Elasticity provides a signature of the strength of precipitation and wetting thresholds that cause nonlinearity in the runoff volume and can be applied separately to fast and slow runoff components (Harman, Troch, & Sivapalan, 2011).

3.10 | Human alteration

Human alterations leave their mark on the characteristics of flow series. For example, when applying the indicators of hydrologic alteration method, Richter et al. (1996) found that the dam-altered Roanoke River in North Carolina showed fewer extreme floods, more and shorter high and low flow pulses, later and lower annual low flows, flatter rising limbs, and reduced flow variability. Some of these impacts can be attributed to specific processes (e.g., dam requirements for flow pulses or rising limb slope reflecting the maximum output of the turbines). Knowledge of human alterations can guide signature choice. For example, unusually high runoff coefficients for agricultural areas in semi-arid climates (e.g., herbaceous crops in Mediterranean climates) may be indicative of tile drains (Estrany et al., 2010). Tile drains are also implicated by very high BFI values, for example, >90%, suggesting that subsurface, saturated processes dominate.

Baker, Richards, Loftus, and Kramer (2004) suggest that changes in flashiness index (defined as sum of absolute differences between consecutive daily flows) can be used to quantify the overall human impact on a watershed, from processes such as agricultural drainage and channelization of tributaries/ditches. This finding agrees with the work of Schwartz and Smith (2014), who used a variety of baseflow signatures to show that urbanization led to faster recession and less sustained baseflow. As with many of the signatures described in this review, there are several possible process explanations for flashiness, and expert knowledge is critical in determining the most appropriate explanation.

4 | REVIEW RESULTS: SUMMARY

In Table 1, we provide a summary table listing each signature, grouped by hydrologic process, and including the signature description, hydrologic process description, and literature reference.

5 | DISCUSSION

5.1 | Signature completeness

After completing the review, we are interested in whether the current library of signatures is sufficient to analyse the major processes in the hydrologic cycle, whether some processes are missing, and whether some processes have a more extensive range of signatures than others. Figure 6 shows a summary of the signatures from Table 1, splitting them according to process, timescale (event or seasonal/longer), and whether the signature quantifies the process or solely tests for its occurrence.

Figure 6 shows substantial variability in signature coverage. Some processes have few signatures available: surface processes (ET, snow, permafrost, infiltration, and saturation excess) have no signatures at the event timescale. Channel processes have signatures to test for occurrence but no quantification. The processes with the fewest signatures overall are snow storage, snowmelt, and human alteration. Further, there may be subsets of these processes (e.g., interception as a contributor to ET, vegetation dynamics) or processes from specific environments (e.g., wetlands or locations with extremes of rainfall or temperature) whose impact on streamflow and resulting signatures are missing or not well known in the hydrology literature. Efforts to bring this knowledge together would be valuable to the hydrology community. Processes that are well served with a range of signatures are groundwater storage, partitioning and connectivity, all related to the split between fast and slow processes. In general, there are many more signatures related to the seasonal scale than the event scale, often with several options to analyse each process.

We note that although process occurrence at a seasonal scale appears a low bar for a signature to meet, where a signature can be unambiguously linked to a process, then it would be sufficient in order to choose a suitable hydrologic model structure and therefore a valuable piece of knowledge. Where signatures do quantify the process, this is usually a metric that can be compared between watersheds to specify the process as less/more prevalent, rather than an absolute definition in volume units. Therefore, we find that there is a need for a "climatology" of signature values so that a user can determine whether the value of a signature in a new watershed is high or low.

5.2 | Types of signature

The review described in this paper classifies signatures by the hydrologic process that they can identify. Classifying signatures is useful because it lays the groundwork for a framework in which users can choose from a catalogue of signatures according to the needs of their application. For example, a user might view all signatures of a particular class before choosing the most appropriate one or might choose a number of relevant classes and request a recommended signature from each class.

