Fundam. Appl. Limnol. 193/1 (2019), 21–38

Visualising and quantifying the variability of hydrological state in intermittent rivers

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With 7 figures and 3 tables

Abstract: The hydrology of intermittent rivers has been characterised using either flow regimes, with limited spatial resolution, or network contraction, with limited temporal resolution. Exploration of the dynamic behaviour of these rivers, on which highly diverse biological communities depend, requires longitudinal, year-round observations with a more detailed classification of hydrological state than can be provided by gauging stations or wet/dry mapping alone. Observations of dry, ponded, moderate flow and high flow hydrological states spanning 20 years with approximately monthly frequency along ten chalk rivers in the south-east of England were visualised. There was slower transitioning between hydrological states and less spatial fragmentation on rivers with groundwater-dominated regimes than on those more influenced by superficial deposits. Seasonal patterns in both the composition and configuration of states were demonstrated using adapted landscape metrics. Responses to hydrological extremes and anthropogenic influences included drying downstream of the source and an artificially near-perennial reach. A framework is proposed for the categorisation of metrics of hydrological state and demonstrates that the classification and dimensional limitations of traditional approaches cannot fully characterise the hydrological behaviour of intermittent rivers. Such characterisation is an important step towards the tailored assessments required for effective management of these dynamic systems.

Keywords: ephemeral streams; temporary streams; ponding; pools; aquatic state; network contraction

Introduction

Intermittent rivers and ephemeral streams (IRES) are ecologically diverse (Stubbington et al. 2017), but are at risk of deterioration as climate change and local anthropogenic activity, such as impoundment, abstraction, effluents and augmented flow are changing the natural variability in their hydrological behaviour and the ecosystem services they provide (De Girolamo et al. 2015; Datry et al. 2017; De Girolamo et al. 2017b). Despite the ecological importance of IRES, and the primary role of drying as a hydrological determinant of biodiversity (Leigh & Datry 2016), the study of headwater hydrology has been overlooked historically (Bishop et al. 2008), and IRES are under-represented in monitoring networks (Beaufort et al. 2018), digital resources and maps (Brooks & Colburn 2011), and protective legislation (Acuña et al. 2014; Fritz et al. 2017; Marshall et al. 2018). Hydrological data for the study of IRES need to be of a resolution and type that capture the variability in time and space in an ecologically relevant way. Analysis techniques need to offer visualisation and quantification of these dynamics for effective assessments of the impact of hydrological extremes and artificial influences.

Existing data and techniques applied to the hydrological study of IRES focus on changes in time or space, capturing high or medium resolution dynamics

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DOI: 10.1127/fal/2019/1149 E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, www.schweizerbart.de

in one of these dimensions, but rarely both. Traditional approaches to characterising hydrological regimes using gauged or estimated flow data (Richter et al. 1996; Poff et al. 1997) have been adapted to derive IRES flow duration curves (Croker et al. 2003; Fleig et al. 2005; Pumo et al. 2014; Gallart et al. 2016). Metrics have been identified for the characterisation of flow intermittence (D'Ambrosio et al. 2017), such as flow permanence (Smith et al. 2003; Schmidt et al. 2009; Yu et al. 2018), and the duration, frequency and timing of drying (Costigan et al. 2017). Such approaches capture the temporal dynamics of hydrological regimes at daily or monthly resolutions but are limited in spatial resolution to individual sites representing whole catchments. Other studies have considered the spatial dynamics of IRES, collecting longitudinal observations at multiple locations along the river, but on a limited number of occasions and often only during the driest season (Turner & Richter 2011; González-Ferreras & Barquín 2017). To robustly assess the hydrological dynamics of these river systems in both time and space, year-round observations at multiple locations along the river are required (White et al. 2018; Wilding et al. 2018), and over a sufficient duration to capture both hydrological extremes.

For a characterisation of IRES that facilitates hydroecological research, data and techniques should include multiple hydrological states that indicate the presence or absence of ponding as well as flow (Gallart et al. 2012; Stubbington et al. 2017). Since gauging stations are designed to measure flow, most return a flow rate or a recording of zero flow which encompasses both ponded and dry states. Studies of spatial dynamics such as network contraction have been concerned with the presence or absence of flow or water (Godsey & Kirchner 2014; Goulsbra et al. 2014; Jensen et al. 2017). Data collection by citizen science (Turner & Richter 2011; Allen et al. 2019) or telemetry (Goulsbra et al. 2014, Jensen et al. 2019) and modelling approaches (Larned et al. 2011; De Girolamo et al. 2017a; Beaufort et al. 2019) have considered wet/dry or flow/no flow dynamics. Yet the ponding that occurs as IRES transition between aquatic and terrestrial habitats is an ecologically significant state, making a vital contribution to their high biodiversity (Stubbington et al. 2017; Hill & Milner 2018). Furthermore, depending on the monitoring approach, ponding conditions may be included in either the wetter (Jensen et al. 2017) or drier condition (Beaufort et al. 2018). Recent initiatives in monitoring and analysis are addressing the need for multiple state data and techniques. Citizen science has been used to collate data with good temporal (Gallart et al. 2016) or spatial resolution (Datry et al. 2016), with associated IRES-specific innovations in the visualisation (Gallart et al. 2012) and quantification of multiple state data. A major impediment to such research thus far has been the lack of available year-round, longitudinal, multiple state data.

In the south of England, a monitoring programme on the intermittent headwaters of ten chalk rivers has delivered a longitudinal dataset of multiple hydrological states with approximately monthly resolution spanning 20 years. Using this rare dataset, this study aimed to demonstrate the data and suitable techniques required for capturing the variability in hydrological state within intermittent rivers, both along the channel and through time. The first objective was to visualise the patterns in hydrological state observed in the study rivers, and the second to quantify those patterns using suitable metrics. Utility of the data and techniques is highlighted in the assessment of drought, groundwater flooding, artificial influences and hydroecological impacts.

