Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

Visualising and quantifying flow intermittence patterns in chalk streams

The Springs and Sources dataset of Hertfordshire and North London Area of the Environment Agency

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Executive summary

The headwaters of many rivers are not perennial. Some flow briefly in response to rain (ephemeral), others experience annual patterns of drying and wetting in response to groundwater level (intermittent) and others dry wholly or partially because of artificial influence. The biodiversity of these intermittent rivers and ephemeral streams (IRES) is high because of the cycling between terrestrial and aquatic conditions, and there is potential for deterioration caused by changes to the natural patterns of wetting and drying both in time and in space. However, monitoring and therefore understanding of IRES is scant, and the tools that currently exist to assess water resource activities in the UK require adaptation because of an implicit assumption of perennial flow. Many of the chalk rivers in Hertfordshire and North London Area are intermittent in their headwaters or along their lengths and are subject to artificial influences in the form of abstractions, discharges and historical mill workings. Area staff have been surveying the hydrological behaviour of ten of these rivers since 1997, producing a dataset of flow intermittency that is rare in its temporal and spatial extent, and in its year-round continuity, on an international scale.

The objectives of this collaboration were concerned with developing techniques for the visualisation and quantification of the flow intermittency patterns observed on the surveyed rivers. Heat maps, in which observations of dry, pooled, moderate flow and high flow are simply colour coded, capture the prevalence of hydrological states both along the channel and through time, in a way that is readily assimilated by the human eye. These reveal the rapidly changing occurrence of pooling and fragmentation in the clay-influenced rivers such as the Ash and the Rib, which is in marked contrast to the slower cycling between wet and dry conditions at sites along the groundwater-fed rivers such as the Mimram and the Gade. The continuity of the dataset means that monthly average heat maps are also possible, drawing attention to those features of the patterns that are stable in time, such as the seasonal source migration of the Gade, or in space, such as a sewage treatment discharge on the Ver.

Ecologically relevant quantification of the drying and wetting patterns has been addressed using metrics that capture the composition (abundance and evenness) and configuration (patch length, fragmentation and lotic connectivity) of the hydrological states observed along the channel. Measures of their distributions are presented visually and numerically for the comparison of rivers, and the metrics are charted in summary sheets for each river. Application of the metrics is demonstrated by exploring the response of the Misbourne to natural drivers such as groundwater level and effective rainfall and the interference of artificial

influence. The metrics also present an opportunity to quantitatively explore the response of the rivers to extremes since the temporal extent of the dataset captures the dry periods of 2004/2006 and 2010/2012 and the groundwater flooding of 2000/2001 and 2013/2014. Metrics quantifying the hydrological states observed following the dry winter of 2016/2017 suggest that conditions were not as severe as they were in March 2006 but the impact of a second dry winter in 2017/2018 would be similarly, if not more significant.

It is recommended that the surveys continue, not least to monitor recovery following the current sustainability reductions in abstraction on the Misbourne and the Ver, and the procedures perfected with a view to training hydrologists and collecting similar data in other parts of the country where water resource assessments on IRES are required.

Further research is recommended in the following areas:

- the seasonal dynamics of the dataset - this will enable the identification of unseasonal behaviour with implications for IRES ecology;
- the relationship between hydrological state observed along the channel and river flow recorded at gauging stations further downstream – this presents opportunities in the estimation of intermittency on unsurveyed catchments;
- the ecologically-relevant classification of hydrological states - this is a vital step in the assessment of ecological status;
- the hydroecology of IRES, for example, comparison of the newly quantified patterns of intermittency with ecological data.

The methods presented here are thus a first step towards the longer-term aim of developing tools and techniques tailored to the assessment of water resource activities in IRES catchments. Such developments are vital if the needs of water users and the environment are to be balanced in these potentially sensitive and highly dynamic habitats.