It is useful to consider alternative classifications, such as the type of calculation embodied by the signature. Facets of this "signature type" might include the timescale of the signature (daily, event-based, or seasonal), data requirements (hourly/daily data, flow/rainfall/auxiliary data, pre-processing), the method of calculation (graphical or numerical), and the datatype returned (binary, categorical, or numeric). A "signature type" classification would be useful for multiple reasons. Signatures of the same type might have similar applications and similar uncertainty properties. They might require the same preliminary work, for example, event separation for event

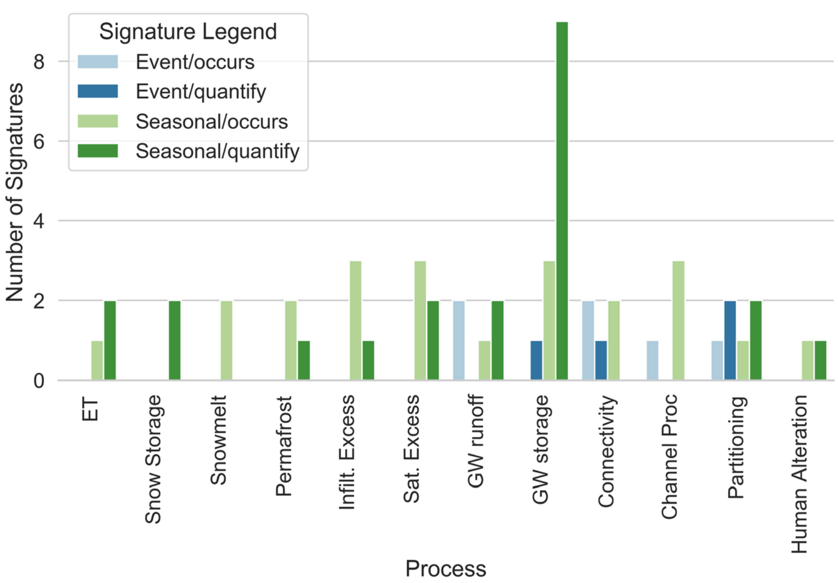

FIGURE 6 Numbers of signatures available to characterize each process, split by timescale (event or seasonal), and whether the signature quantifies the process or tests for its occurrence

TABLE 1 Summary of signatures and corresponding processes, with literature references

Process	Signature	Process description	Reference
Evapotranspiration	Total runoff ratio	Volume of water that bypasses flow gauge	McMillan et al. (2014); Safeeq and Hunsaker (2016)
	Streamflow seasonality	Variability in ET	Wrede et al. (2015)
	Diel cycles in streamflow	Morning maxima signify ET (often riparian), competing hypotheses for seasonal changes in magnitude	Schwab et al. (2016); Wondzell et al. (2010); Graham et al. (2013)
Snow storage, melt and permafrost processes	Winter precipitation excess over streamflow using mass curve	Total snow storage	Schaefli (2016)
	Water year hydrograph centre.	Snowmelt timing and the dominance of snowmelt	Cortés et al. (2011)
	Timing of diel cycle maxima	Travel time of snowmelt to river	Lundquist et al. (2005)
	FDC slope	Storage, including snow	Safeeq and Hunsaker (2016)
	Flashiness and high total and quickflow runoff ratios	High percentage area of permafrost with low infiltration into groundwater and continuously saturated surface water tracks.	Woo (1986); McNamara et al. (1998)
	High quickflow ratios with large reductions (e.g., 0.8 to 0.2) during the melt season	Indicator of permafrost with summer melt	Yamazaki et al. (2006)
	Very long characteristic recession times by area	Permafrost process of infiltration into a highly absorptive surface layer, then slow release.	McNamara et al. (1998)
Infiltration excess	Intensity threshold before flow is produced	Infiltration excess occurs	Ali et al. (2013)
	High-intensity summer storms don't produce flow	Infiltration excess doesn't occur	Wrede et al. (2015)
	Peak magnitude/volume regression against intensity metrics	Positive coefficients show infiltration excess occurs	Estrany et al. (2010)
Saturation excess	Peak magnitude/volume regression against antecedent condition metrics	Positive coefficients show saturation excess occurs	Estrany et al. (2010)
	No rainfall depth threshold before flow is produced	Saturation excess flow from riparian zones	Tani (1997)
	Storage threshold before flow is produced	Saturation excess occurs	Ali et al. (2013) McGrath et al. (2007)
	Slope of event-based precipitation against runoff, above threshold	Rate at which saturated areas expand with additional rainfall	Tani (1997)
	Quickflow as a percentage of precipitation	Minimum observed = impermeable area contribution, slope relates to saturated area expansion	Becker and McDonnell (1998)
Groundwater	Double peaks in streamflow	Dual saturation excess/sub-surface flow mechanism	Graeff et al. (2009); Martínez-Carreras et al. (2016)
	Logistic regression to predict bimodality	Predictors of total precipitation and antecedent flow indicate displacement of groundwater. Predictors of antecedent precipitation index indicate subsurface storm flow.	Graeff et al. (2009)
	Long duration of second peak	Runoff from groundwater displacement mechanism.	Graeff et al. (2009)
	Double peak only occurs in winter	Fill-and-spill process	Fenicia et al. (2014)