Material and methods

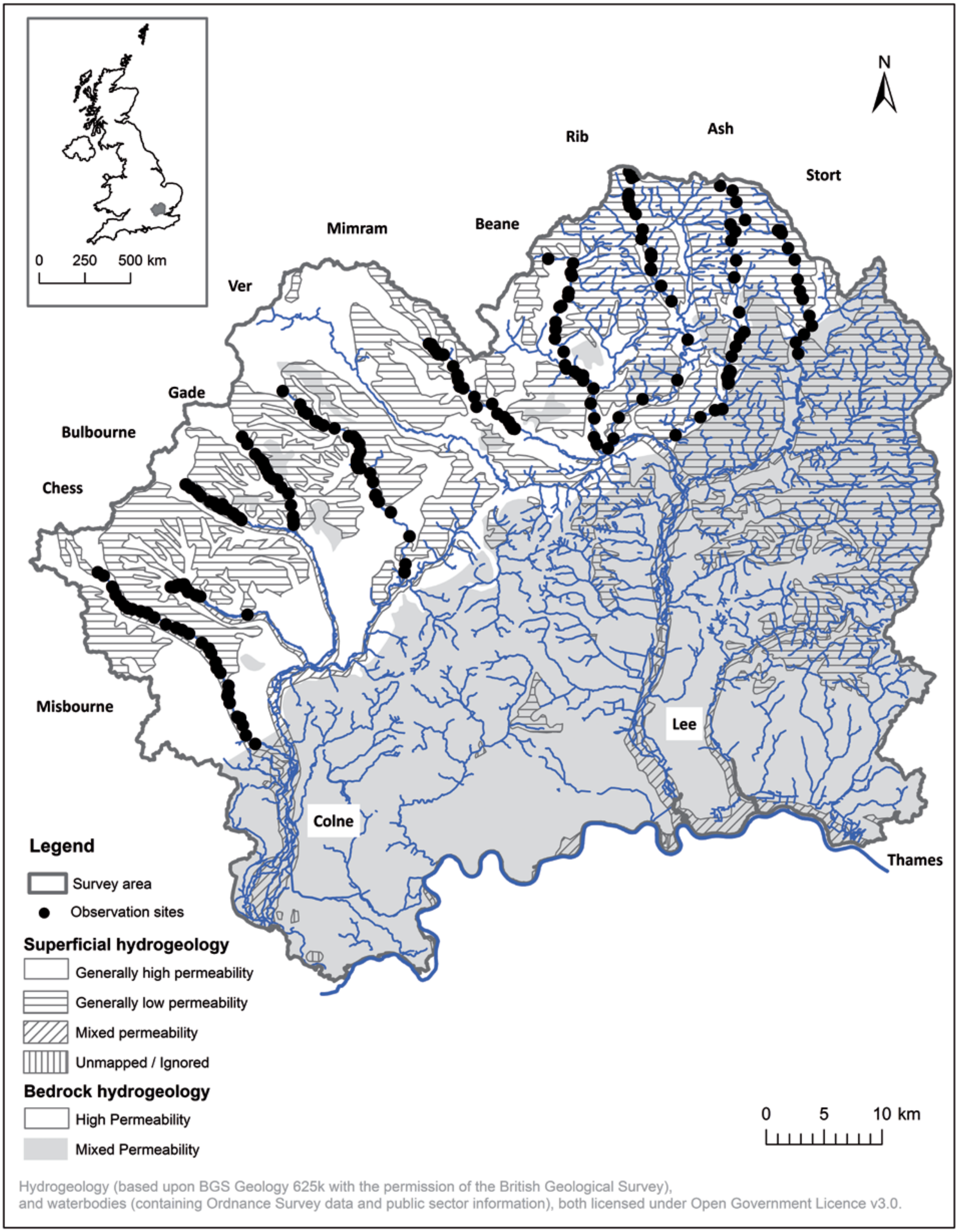
Study area

The study area is located in the headwaters of the Thames catchment in the UK and comprises ten rivers (Fig. 1), five within the Colne sub-catchment (the Misbourne, Chess, Bulbourne, Gade and Ver), and five within the Lee sub-catchment (the Mimram, Beane, Rib, Ash and Stort). The intermittent upper reaches of the Colne tributaries flow in a south-easterly direction, fed by groundwater from the chalk of the Chiltern Hills. In the Lee catchment, the area of exposed chalk decreases from west to east as it becomes overlain by clay and glacial drift, resulting in higher drainage densities and lower base flow indices (Gustard et al. 1992; National River Flow Archive 2018) in the Rib, Ash and Stort than in the Misbourne, Gade or Ver. Standardised average annual rainfall across the surveyed rivers is 675 mm (1961–1990, National River Flow Archive 2018).

Monitoring protocol

River surveys observing hydrological state were conducted by regulation authority hydrologists and spanned 20 years, from 1997 to 2017 with a review and standardisation of approach in 2004. The frequency of surveys was approximately monthly, lower during 2001–2004 and higher during periods of hydrological extremes, in particular, the droughts of 1995–1997 and 2004–2006.

The spatial extent of the surveys, hereafter referred to as survey length, extended from the farthest upstream observation of flowing or ponded water into the perennial reaches downstream. Survey length as a percentage of river length, measured from the same upper limit to the confluence, ranged from 38 % to 99 % with 18–32 sites on each river depending on survey length, hydrological behaviour and access (Table 1).



Hydrogeology (based upon BGS Geology 625k with the permission of the British Geological Survey), and waterbodies (containing Ordnance Survey data and public sector information), both licensed under Open Government Licence v3.0.

Fig. 1. Survey area showing hydrological state observation sites on surveyed rivers; five within the Colne catchment (Misbourne, Chess, Bulbourne, Gade and Ver), and five within the Lee catchment (Mimram, Beane, Rib, Ash and Stort). Broad hydrogeological classifications of bedrock and superficial deposits are also illustrated.

Table 1. Number of observation sites, survey length and base flow index (Gustard et al. 1992; National River Flow Archive 2018) on surveyed rivers.

	Misbourne	Chess	Bulbourne	Gade	Ver	Mimram	Beane	Rib	Ash	Stort
Number of sites	31	19	22	18	32	22	24	23	21	20
Survey length (km)	24.0	8.1	10.7	9.7	24.9	15.0	24.6	34.4	24.5	22.5
Survey length as % of total river length	86	49	71	38	94	67	97	99	91	49
Base flow index (BFI)	0.90	0.95	0.88*	0.88	0.88	0.93	0.75	0.58	0.55	0.48

* The BFI for the Bulbourne is derived from a non-NRFA Environment Agency gauging station on the Gade, (Environment Agency unpublished data).

Table 2. Composition metrics quantifying the amount of each hydrological state present along the survey length of a river, and configuration metrics quantifying their arrangement.

Metric	Definition	Example
Composition		
Proportion, P, of hydrological state	Proportion of survey length (L) in each hydrological state (i) $P(i) = \frac{L(i)}{\sum_1^4 L(i)}$	If 10 km of the survey length of 20 km has moderate flow, 2 km ponding and 8 km is dry, the proportion of each hydrological state is 0.5, 0.1 and 0.4, respectively.
Evenness (Turner 1989)	Standardised measure of diversity of hydrological states present (n) $\frac{-\sum_1^n P(i) \times \ln P(i)}{\ln n}$	If equal to one, the proportions of each hydrological state present on the survey length are equal. If close to zero, one of the hydrological states is dominant.
Configuration		
Mean patch length (km)	Mean length of all patches	If there are two flowing patches of 6 km and 2 km, and one ponded patch of 1 km, the mean patch length is 3 km.
Fragmentation (Hargis et al. 1998)	Number of changes in state (edges) as a proportion of the number of reaches	If equal to one, there is a change of hydrological state at every reach boundary going downstream. If zero, there are no changes of state.
Lotic connectivity (Ward et al. 2002)	Length of flowing reach (moderate or high flow) connected to the most downstream site as a proportion of study length	If the survey length comprises 5 reaches of 1 km, the top two dry and the other three flowing, the lotic connectivity is 0.6.

At each site on each visit, the hydrological state was observed and photographed. The dataset was rationalised into four ecologically relevant flow states (Gallart et al. 2012): dry, ponded, moderate flow and high flow (bankfull or out of bank). Each river was represented as a series of reaches with boundaries equidistant between observation sites, such that each survey length comprised 17–31 reaches of length ranging from < 100 m to 5.5 km and averaging 0.9 km across all ten rivers.

Visualising and quantifying patterns in hydrological state

Simple heat maps visualised the hydrological state along the river on each observation date by assigning the state observed at each site to the reach that it represented. The frequency and consistency of observations were revealed, and periods of missing data indicated. Monthly modal hydrological state was used to visualise the typical behaviour observed at each reach-month combination, and the monthly minimum (driest) and maximum (wettest) states indicated the extremes. For bimodal results (two equal modes), the wetter state was used, offsetting the bias introduced by the generally increased frequency of monitoring during drought conditions.

Metrics from the field of landscape ecology were applied to the riverscape (Turner 1989; Erős & Campbell Grant 2015; Datry et al. 2016) to quantify each river's behaviour by describing habitat dominance, and the size and arrangement of habitat patches, where a patch is a run of spatially contiguous reaches observed to be in the same hydrological state. The implicit assumptions in applying this methodology to intermittent rivers are that hydrological states represent broad habitat types as they transition between terrestrial and aquatic conditions (Stubbington et al. 2017), and that metrics defined for a two dimensional area may be adapted to describe a one dimensional length of river.

Composition metrics were selected to quantify the proportion of the four hydrological states (dry, ponded, moderate flow and high flow) present on each survey date, and their evenness (Table 2). The latter is a metric representing the diversity of hydrological states present (Turner 1989) and was derived from their proportions – a standardised equivalent of the Shannon diversity used by Datry et al. (2016).

Similar summary metrics for the configuration of hydrological states along the survey length at a given time quantified firstly, the mean length of patches, and secondly, the degree of fragmentation (Table 2). Following landscape ecology terminology, a difference in hydrological state between neighbouring reaches was termed an edge (Turner 1989); fragmentation was here defined as standardised edge density, a unitless metric for quantifiable comparison of rivers. A third configuration metric, lotic connectivity described the arrangement of flowing patches, and the portion of survey length in continuity with the downstream limit. These configuration metrics allowed comparison of the longitudinal arrangement of hydrological states along the rivers and between water years (starting 1st October).