Acknowledgements

The authors wish to acknowledge the support of the European COST Action (CA15113) on the Science and Management of Intermittent Streams (European Cooperation in Science and Technology, 2017) in the initiation of this study, not least the contribution of Dr Rachel Stubbington of Nottingham Trent University. The contribution of Rebecca Ross, HNL Area hydrologist, in providing data and local knowledge, and that of her past and present colleagues in conducting the surveys is also gratefully acknowledged.

1 Introduction

Intermittent rivers and ephemeral streams (IRES) are watercourses that do not have continuous flow all year round, along their entire length. Flow cessation may result from low rainfall, low groundwater level, artificial influence or even freezing. It is thought that IRES account for more than 50% of the global river network with upward pressure from climate change and population growth (Skoulikidis et al., 2017). However, their ecosystem services have been largely undervalued, and they have been neglected in research and inadequately protected (Datry et al., 2017). One consequence of this is that hydrological data are extremely scarce; where they exist, for example in France, they are limited in their duration and season of observation (Datry et al., 2016). Citizen science (Gallart et al., 2016) and aerial imaging methods (González-Ferreras and Barquín, 2017) are being developed in Spain to address this deficiency. However, historical records of flow intermittency covering multiple years, rivers and seasons are needed to study these dynamic hydrological regimes and to provide validation for modelling approaches, as demonstrated in New Zealand (Larned et al., 2011).

The study area for this collaborative project comprises ten rivers in Hertfordshire and North London (HNL) Area which have been the subject of year-round ‘Springs and Sources’ surveys by area water resource hydrologists since 1997. A dataset of observations of hydrological state along the intermittent reaches of the rivers has thus been collated that is rare on an international scale.

The dataset provides an opportunity to study the wetting and drying patterns of IRES which can in turn inform our understanding of the vulnerability of their ecology to changes in the temporal and spatial variability brought about by artificial influence. The rivers support a diverse range of taxa because of the cycling of flowing, pooled and dry habitats available (Stubbington et al., 2017). These may include specialists that are able to exploit the changing conditions, for example by recolonising quickly after drying. The ability of the taxa to do this will depend upon the patterns in flow intermittency in space and time. Variability in space is important because the amount of flowing, pooled and dry conditions directly affects the availability of suitable habitats for aquatic and terrestrial species. Variability in time is important because the frequency and duration of cycling between the states has implications for the opportunity presented to specific taxa during key parts of their life cycle.

In England, responsibility for the assessment of IRES to inform water resource decision-making lies with the Environment Agency. Such assessments require the separation of natural and artificial causes of drying (England et al., 2008), a task made extremely challenging by insufficient evidence due to the scarcity of hydrological and biological monitoring. Furthermore, an implicit assumption of perennial flow in the tools and techniques currently applied means that they are not well suited to the dynamics of these rivers. This project is the first step, seeking to apply current science to this problem in the UK, and to contribute to the advancement of IRES science.

1.1 Project aims

Although it is understood that hydrological assessments in IRES are not adequate, the scale and extent of the problem is not yet known. The Springs and Sources dataset provides an opportunity to explore methods which assimilate and communicate the available information, enabling informed decisions to be made on what further work is needed. This project is the first step towards being able to adequately assess the impact of water resources activities such as public water supply abstraction in these watercourses. The results will aid operational staff in their decision-making with their need to assess, manage and mitigate the impact of artificial influence on the rivers, notably abstractions, discharges (effluents) and the returning of rivers historically diverted into mill leats back down to the valley bottoms. This will help to ensure that the needs of water users and the environment are balanced in water resources licensing decisions and meet obligations under the Water Framework Directive (WFD). The specific objectives were to:

1. Quality assure the Springs and Sources dataset;
2. Develop hydrological metrics to describe and visualise the drying/wetting cycles of the rivers, for example, the duration, timing and longitudinal connectivity of flow;
3. Demonstrate how the analysis of drying/wetting patterns can be used to explore the response of the rivers to drought and to artificial influences.