(Continues)

TABLE 1 (Continued)

Process	Signature	Process description	Reference
	Total runoff ratio, especially differences in neighbouring watersheds with similar ET	Overall water loss to deep groundwater	Hrachowitz et al. (2014); McMillan et al. (2014)
	Ratio between summer and winter runoff ratios	Low ratios show high bedrock permeability	Pfister et al. (2017)
	Event runoff ratio	Low ratios show rapid vertical drainage of water to groundwater	McMillan et al. (2011) Noguchi et al. (1997)
	Ratio of active storage volume (maximum storage deficit) to total storage volume (extrapolated storage deficit at near-zero flow)	Low ratios show permeable bedrock and high total storage; and vice versa	Pfister et al. (2017)
Storage (especially groundwater)	Seasonal variations in recession rate	Impact of evapotranspiration on watershed storage	Shaw and Riha (2012)
	Relationship between storage and discharge from water balance approach	Average watershed storage calculated from average baseflow	McNamara et al. (2011); Peters and Aulenbach (2011)
	Recession relationship (Q vs. dQ/dt)	Storage-discharge equation	
	Changes of slope in a recession analysis plot	Presence of multiple linear reservoirs e.g., hillslope, riparian zone and perennial aquifer	Clark et al. (2009)
	First, steep section of the master recession curve	Storage near the soil surface that is quickly depleted	Estrany et al. (2010)
	Gradient of the mid-section of the master recession curve	Water retention capacity of the watershed	Estrany et al. (2010)
	Non-uniqueness in the recession relationship	Presence of multiple storage reservoirs and sensitivity of flow to the recharge history of the watershed	McMillan et al. (2011); Harman et al. (2009)
	Low event runoff coefficients and high yearly runoff coefficients	Large storage capacity	Blume et al. (2008)
	Variability index of flow	Low variability index shows higher water storage	Estrany et al. (2010)
Baseflow	Visual inspection of hydrograph for stable base flow	Importance of groundwater influence	Wrede et al. (2015)
	Baseflow index (various methods)	Baseflow proportion and baseflow residence time	Yilmaz et al. (2008) Bulygina et al. (2009) Hrachowitz et al. (2014)
	Baseflow recession constant	Slower recessions show greater groundwater influence and longer subsurface flow paths	Safeeq et al. (2013)
Connectivity	Angle of summer segments of precipitation-flow double mass curve	Lack of connectivity between hillslopes and channel in summer	Wrede et al. (2015)
	Sharp drop in event runoff coefficients in spring	Drying of soil; loss of connectivity	Li et al. (2012)
	Very low event runoff ratios (<10%)	No hillslope connectivity; runoff generation solely from the riparian zone	Detty and McGuire (2010)
	Increase in overland flow response times	Increase in connectivity of hillslopes far from the steam	Li and Sivapalan (2011)
	Flow gains along channel	Connectivity of surrounding hillslopes	Blume and Van Meerveld (2015)

(Continues)

TABLE 1 (Continued)