For the analysis of temporal dynamics, a seasonal dataset was prepared for two of the study rivers, one that is groundwater-dominated (Gade) in the Colne sub-catchment, the other more influenced by superficial deposits (Ash) in the Lee sub-catchment. Observations were extracted at three-month intervals for spring (March), summer (June), autumn (September) and winter (December).

Results

Visualising patterns in hydrological state

Period of record

The hydrological state observed on each survey date at each reach was visualised for the Gade and the Ash (Fig. 2). On the Gade, intermittent behaviour was common in the upper reaches, with perennial flow predominating in the lower reaches of the survey length (Fig. 2a). The extent of flowing states was lowest during the drought responses of 1997–1998 and 2005–2006 (shown in greater resolution due to enhanced survey frequency) and highest during the winters of 2000–2001 and 2013–2014, when groundwater levels were high (Fig. 2a). A horizontal slice of the heat map provided information on the duration of, and transition between, hydrological states for a given reach. Transitioning was slow, with many reaches remaining dry or moderately flowing for two or more years. Vertical slicing of the heat map revealed that spatial variability was similarly low, with reaches of the same hydrological state rarely separated. The ponding and drying conditions in 1997 and 2006, in the otherwise perennial lower reaches of the survey length were a notable exception (Fig. 2a).

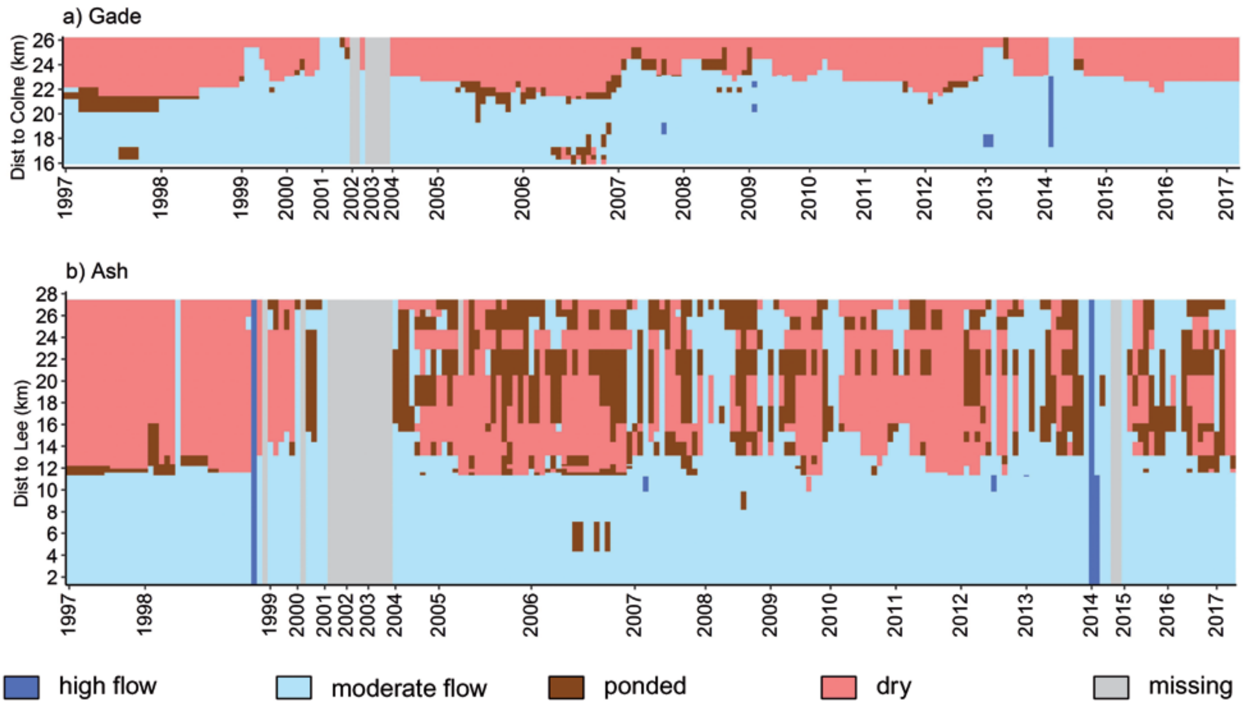


Fig. 2. Hydrological state observed on each survey date at each reach during the period of record (April 1997–April 2017) along: **a)** the Gade; and **b)** the Ash.

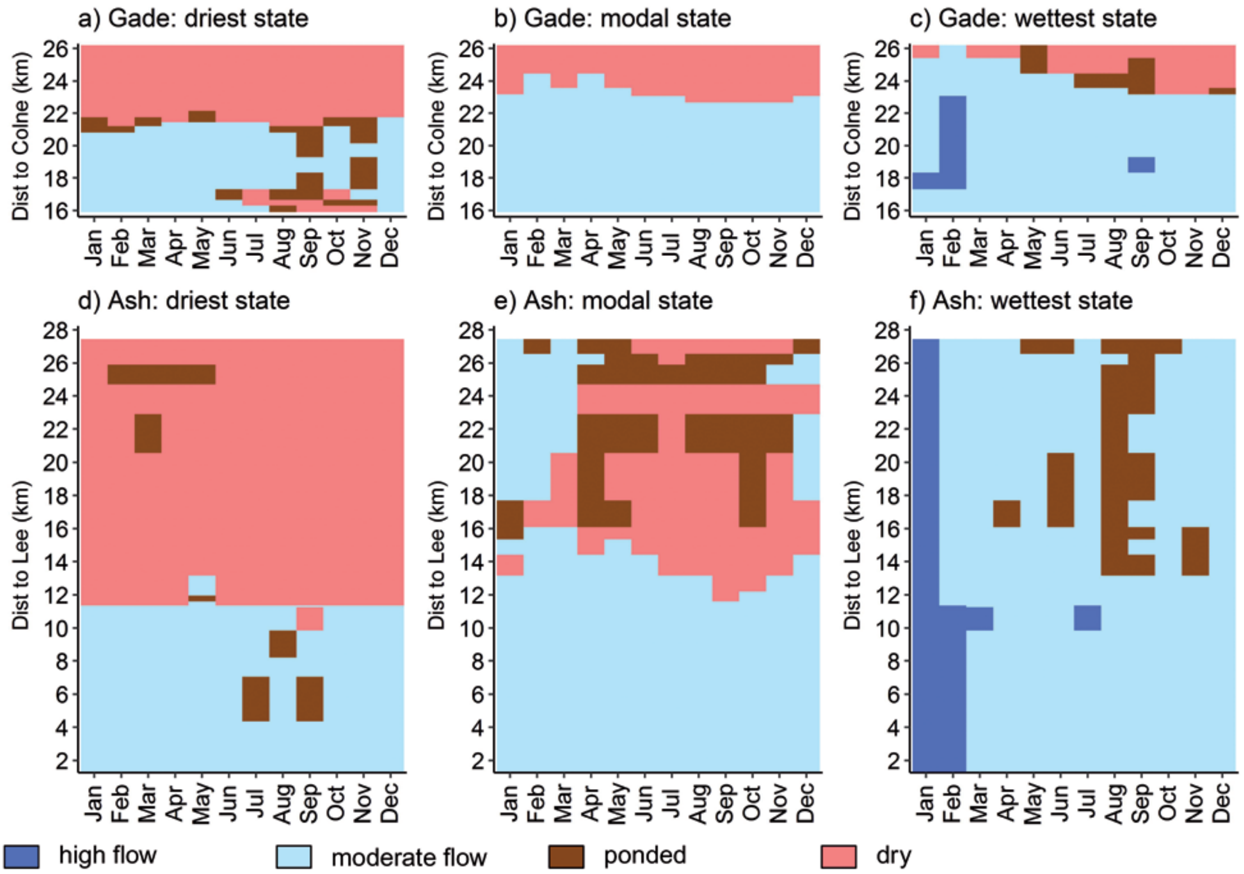


Fig. 3. Monthly hydrological state at each reach along the Gade **(a-c)** and Ash **(d-f)** representing the driest **(a** and **d),** modal **(b** and **e)** and wettest **(c** and **f)** hydrological states observed in the March 2004 to February 2014 period.