1.2 Report structure

This report is laid out in five sections. Section 2 describes the study area and Springs and Sources Surveys and details the methods used in the collation, quality control, visualisation and quantification of the data. Section 3 presents the results including survey completeness, selected heat maps and metrics, and examples of temporal analysis and response to drought and drivers. Conclusions and recommendations are made in Sections 4 and 5 respectively. The report is accompanied by electronic copies of the data deliverables (D1.1 and D2.1), and by five Appendices (A to E) presenting the full set of results.

2 Methods

2.1 Study area

The survey area lies to the north of London, and consists of ten rivers, five within the catchment of the River Colne, and five within the catchment of the River Lee.

The surveyed rivers in the Colne catchment are the Misbourne, Chess, Bulbourne, Gade and Ver (Figure 1). Their intermittent upper reaches flow in a south-easterly direction, fed by groundwater from the Chalk of the Chiltern Hills, whilst downstream they culminate in a complex network of rivers in more urban landscapes. The Colne flows into the Thames in west London, upstream of Teddington Lock. The geology is dominated by unconfined chalk, overlain by clay in the south east (Environment Agency, 2006a).

The surveyed rivers in the Lee catchment are the Mimram, Beane, Rib, Ash and Stort. Whilst the geology of the Mimram is similar to that of the Colne rivers, the area of exposed Chalk decreases from west to east as it becomes overlain by the clay and glacial drift. The drainage densities are therefore notably higher in the Rib, Ash and Stort than further west (Environment Agency, 2006b). The Lee flows into the Thames in east London, near the Isle of Dogs.

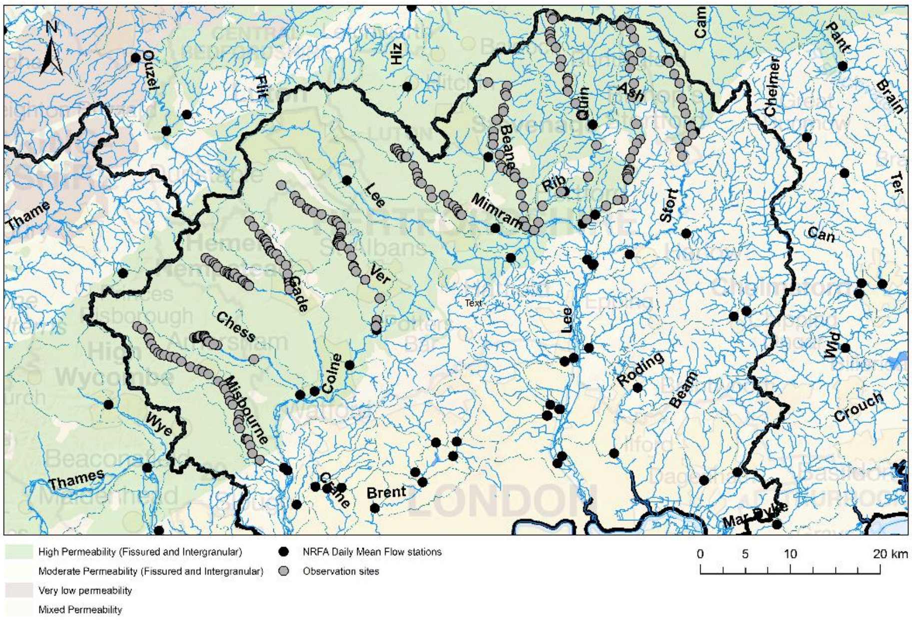


Figure 1 *Map of survey rivers, observation sites and geology*

2.2 Springs and Sources Surveys

2.2.1 Survey procedure

The rivers were surveyed from 1997 until 2001 and from 2004 until 2017 and are ongoing. The exception is the Beane where observations continued through much of the break until the autumn of 2003. Surveys began in response to drought and low flows in the mid to late 1990s with a view to observing the extent and duration of the drying. They were conducted by area water resources hydrologists, having both the required expertise regarding the expected hydrological behaviour of the rivers and the local knowledge of known artificial influences. Efforts have been made within operational constraints to maintain regular intervals between observations by undertaking surveys close to the middle of the month. Regularity has been prioritised over the removal of runoff from observations by avoiding periods of heavy rain, and this is appropriate in this study area, since the varying geology of the two catchments means both groundwater and rainfall may be drivers of intermittency. The frequency of observations throughout the survey period is presented in Section 2.3.2.