Process	Signature	Process description	Reference
Channel processes	Last (lowest flow) change of slope in a recession plot of flow against its derivative	Point at which ephemeral streams stop flowing	Ghosh et al. (2016)
	Rising limb density	High RLD shows routing and delay processes dominate over hillslope processes	Shamir et al. (2005)
	Number of flow peaks over a threshold	Declines with channel roughness e.g. in mature forest	Archer and Newson (2002)
	Coincident timing of downstream flow peaks	Downstream travel of subsurface flow	McGlynn et al. (2002); Mosley (1979)
Partitioning/Percolation	Time lag between rainfall and flow series (from rain/flow centroids or by cross-correlation)	Partitioning between surface/near-surface flow and base flow	Clark, McMillan, et al. (2011); McMillan et al. (2011) Yilmaz et al. (2008)
	Event runoff ratio	Partitioning between fast and slow runoff processes	McMillan et al. (2014)
	Mid-section slope of the Flow Duration Curve and volume of high flow segment	Flashiness/vertical redistribution: a steep slope shows small soil capacity and higher overland flow	Yilmaz et al. (2008)
	Low-section slope of the Flow Duration Curve	Flow and flow nonlinearity of deep groundwater reservoir	Farmer et al. (2003)
	Timescale of smoothing applied to rainfall data that best mimics runoff data	Integration time of the watershed (strength of attenuation)	Morin et al. (2002)
	Fast streamflow response and fast recessions in forested landscape	Macropore flow	Blume et al. (2008)
Human alterations	Changes in flashiness index	Overall human impact on a watershed	Baker et al. (2004)
	Unusually high runoff coefficients and/or very high baseflow index for agricultural areas	Presence of tile drains	Estrany et al. (2010)

Note. Some signatures may relate to multiple processes.
Abbreviations: ET, evapotranspiration; FDC, flow duration curve; RLD, root length density.

behaviour signatures, or the same methodological decisions, for example, how to calculate the strength of a threshold and other decisions on how to generalize/automate the signature for multiple watersheds. The classification would also draw attention to the range of signature types available beyond the most commonly used. Based on our review, we therefore propose the following signature typology.

Type 1: Time series visuals. Type 1 signatures are qualitative, visual interpretations of time series data (usually streamflow). Examples include double peaks, diel cycles, and assessments of baseflow stability. They are easy to apply although potentially difficult to automate.

Type 1, time series visuals, acknowledges that the signatures proposed in several papers are descriptive rather than quantitative, such as the existence of a double peak in runoff response (Graeff et al., 2009). Although it would be possible to craft a quantitative test for the double peak, the authors did not choose to do so. Such descriptive signatures are similar to the concept of "soft data" (Seibert & McDonnell, 2002), where qualitative process knowledge is used to constrain model parameters. Winsemius, Schaefli, Montanari, and Savenije (2009) make a related definition of soft information from hydrologic signatures that cannot be directly used to constrain model parameters and/or has unknown uncertainty. [Correction added on 6 March 2020 after first online publication: this paragraph was mistakenly included under subsection heading 'Type 5' and has been corrected in this version by moving it to the end of subsection heading Type 1.]

Type 2: Quantified event dynamics. Type 2 signatures are quantitative descriptors of event-timescale dynamics, and how these dynamics differ between events. They may involve plotting a graph, where each event is one point, and fitting a relationship. Examples include event-based flow thresholds, recession shapes, and runoff or quickflow ratios by event. They are often difficult to apply and require preprocessing of the data to extract event statistics. They typically relate to overland flow, thresholds, storage–discharge processes, and connectivity changes.

Type 3: Quantified seasonal dynamics. Type 3 signatures are quantitative descriptors of time series dynamics, averaged overtime. Examples include some of the most well-known signatures, including peaks over threshold, rising limb density, flashiness, BFI, and master recession curve. They require moderate effort to apply. They typically relate to partitioning between different flow pathways, such as baseflow importance and residence time, ephemeral stream contributions, channel processes, partitioning between fast/slow processes, and human impacts on flow pathways.

Type 4: Seasonal statistics. Type 4 signatures are statistical properties of the flow distribution, calculated at seasonal or longer scales. Examples include runoff ratio, properties of the double mass curve, slope of the flow duration curve, and variability indices. They require moderate effort to apply. They typically relate to storage volumes (snow, groundwater, and bedrock permeability), flashiness, and vertical redistribution, including natural and artificial factors (macropores and tile drains).