There was more ponding on the Ash than on the Gade, and the extent of the intermittence was higher (15 km and 5 km respectively), with changes of hydrological state generally more common along the upper reaches (Fig. 2b). However, during times of hydrological extreme, such as the unseasonably dry winter of 2011–2012 and its abrupt termination in the summer of 2012, the spatial variability on the Ash was low.

A discontinuity in the amount of ponding was apparent on the Ash between the early (pre-2004) and more recent data (Fig. 2b). Whilst this may reflect a historically consistent record of conditions in 1997–1998 in response to a period of drought, the contrast with 2005–2006 suggests a likely influence of the protocol standardisation. Missing data periods were evident on both rivers, but not concurrent; this applied to each of the other rivers in the respective Colne and Lee catchments.

Typical and extreme hydrological conditions

The heat maps identified a ten-year period (starting 1 March 2004) least affected by the identified inconsistencies and missing data, and inclusive of hydrological conditions at both extremes. All the results presented hereafter are based on this ten-year period. Typical and extreme patterns were revealed using the driest, modal and wettest state observed for each reach-month combination (Fig. 3). The representations of driest and wettest states showed extremes of the spatial extent of drying and high flows recorded during the ten-year period.

Typically, the lower reaches of the Gade were in the moderate flow state year-round and the upper reaches dry (Fig. 3b). However, most upper reaches flowed at least once during a January, February, March and April during the ten years of interest (Fig. 3c), and the driest conditions stopped flow in the lower reaches in at least one June, July, August, September, October and November (Fig. 3a). The Ash typically flowed along much of its length in January and February and a dry reach, developing in March at around 18 km from the confluence with the Lee, extended both upstream and downstream as the year progressed (Fig. 3e). A non-flowing state was observed in the lower reaches in at

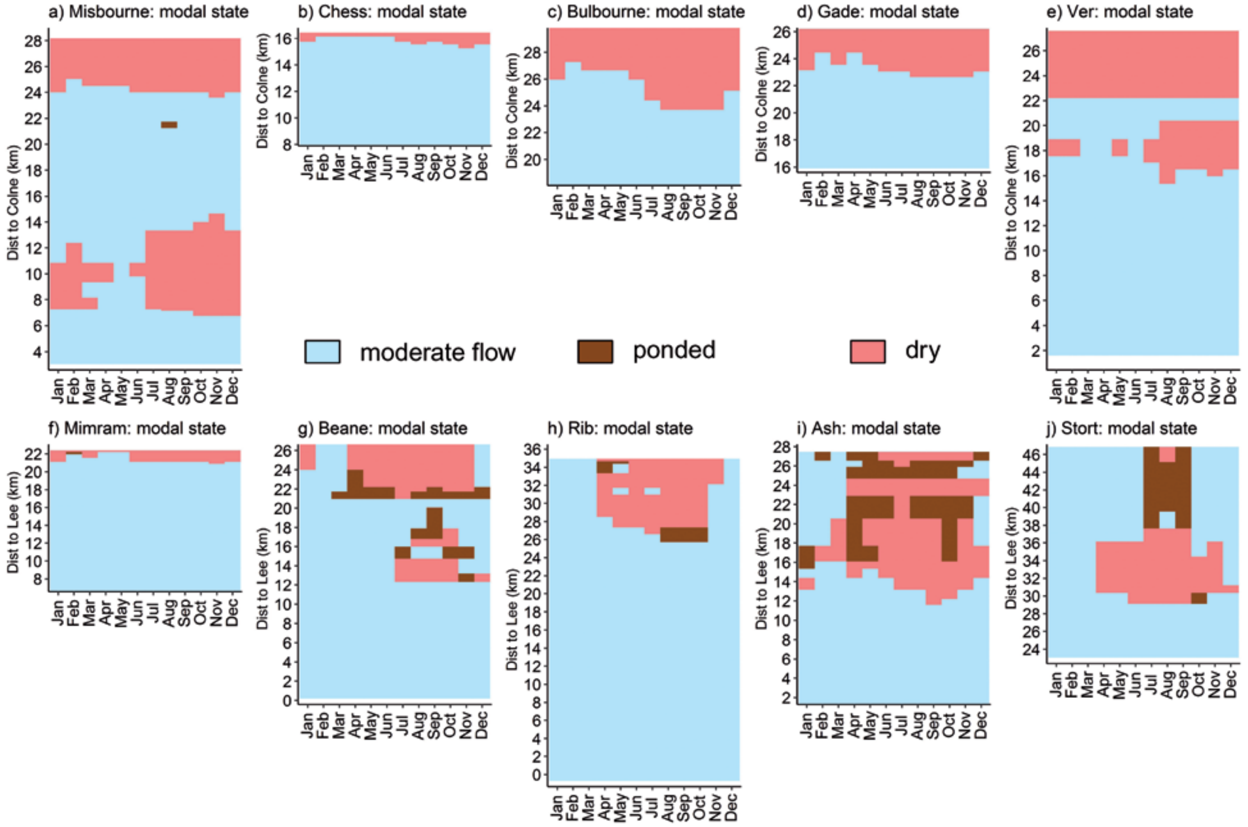


Fig. 4. Modal monthly hydrological state for March 2004 to February 2014 at each surveyed reach in the Colne **(a–e)** and Lee **(f–j)** catchments: **a)** Misbourne; **b)** Chess; **c)** Bulbourne; **d)** Gade; **e)** Ver; **f)** Mimram; **g)** Beane; **h)** Rib; **i)** Ash; and **j)** Stort.

least one July, August and September during the ten years of interest (Fig. 3d). Observations of high flow extended into the upper reaches in January and were predominantly restricted to the first two months of the year, even under the wettest conditions (Fig. 3f).

The monthly modal heat maps for all ten rivers (Fig. 4) revealed features of their typical behaviour that were stable in time and space, whether natural or artificial in origin. In the Colne catchment and also on the Mimram, ponding was relatively infrequent, and reaches of the same hydrological state were separated only on the Ver and the Misbourne. Source migration upstream through the winter and spring, and downstream during the summer and autumn was apparent on the Bulbourne and the Gade. The annual cycle in the spatial extent of moderate flow was more marked on the Beane, the Rib, the Ash and the Stort.

Quantifying patterns in hydrological state

Distributions of the metrics gave a clear indication of the variability in the hydrological behaviour exhibited by the ten rivers during the ten-year period (2004–2014; Fig. 5). The proportion of ponding was higher and more variable on rivers in the east than in the west of the study area (Fig. 5c). Half of all surveys conducted on the Ash recorded ponding along 5-30 % of the study length. This interquartile range (IQR) of 0.25, as a proportion of the study length was similar to the ponding on the Beane (0.19) and Stort (0.25), and greater than the ponding on the Colne catchment (maximum IQR of 0.09; Fig. 5c). Surveyed instances of high flow were rare, occurring in no more than eight surveys on any given river (Fig. 5a), and with the proportion of the study length exceeding 0.5 only once in a decade on any river and not at all on the Chess, the Bulbourne, the Ver or the Mimram. Evenness was lowest on rivers that were often dominated by a single hydrological state (Fig. 5e), such as the Mimram, where moderate flow dominated (median evenness 0.42). By contrast, the high median evenness of the Ash (0.90) combined with its small IQR (0.16) reflected a more balanced distribution of states along the river.