The spatial extent of the surveys encompasses the farthest upstream observation of flowing or ponded water and extends down to an observation site where flow is thought to be perennial, based on the period of record and local knowledge. The spatial resolution is such that the median distance between observations is 0.7km and distances range from 0.1km in the upper reaches of shorter rivers such as the Chess, to 4 or 5km, between downstream observation sites on longer rivers such as the Rib.

2.2.2 Observation sites

Multiple sites on each river were selected by the survey teams according to the length of the river, its hydrological behaviour and operational considerations such as permitted access. The number of sites on the majority of rivers is between 20 and 30; the Ver has the greatest at 32, the Gade the fewest at 18. The sites are shown in Figure 1 and their names and locations may be found in the electronic datafiles (Deliverable D1.1, see Appendix A).

2.2.3 Observation categories

The data are unusual in the field of hydrology in that they take the form, not of flow measurements, but of observations of hydrological state. Eight such states are identified, and described both qualitatively (Table 1) and with photographs in the guidance documentation provided to the surveyors.

Table 1 *Observed categories of hydrological state*

Hydrological state	Description
dry bed	No wet mud in river bed
wet bed	Muddy bed with small puddles
ponded	Large areas of water present but not moving
very low flow (trickle)	In some rivers a trickle, in others extremely slow moving water
low flow	Starting to be under stress but more than a trickle
medium flow	Wide range of flows
high flow	River moving fast and is approaching bank full
over bank flow	Water is out of channel and flooding adjacent areas

2.2.4 Observation frequency

Whilst the aim of the Area hydrologists is to complete the survey on all ten rivers once in each calendar month, there are periods of increased or reduced frequency in response to hydrological conditions and resources. The visualisation and quantification results presented in this report make use of the complete dataset but the compilation of a complete monthly dataset is an aspiration for the study of temporal variability in the patterns of intermittency. The frequency of observations was therefore explored and the results are presented in visual form in Section 3.1.1.

2.3 Data quality control

2.3.1 Infilling of missing data

Observations of hydrological state were infilled by comparison with past and future years and with hydrologically similar rivers surveyed on the same date. This task was conducted by the HNL Area hydrologists using their local knowledge to infill as accurately and completely as possible, leaving only a handful of sites and dates at which estimation was not possible with an acceptable degree of certainty.

2.3.2 Data cleaning

Following infilling, the dataset was cleaned in two ways. Firstly, where survey dates were known to be erroneous, for example, because two sets of observations were recorded on the same date, corrections were made by comparison with the survey dates on neighbouring rivers; 35 such corrections were made. Secondly, where the terminology used to record the hydrological states was not one of those listed in Table 1, they were reworded, for example, by adding "(trickle)" to "very low flow". These corrections were mostly the result of small typing errors and resolution was therefore straightforward. The data cleaning process served to minimise errors encountered in the running of computer programmes, or codes, written to perform the visualisation and quantification of the intermittency patterns. The infilled and cleaned dataset is provided electronically as Deliverable D1.1 (see Appendix A).

2.3.3 Rationalisation of observation categories

Following consultation amongst the project group, the eight categories of hydrological state observed (Table 1 in Section 2.2) were simplified into four as shown in Table 2. It was recognised that some ecologically significant detail of the observations would necessarily be lost; for example, a wet bed may offer a refuge to taxa during a short dry period that is not possible in a dry bed. However, this loss was offset by a significant increase in confidence because notwithstanding the definitions in Table 1, there are inevitably inconsistencies in the way the states are identified between sites, times of year and the person making the observations. A flow rate identified as "low" may be low for the time of year, low compared to last month's observation, or low in comparison to the previous site.