Type 5: Mini-model. Type 5 signatures are quantities derived from simplified statistical or time-stepping models and as such are more difficult and time-consuming to apply than other types of signatures. Examples include regression predictors tested for strong performance, or simple water balance models used to predict storage volumes or storage–discharge relationships. They may require preliminary work, such as calculation of the statistical predictors. These signatures help to capture dynamics of watershed stores and fluxes that cannot easily be inferred, such as subsurface flow, storage, and ET.

We note that the five types suggested are broad categories, and subtypes might be useful for further classification. Signatures may also reoccur in different contexts, such as thresholds that occur at process level, watershed level, and due to human-caused disturbances overtime (Zehe & Sivapalan, 2009).

5.3 | Signature quality and uncertainty

As demonstrated in this review, there are often multiple choices for signatures that represent a selected process. Once a signature has been selected, there may be additional methodological choices that must be made (e.g., time lag after a peak excluded before recession characteristics are calculated or definition of a storm event). To assist in choosing between signatures, several authors have proposed requirements for signature behaviour. Shamir et al. (2005) lay out two requirements of signatures that they should be "consistent" for any specific basin, that is, have low variability when calculated over different time periods (the flow regime being implicitly assumed stationary), and be "distinguishable," that is, sensitive enough that basins with different responses have different signature values. A requirement for "discriminatory power" is added by Schaefli (2016), specifying that signatures should be useful in constraining model parameters when models are evaluated according to their ability to reproduce the measured signatures. Heudorfer et al. (2019) use a different definition of discriminatory power for groundwater signatures, which groundwater time series with large differences in signature values should be visually different. Recently, McMillan, Westerberg, and Branger (2016) defined five guidelines for selecting signatures: Identifiability (small uncertainty), robustness (insensitive to nonrelevant considerations, such as sensor brand), consistency (applicable in a wide range of catchments), representativeness (applicable across multiple scales), and discriminatory power (sensitive to process differences).

The first of these guidelines, identifiability, states that signatures with small uncertainties are more powerful when used in applications that require us to evaluate differences in signature values. These could be differences in time or space when identifying signature patterns or in signature regionalization (e.g., Westerberg et al., 2016) or differences between modelled and observed signature values. Although an analysis of the uncertainty of each signature (and of adherence to the other guidelines) is outside the scope of this review, we note that the signature type identified above will help to identify the relevant types of uncertainty for each signature. For example, Type 5 "mini-model" signatures will include uncertainties in the case that the chosen model is not equally appropriate everywhere. The ability to estimate signature uncertainty magnitudes and distributions will be essential as signature-domain evaluation and calibration of hydrological models (e.g., Fenicia, Kavetski, Reichert, & Albert, 2018) becomes more common.

6 | CONCLUSION

Linking hydrologic signatures to their underlying processes has substantial benefits for using signatures to choose hydrologic model structures and to map and understand the causes of spatial variability of processes across the landscape. However, much of our knowledge of the signature-process link has been scattered across the literature of studies from experimental watersheds. This review brings that knowledge together, searching out and cataloguing more than 50 signatures according to the processes they can identify.

We found substantial variability in the number and type of signatures available for each process. Few signatures were available for snow storage, snowmelt, and human alteration, and surface processes (ET, snow, permafrost, infiltration, and saturation excess) had no signatures at the event timescale. Many signatures were available for groundwater storage, partitioning and connectivity, all related to the split between fast and slow processes. Overall, more signatures were related to the seasonal scale than the event scale.

Our review showed that one signature was often related to multiple processes, making it more difficult to use signature values to characterize watershed processes. Strategies, such as testing narrower hypotheses about watershed function, adding expert knowledge of watershed characteristics, signature clustering, and examining signature changes, can all help to alleviate this issue. As increasing data availability motivates large-sample studies of watershed dynamics, such strategies will be important to improve automated signature applications in the face of multiple possible process interpretations. Such large-sample studies will further improve our knowledge of the link between signatures and processes, by helping to confirm where and when signature knowledge gained from experimental catchments can be upscaled to regional or national scales.

DATA AVAILABILITY STATEMENT

Data for Figures 1 and 3 are provided by the National Institute for Water and Atmospheric Research, New Zealand, Waterscape programme. Data for Figure 5 are provided by the UK National River Flow Archive, https://nrfa.ceh.ac.uk, NERC CEH, Wallingford.

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