Configuration metrics (mean patch length, fragmentation and lotic connectivity) indicated the longi-

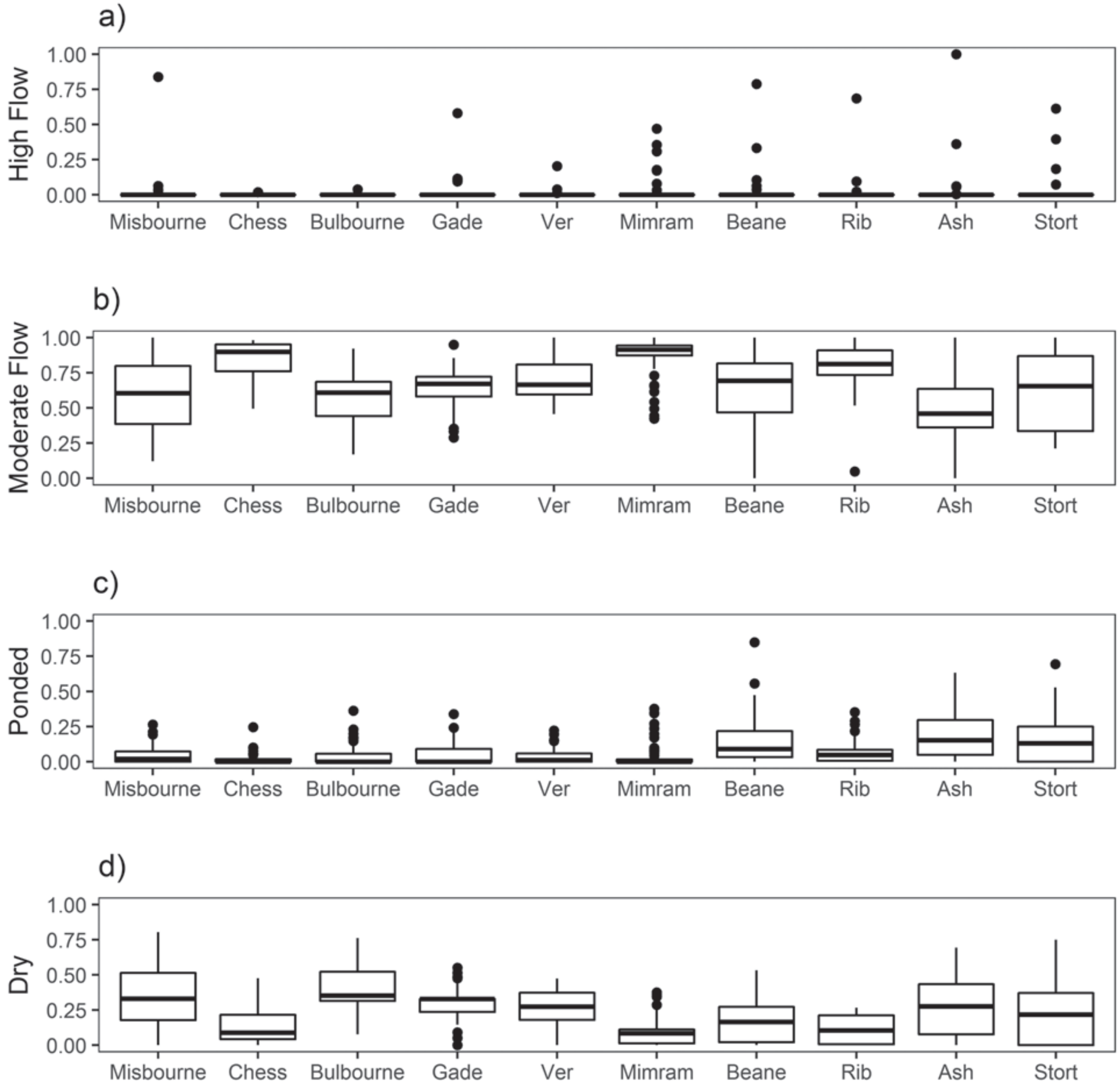


Fig. 5. Distribution of metrics by river (March 2004 to February 2014): proportions of study length under the following hydrological states: **a)** high flow; **b)** moderate flow; **c)** ponded; and **d)** dry. Distributions are also presented for the following composition and configuration metrics: **e)** evenness; **f)** mean patch length; **g)** fragmentation; and **h)** lotic connectivity.

tudinal arrangement of hydrological states during the ten-year period (2004–2014). The mean patch length was relatively consistent across the rivers (Fig. 5f) with some rivers (Chess, Bulbourne and Gade) showing little variability and the Rib the greatest. Fragmentation was more variable and higher within the Lee than the Colne catchment. Lotic connectivity expressed as a proportion of the study length was usually kept low along the Misbourne by the dry reach downstream of the source and approached unity only rarely (Fig. 5h; median 0.14, IQR 0.06). With a lotic connectivity of 1.0, the Misbourne provided 24.2 km of flowing water in connection with the downstream extent of its survey length, whereas under the driest conditions, less than 1 km of water was flowing. In comparison, the Mimram was usually observed flowing along most of its survey length (median 0.91, IQR 0.08), and lotic connectivity dropped below 0.25 for only one spell during the ten-year period. For all ten rivers together, including the assumed perennial reaches downstream

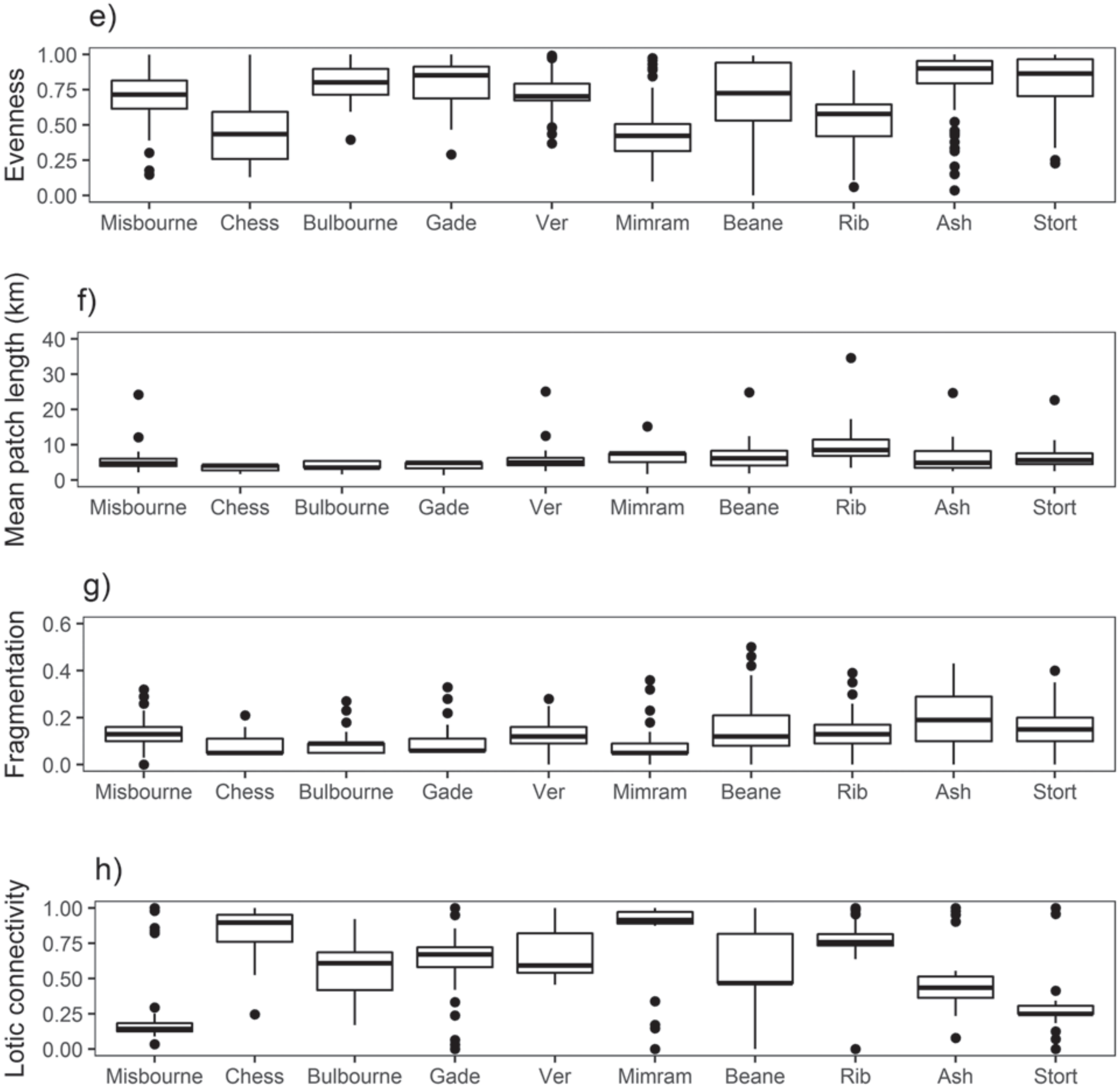


Fig. 5. Continued.