Table 2 *Rationalisation of hydrological states*

Observed hydrological states with percentage of observations		Rationalised hydrological states with percentage of observations	
25.0%	dry bed	DRY	26.5%
1.5%	wet bed		
3.9%	ponded	PONDED	6.9%
3.0%	very low flow (trickle)		
11.2%	low flow	MODERATE FLOW	62.2%
51.0%	medium flow		
0.9%	high flow	HIGH FLOW	1.0%
0.1%	overbank flow		

The rationalisation of the states into just four thus goes some way to standardising the definition of the hydrological states across rivers and observation dates. Photographs taken at many of the sites present the future possibility of attempting to standardise the observations using all eight observed states, or indeed alternative categorisation. For example, "very low flow (trickle)" covers a wide range of observations including connected pools, trickling flow without pools and deeper slow-moving water, each presenting markedly different aquatic habitats. The rationalisation approach used here allows analysis to be undertaken with the existing dataset, and recommendations are made for the robust augmentation of the number of hydrological states in future analyses (see Section 5).

The dataset with four categories has been provided electronically along with Deliverable D1.1 (see Appendix A).

2.3.4 Representation of the river network

2.3.4.1 Spatial extent

An important contextual feature of the dataset is the length of channel surveyed in comparison to the length of the river. The sensitivity of metrics to the intermittent behaviour that is the focus of the study is highest if they are calculated for the surveyed reach alone. However, such metrics do not, by definition, fully represent the hydrological conditions present along the length of the river.

This is illustrated by decisions made on the reaches represented in the visualisations and metrics by the farthest upstream and downstream observation sites. The option to extend the farthest downstream reach to the confluence was rejected because this would result in a dominance of flowing states, particularly in those rivers where the intermittent reach is short in comparison with the total length of the river. At the upstream end, conversely, extending upstream to a permanently dry location introduces a potential bias towards dry conditions which is compounded by the practical difficulties of pinpointing the upper extent on the ground. Under wet conditions, observations are commonly made upstream of the clearly defined channel, with water spreading laterally under groundwater flooding conditions. The upstream limit observed therefore, unlike the downstream limit, depends on the extremes that occurred during the period of record, and may be exceeded in future years. The upper and lower reaches therefore were defined as extending 100m upstream and downstream of the observation site respectively. This was ultimately a pragmatic judgement, based upon the approximate distance visible during a site visit.

The surveyed lengths and total river lengths from source to confluence are presented in Section 3.1.2.

2.3.4.2 Spatial resolution

Each river is represented as a series of reaches, with an observation site at its mid-point. The alternative, of defining the reach with the observation site at its lower or upper limit was rejected because the confidence in the assumption being made, that the site is representative of the whole reach, is lower. For example, were an observation site to be located at the top end of its reach and the source a short distance downstream, the reach would be recorded as dry when in fact it is flowing along the majority of its length. The decision to locate the observation sites at the mid-point of each reach reduces the risk of such misrepresentations of the data.

2.4 Visualising drying/wetting patterns

Heat maps are used to present the data in visual form, with categories of hydrological state represented as colours. Dry states are shaded pink, ponded brown, moderate flow light blue, high flow dark blue and missing data grey. Each observation is presented along the x-axis, with no temporal scaling, whilst the distance between sites on the y-axis is proportional to their location along the channel.

The heat maps are a useful tool as they show all observations in a single image that is readily assimilated by the human eye. Wet and dry periods are easily identified and features of the rivers' behaviour exposed, such as the change in longitudinal connectivity with time and the frequency of cycling between wet and dry conditions at a given location.

A useful adaptation of the heat maps is derived by assigning numerical values to the states (1 = dry, 2 = ponded, 3 = moderate flow, 4 = high flow) and calculating long term monthly averages. The plots produced by this method provide a single image for each river that summarises the long term intermittency behaviour, drawing attention to those features that are stable in time, occurring year in year out, or space, reliably at the same point along the channel.

Long term averages are calculated as medians (that is, the middle of all ranked observations in each month at each site) as these tend to highlight the hydrological state most commonly observed at that location at that time of year. This method integrates the flow intermittency signal across all values in the period of record, a perspective that is difficult to interpret from the heat maps alone. However, since monthly medians offer no information regarding the range of observations, mean graphs are also presented with the more graduated colours reflecting the variable nature of the sites across all years in the period of record. Standard deviation graphs highlight those months and locations where the greatest variability in observed hydrological state is observed from year to year.

2.5 Quantifying drying/wetting patterns

The characterisation of drying/wetting patterns with metrics is important because it allows the quantification of changes in time and in space, both along and between rivers. It complements the visualisation techniques by putting numbers to the patterns and by drawing out aspects that may not be apparent by visual inspection.

2.5.1 Landscape approach

Landscape metrics are widely used to describe the habitats provided by the variety of vegetation present in a study area. The metrics fall into two categories; composition metrics that describe the abundance of the various habitats in the landscape, and configuration metrics that describe the size and arrangement of patches of each habitat. The temporal dynamics of the metrics can then be used to explore how the landscape changes with time.

For this study, after Datry et al., (2016), the landscape approach has been applied to intermittent rivers using two assumptions. The first is that a hydrological state presents a habitat and it is a defining characteristic of intermittent rivers that some of these habitats are terrestrial and others aquatic. The second is that metrics defined for a two dimensional area may be adapted to describe a one dimensional length of channel. A selection of composition and configuration metrics has been adapted to capture the changing provision of aquatic and terrestrial habitats.

2.5.2 Calculation of metrics

The observation sites and the reaches they represent (Section 2.3.4) are used in three different ways to define spatial units for the derivation of metrics:

i) Number of sites – allows a simple count of the number of sites observed to be in each state;

ii) Reach length – allows the proportion of channel length of each state to be calculated;

iii) Patch length – the total length of channel in one state, comprising either a single or consecutive reaches.

The most appropriate spatial unit depends upon the feature of intermittency under consideration. The number of sites, for example, is useful in considering the variety of states observed or the fragmentation of the channel, whilst the distance between sites is required to calculate the overall habitat availability presented by a river. The third unit, a patch, is derived by identifying consecutive sites of the same state.

The selected metrics (see Sections 2.5.3 and 2.5.4 below) have been calculated for each observation date on each river using the most suitable spatial unit. If appropriate, they are also separated by hydrological state, although most represent all hydrological states in a single value.

2.5.3 Composition

Composition metrics provide a means to measure the variety and abundance of the hydrological states that exist along a river on a given date. The most important metric is arguably the abundance of each hydrological state observed, and this is most meaningful when derived from distances rather than number of sites. Combined metrics include richness, which is the number of states observed, and diversity, which is derived from the proportional abundance of each of these states. Since diversity scores can be difficult to interpret they are standardised into an evenness score which ranges from 0 to 1. A full list of composition metrics is detailed in Appendix D, and full populated tables are provided electronically (Deliverable D2.1). For the purposes of reporting and analysis, a selection from these metrics has been made to quantify the composition of the rivers. These are described in Table 3.

Table 3 *Composition metrics*

Metric	Definition	Interpretation
Abundance [Dry/Ponded/ Moderate flow/High flow]	Length of river in each hydrological state	If 5.5km is moderate flow and 4.5km is dry, just over half of the river's survey length was observed to be flowing and the remainder was dry.
Relative abundance [Dry/Ponded/ Moderate flow/High flow]	Proportion of river length in each hydrological state	If 55% for moderate flow and 45% for dry, just over half of the river's survey length was observed to be flowing and the remainder was dry.
Evenness	Standardised measure of state diversity	If equal to one, each of the states present is equally abundant. If close to zero, one of the states was very dominant e.g. mostly moderate flow.