(Fig. 1), the length of perennial river during the 2004–2014 period was 86.6 km, accounting for 32 % of the total length of the surveyed rivers down to their respective confluences.

In the temporal dynamics of the Gade (Fig. 6) and the Ash (Fig. 7), an annual cycle of network contraction was evident, especially on the Ash, with lotic connectivity (Fig. 7h) often highest in December/March and lowest in September, tracking the proportion of moderate flow (Fig. 7b). The inverse pattern was seen in both dry and ponded proportion (Fig. 7d & 7c), which in turn were tracked by fragmentation (Fig. 7g). On the Gade, resumption of flow following summer drying usually lagged into the winter (dry proportion median 0.31 and IQR ≤ 0.05 in both September and December; Fig. 6d). On both rivers, evenness tended to increase during the summer months, as the spring dominance of flowing states receded, and was typically highest in the autumn (Figs 6e & 7e).

Discussion

Heat maps and landscape metrics are valuable techniques in the hydrological study of intermittent rivers, allowing identification of spatiotemporal changes in

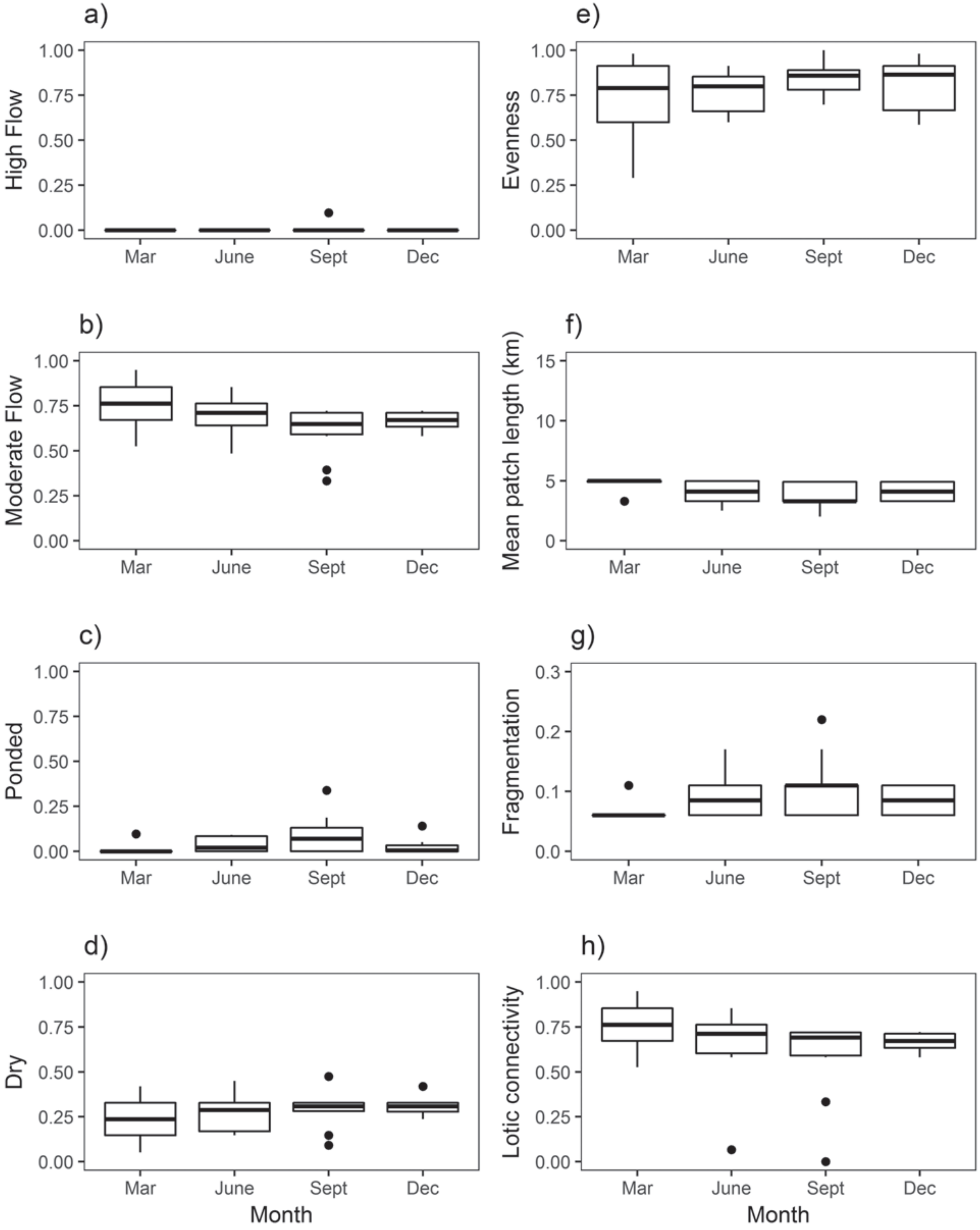


Fig. 6. Distribution of metrics for the Gade by season (March 2004 to February 2014): proportions of study length under the following hydrological states: **a)** high flow; **b)** moderate flow; **c)** ponded; and **d)** dry. Distributions are also presented for the following composition and configuration metrics: **e)** evenness; **f)** mean patch length; **g)** fragmentation; and **h)** lotic connectivity.