2.5.4 Configuration

In the landscape approach, configuration metrics are used to quantify the size and spatial arrangement of patches of habitat. When applied to a river, a patch is defined as a run of spatially contiguous sites observed to be in the same hydrological state (Section 2.5.2). The observation sites were therefore first grouped spatially at each observation date to form patches. Configuration metrics were then selected to quantify the length, fragmentation and connectivity of the patches as they lie along the river at a given time (see Table **4**). As for the composition metrics, the full list of configuration metrics is detailed in Appendix D and provided electronically in Deliverable D2.1.

Since a river with low patch length is one that is highly fragmented, these two metrics are inversely related. However, the relationship varies between rivers since patch length is a measure of the distance of unbroken hydrological states, whereas fragmentation is a standardised metric concerned with the number of changes of state along the channel. Lotic connectivity is the length of flowing reach (moderate or high flow) that is available to fish and other mobile aquatic taxa, subject to other barriers to movement.

Table 4 *Configuration metrics*

Metric	Definition	Interpretation
Mean patch length (km)	Mean length of all patches	If there are just two patches, the lower 5.5km of the river flowing and the upper 4.5km dry, the mean reach length is 5.0km.
Fragmentation	Number of changes in state (edges) as a proportion of the maximum possible number of edges	One means there is a change of hydrological state at every site going downstream, zero means there are no changes of state.
Lotic connectivity (km)	Total length of flowing reach (moderate or high flow) stretching upstream from the most downstream site	Lotic connectivity of 5km means this length of flowing channel is available to fish and other mobile taxa, subject to other barriers.

2.6 Temporal analysis

The visualisations and metrics are used to demonstrate some simple analyses of the behaviour of the rivers in relation to time, both long term average and temporal dynamics.

Metrics have valuable application in quantifying the long term conditions both of the survey area as a whole and of the differences in hydrological behaviour between the surveyed rivers. The mean value of selected metrics is presented, with abundance expressed in absolute terms (km) rather than relative so that the total availability of the various states is quantified. Richness is included to assist in the interpretation of the evenness scores.

When calculated for each observation date in turn, the metrics allow quantification, and by charting, visualisation of the changes in composition and configuration with time.

2.7 Response to drought and drivers

Exploring response to drought and drivers is an important step in separating the natural and artificial causes of drying. The drivers in question in this context are not those of policy such as the Water Framework Directive, but agents of change, that is, inputs to a system that when varied, result in variations in the outputs. In the study of IRES as for any river, the drivers may be both natural, such as rainfall and groundwater level, and/or artificial such as abstractions and discharges.

The metrics calculated for this study are a tool that can be used to compare the severity of the impact of drought periods upon the rivers. This is demonstrated by comparing all ten of the surveyed rivers during the dry winter of 2016/2017 to a previous dry period (2005/2006) using relative abundance by distance as a metric.

Similarly simple analysis of the response to drivers is demonstrated by visual inspection, comparing the temporal dynamics of the proportion of flowing channel of the Misbourne with time series of with rainfall, effective rainfall, groundwater level measured at a nearby observation borehole and gauged river flow. Monthly mean heat maps on the Bulbourne illustrate their use as a tool to investigate the extent and timing of drying caused by abstraction.