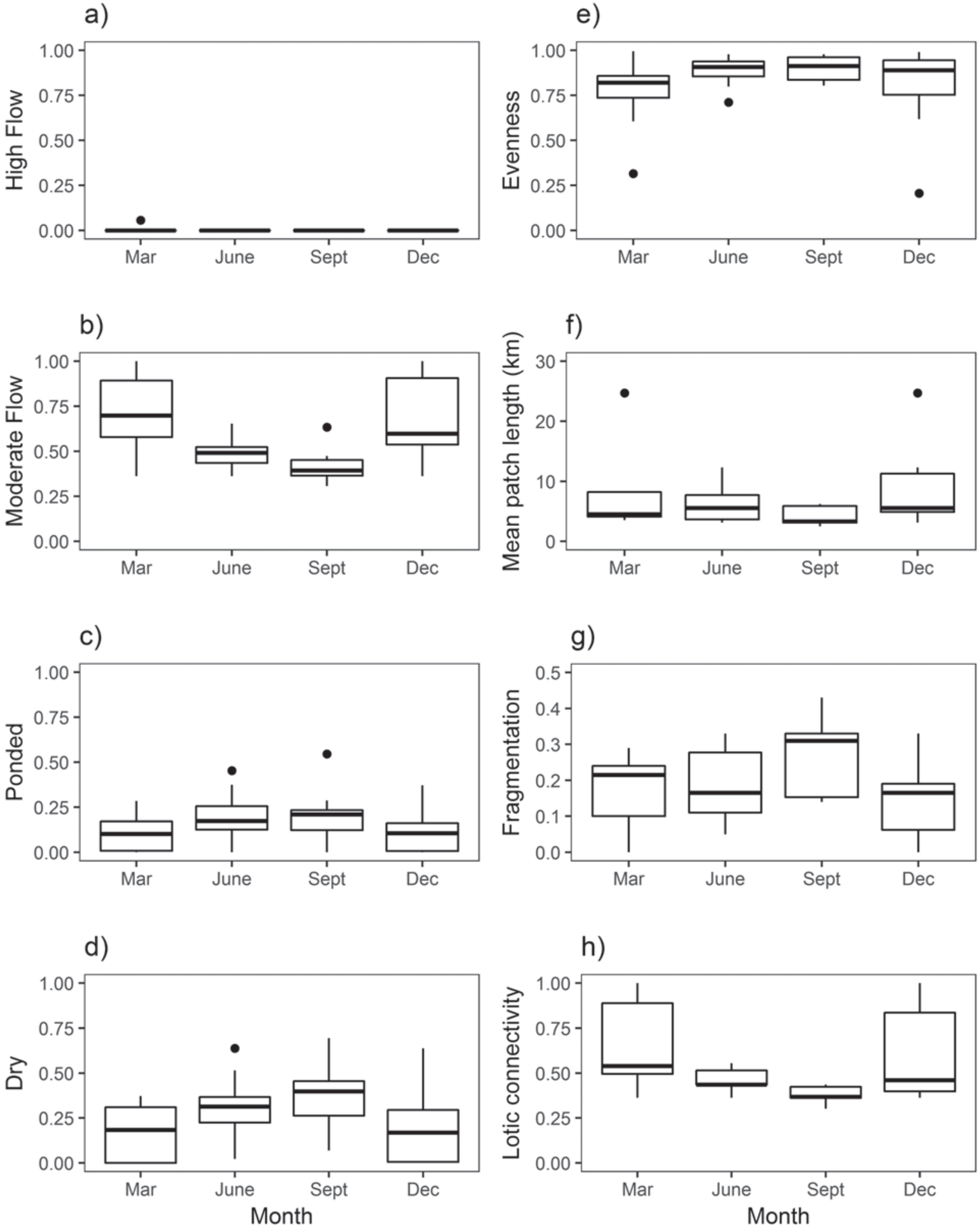


Fig. 7. Distribution of metrics for the Ash by season (March 2004 to February 2014): proportions of study length under the following hydrological states: **a)** high flow; **b)** moderate flow; **c)** ponded; and **d)** dry. Distributions are also presented for the following composition and configuration metrics: **e)** evenness; **f)** mean patch length; **g)** fragmentation; and **h)** lotic connectivity.

hydrological state on river ecosystems. The application of techniques for the visualisation and quantification of hydrological patterns is useful in identifying typical, seasonal and more variable features of the rivers' behaviour, and in highlighting natural and artificial features. Furthermore, a framework proposed for spatiotemporal metrics allows the characterisation of the habitat mosaics within these valuable transitioning aquatic-terrestrial systems (Datry et al. 2016).

Visualising patterns in hydrological state

Visualisation of the hydrological changes within the heat maps enabled tracking of source migration in response to groundwater levels as they typically rose to a maximum in the spring and fell to a minimum in the autumn, a behaviour partially masked by variability arising from the multi-year response time. Where a more consistent annual cycle in the spatial extent of flow and the greater incidence of ponding occurred, the more rapid hydrological response of the superficial deposits was evident. The mutual incidence of these patterns in hydrological state on the groundwater-dominated and flashier rivers suggests that they are naturally occurring. These results demonstrate the usefulness of the data and heat maps in the characterisation of similar river types, the conceptualisation of IRES channels as physical habitat mosaics (Datry et al. 2014), and the spatial variability which can only be captured by fine-scale characterisation (Jensen et al. 2019).

The influence of the superficial deposits was also evident in the frequency of transitioning between hydrological states in a given water year. On the most dynamic reaches of the Gade, for example, at 22 km from the confluence with the Colne, there were up to seven changes in hydrological state during a water year (2005-2006). However, there were four water years during which no changes in hydrological state occurred. On the Ash, where the flashier response to rainfall causes ponding on the river bed, transitioning between hydrological states was more common (on average three changes in state per water year along the upper reaches) and of shorter duration (typically months rather than years). Across river types, our results demonstrate that hydrological dynamism varies greatly, with consequences for the aquatic-terrestrial habitat mosaic that are of key importance to both aquatic and terrestrial biodiversity (Datry et al. 2016; Stubbington et al. 2017).

Anthropogenic activities can influence hydrological patterns in both groundwater-dominated and flashier IRES, including both increases and decreases in intermittence (Steward et al. 2012; Luthy et al. 2015), as seen in the spatial fragmentation of dry state conditions. Historical mill workings and associated realignment on the Misbourne compound natural drying caused by local discontinuities with the aquifer, with loss of water through the river bed causing periods of negative accretion on some reaches. On the Ver, the effluent from a sewage treatment works contributed to a flowing reach that dried only once (October 2006 – January 2007) during the ten-year period. Thus, whilst heat maps may be too coarse to identify the diffuse impacts of anthropogenic losses and gains (White et al. 2018), they provide evidence of more stable features, such as effluents that cause artificially near-perennial flow, and natural or artificially influenced dry reaches downstream of the source. Such characterisations can inform management interventions that seek to restore natural flow intermittence regimes (Clayton et al. 2008; Bond et al. 2010; Reich et al. 2010).

Quantifying patterns in hydrological state

Differences in the composition and configuration of hydrological state on groundwater-dominated and flashier rivers included the proportion of and variability in ponding. This was markedly higher within the four flashiest rivers than across the more groundwater-dominated rivers. Ponding was often localised, reflecting the distribution of superficial deposits and resulting in higher spatial fragmentation. It is important to understand the spatial and temporal distribution of the ponded state since it provides a refuge for macroinvertebrates and makes a significant contribution to aquatic diversity in IRES (Hill & Milner 2018). Seasonal dynamics revealed slower rewetting of the groundwater-dominated rivers because of their greater dependency upon the recharge of the permeable geology, supporting previous studies (e.g. Leigh et al. 2010), and highlighting the importance of groundwater levels in creating dynamic habitat composition (Datry et al. 2016).

Hydrological state data

Citizen science, hydrometry, time lapse photography, drones and remote sensing have the potential to generate or support the generation of similar datasets across a wider geographical area, facilitating the characterisation of a wider range of IRES (Stubbington et al. 2018). Tools for the objective identification of multiple hydrological states are also required (Gallart et al. 2017), in conjunction with methods delivering consistency in longitudinal coverage and the frequency and duration of monitoring for capturing seasonal differences and hydrological extremes. However, the quality of these data is unlikely to meet the standard achievable by trained hydrologists performing a well formulated sampling strategy with consistent objective definitions of hydrological state.

Developments in multiple-state monitoring would deliver data that may be used alongside more traditional hydrological records providing accurate and continuous state measurement for a single point on the network. In study areas such as the Colne and Lee sub-catchments, where both data types are monitored, the potential exists for exploring their relationship and modelling intermittence, subject to the impact of artificial influences, and comparing with alternative approaches to simulation applied elsewhere (e.g. Allen et al. 2019; Beaufort et al. 2019).

Capturing spatial and temporal dynamics

In our study, both spatial and temporal intermittence were captured at a resolution that is ecologically meaningful. For example, the response to hydrological extremes was revealed in the timing of the high and low limits of lotic connectivity. The presence or absence of such seasonal anomalies is ecologically significant because it indicates whether or not the normal transitioning between terrestrial and aquatic habitats has been disturbed by the extreme hydrological conditions (Datry et al. 2016). Lotic connectivity has direct implications for the migration of fish, so the absence of extreme contraction in December during the brown trout spawning season allows access to more extensive spawning habitat (Mann et al. 1989; The Chilterns AONB 2011). Similarly, the range of lotic connectivity on the Misbourne, and the predominance of intermittence across the surveyed rivers demonstrate the importance of understanding the patterns of drying, ponding and fragmentation that influence the source of colonists of aquatic taxa following flow resumption (Stubbington et al. 2016). Hydrological metrics quantifying such behaviours can be compared with biological indices in hydroecological assessments, for example, of the response of aquatic communities to drying (Leigh et al. 2016) or restoration of a natural flow regime (Bond et al. 2010).

Tracking of seasonal patterns using the metrics identified some correlation (moderate flow proportion with lotic connectivity and ponded proportion with fragmentation), and such redundancy in landscape metrics is well documented (Schindler et al. 2008). The inverse relationship between mean patch length and fragmentation depends upon the number of sites and the distance between them, and therefore, varies between rivers. The extraction and infilling of a regular monthly time series of hydrological state would address both the limitation of seasonal resolution in the tracking of drought development and termination, and the influence of spatial extent on metrics. A methodology is required for uniquely defining the length of an intermittent reach, addressing for example, the potential migration of a source beyond the upper limit of the former physical channel during a groundwater flooding event. The effect on metrics of operationally defined study lengths is illustrated by the disproportionately high lotic connectivity on the Rib where the study length extends deep into the perennial reach. However, regular observations or modelled data will not always be available longitudinally for the application of zero-flow thresholds (Delso et al. 2017), the derivation of reach-specific metrics (Gallart et al. 2012), and the classification of regime (Williamson et al. 2015; Costigan et al. 2017).

The techniques used here also have utility in the dissemination and analysis of hydrological state data. Heat maps offer a simple but highly effective tool in communicating with a broad range of stakeholders, including members of the public. Stakeholder engagement is important in improving public attitudes to intermittence in rivers where drying is often seen as 'bad' (Stubbington et al. 2018). The driest state extreme reflects conditions that might be experienced more frequently with climate change predictions (Pumo et al. 2016) and local anthropogenic activities (Datry et al. 2017). The proportions of dry and ponded hydrological states can be used to track the development and termination of a drought, and the extent and duration of network contraction and recovery compared with historical events and predicting ecological response to future changes (Westwood et al. 2006; Bond et al. 2010; Barthès et al. 2015).

A framework for IRES metrics of hydrological state

Whilst a framework exists for the characterisation of metrics derived from measured flow (Richter et al. 1996; Poff et al. 1997), there is none for metrics developed for capturing the spatiotemporal behaviour of hydrological state, as required for the meaningful quantification of intermittent hydrological regimes.

The heat maps visually illustrate that patches used for landscape metrics can be applied temporally and

Table 3. A framework for the categorisation of metrics of hydrological state for intermittent rivers and ephemeral streams.

Class	Number of hydrological states	Dimension	Example questions	Example metrics
Composition How much of the hydrological states are seen?	**Single**	**Spatial**	How much of a given hydrological state is seen along the river at time t?	Proportion[1] of flow/ponded/dry[3] Ratio (Datry et al. 2016)
		Temporal	For how much of the time is a given hydrological state seen at site s?	Flow[2]/pool/dry permanence (Gallart et al. 2017) Number of flow[2]/zero-flow[2] days (Costigan et al. 2017)
	Multiple	**Spatial**	What is the variability in the proportions of all hydrological states seen at time t?	Shannon diversity (Datry et al. 2016) Evenness[1]
		Temporal	What is the variability in the permanence of all hydrological states seen at site s?	Temporal diversity, as visualised by Aquatic States Frequency Graphs (Gallart et al. 2012) and Flow-Pool-Dry plots (Gallart et al. 2017)
Configuration How are the hydrological states arranged?	**Single**	**Spatial**	What is the location or extent of a contiguous patch of a given hydrological state at time t?	Lotic connectivity[1] (Datry et al. 2016) Network contraction[3] (Goulsbra et al. 2014) Drainage density[3] (Godsey & Kirchner 2014)
		Temporal	What is the timing or duration of a continuous period of a given hydrological state at site s?	Flow[2]/zero-flow[2] event duration and event frequency (Costigan et al. 2017) Seasonality of flow[2]/zero-flow[2] days (Gallart et al. 2012; Costigan et al. 2017)
	Multiple	**Spatial**	What is the average length of contiguous patches of all hydrological states seen at time t? How many changes in hydrological state are seen along the channel at time t?	Mean patch length[1] (Datry et al. 2016) Fragmentation[1] (relative edge density)
		Temporal	What is the average duration of continuous periods of all hydrological states seen at site s? How many changes in hydrological state are seen during the period of interest at site s?	Mean event duration Temporal fragmentation

[1] Metrics used in this study; [2] Metrics that can be calculated using a time series of gauged or estimated flows; [3] Metrics that can be calculated using wet/dry mapping

spatially to provide such a framework. Our study has demonstrated how a vertical slice through a heat map delivers metrics that capture a point in time (integrated spatially). A horizontal slice will deliver metrics that capture a point in space (integrated over time). Such temporal metrics could be matched with biological data to help identify those hydrological patterns most relevant for biological communities (Datry et al. 2016), and the ecological consequences of changes in fragmentation (Bond et al. 2010). In either case, the potential exists to derive metrics for any single hydrological state, such as the proportion of moderate flow, and to combine all of these into a summary metric, such as evenness. Each metric can thus be placed within a framework using a three-fold categorisation (Table 3); class (composition/configuration), state (single/multiple) and dimension (spatial/temporal).

Examples of visualisations and metrics have been identified from the literature for many of the fields in the framework (Table 3). Commonly used examples are flow permanence (Smith et al. 2003; Schmidt et al. 2009; Yu et al. 2018), which is a single-state metric of temporal composition, and mean patch length (Datry et al. 2016), which is a multiple-state metric of spatial configuration. Gaps representing opportunities for further work on metrics exist in the proposed framework, for example, in single-state spatial configuration, where metrics to date have focused on flowing or dry states because of the paucity of observations of ponding conditions (Godsey & Kirchner 2014; Goulsbra et al. 2014; Jensen et al. 2017). Whilst metrics for any gap in the framework may be developed using a multiple-state, longitudinal, regular monthly dataset, some gaps may be of higher priority than others. For example, metrics of temporal fragmentation are likely to have utility in the hydroecological assessment of biological sampling sites, since they provide characterisation of transitioning between states, which affects the composition of instream communities (Westwood et al. 2006; Datry et al. 2016; Stubbington et al. 2016). It is apparent that only a limited number of the metrics can be derived from gauging station data or wet/dry mapping (Godsey & Kirchner 2014; Goulsbra et al. 2014; Jensen et al. 2017), underlining the imperative for hydrologists to embrace this new data type of hydrological states in order to provide full characterisation of intermittent rivers. The framework has application in the quantifiable and consistent expression of alterations in the patterns of hydrological state and understanding the ecological consequences of anthropogenic impacts such as changes in spatial and temporal fragmentation (Bond et al. 2010; Chiu et al. 2017).

Conclusion

Data and techniques are required for hydrological and ecological studies of IRES that capture their spatiotemporal variability with a more detailed classification of hydrological state than can be derived from gauging station data or wet/dry mapping alone. Our analyses revealed slower transitioning between hydrological states and lower spatial fragmentation on groundwater-dominated than on flashier rivers, seasonal behaviour in the spatial composition and configuration of hydrological states, and artificial influences on intermittence. The framework proposed for the categorisation of metrics of hydrological state highlights the limited coverage provided by traditional approaches to intermittence and underlines the imperative for hydrologists to embrace this type of data for full characterisation of these variable systems. This research has utility in the assessment of hydrological extremes, in particular, drought and groundwater flooding, and in examining the impact of anthropogenic disturbances to natural variability on aquatic and terrestrial ecology. There is considerable potential for the wider application of the visualisation and quantification approaches presented, but these require the collection of additional datasets compiled with consistent monitoring protocols and objective definitions of hydrological state and intermittence extent. As IRES become more common due to global change, such application would enable effective characterisation of their hydrology, thus informing management strategies that seek to support resilient ecosystems as they adapt to a changing world.

Acknowledgements

The authors gratefully acknowledge the funding provided for this study by the Environment Agency and the Natural Environment Research Council [grant number NE/L01016X/1], contributing to the ENDOWS project (Engaging diverse stakeholders and publics with outputs from the UK Drought and Water Scarcity Programme). The European COST Action [CA15113] on the Science and Management of Intermittent Rivers and Ephemeral Streams (European Cooperation in Science and Technology) was central to its initiation. The role of Environment Agency hydrologists, past and present, in providing data and local knowledge was pivotal; Di Hammond and Rebecca Ross to name but two. Lucy Barker, Katie Muchan and Sandie Clemas (Centre for Ecology & Hydrology) provided helpful comments on a draft, and we thank the anonymous reviewers and the editors for suggested changes which have greatly improved the manuscript. The views expressed within this paper are those of the authors and not necessarily those of their organisations.

Authors' contributions

Catherine Sefton designed the study and wrote the manuscript, with review and constructive input from the co-authors. Simon Parry produced the visualisations and the metrics. Judy England instigated the study and contributed ecological expertise, providing interpretation and context for the results. Geoffrey Angell provided local hydrological knowledge and data.

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Manuscript received: 06 April 2018
Revisions requested: 07 May 2018
Revised version received: 20 May 2019
Manuscript accepted: 14 June 2019