3 Results

3.1 Survey completeness

3.1.1 Temporal frequency

The visualisation of the number of surveys conducted in each calendar month reveals the considerable cumulative effort by Area hydrologists in compiling the dataset (Figure 2). It is apparent that since 2005, observations have been made regularly, on both the Colne and Lee survey routes, with an increased frequency during the drought of 2005-2006. In the earlier surveys (pre-2001) although less regular, the same operational reaction to extreme events is seen during the drought and recovery of 1997-1998 and to a lesser extent during the groundwater flooding of winter 2000-2001. The lower frequency of observations from 2002-2004 reflects a quieter hydrological period with no notable extremes that served to raise awareness and therefore resource availability. Inevitably, resources pressures are a factor in observation frequency, as seen in the gaps in the Lee survey from 2014 until 2016.

Figure 2 *Observation frequency*

3.1.2 Spatial extent

The total length of the surveyed rivers ranges from 14km (Bulbourne) to 46km (Stort), and the proportion surveyed from 38% (Gade) to 99% (Rib). The assumption made in designing the routes is that below the survey limit, the rivers flow perennially. On some rivers, notably the Chess, the Gade and the Stort (see Figure 3) this perennial reach is a significant proportion of the river. The benefit of the focus on the intermittent reaches is that the results are more sensitive to changes in the wetting and drying patterns than they would be if the perennial reach was included. However, on rivers where the survey length as a proportion of total length is high, notably the Rib, Beane, Ver and Ash, the results presented will be a better representation of the river as a whole.

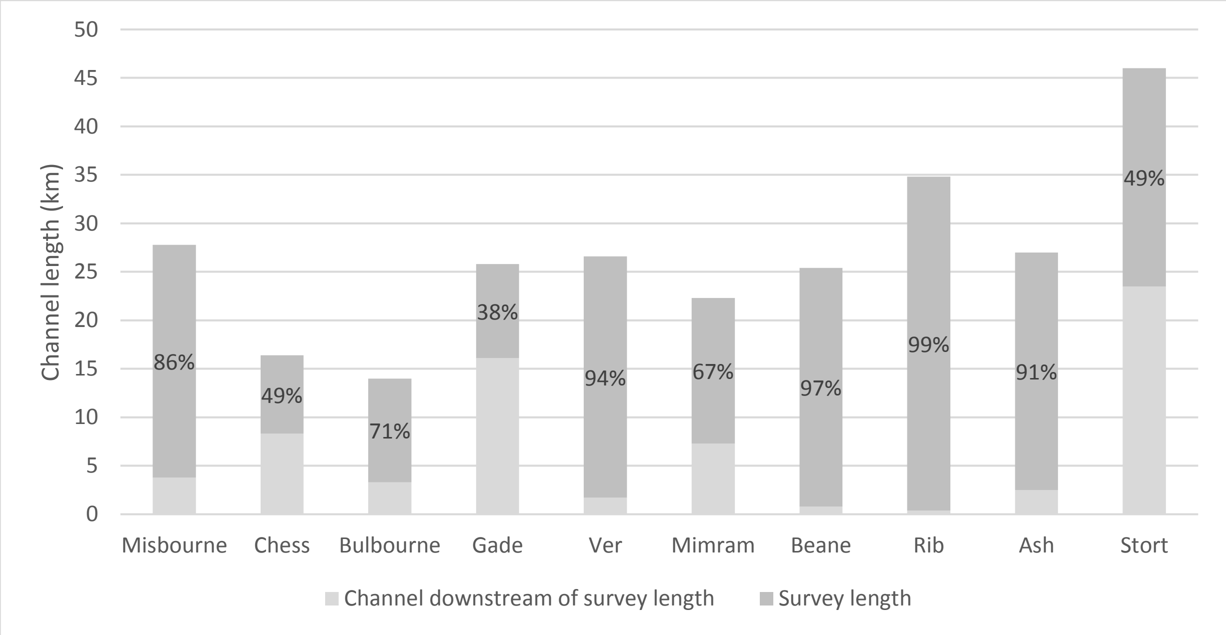


***Figure 3** Survey length (dark grey) as a percentage of total channel length from source to confluence*

3.2 Visualising drying/wetting patterns

3.2.1 Observation heat maps

An example of an observation heat map is presented in Figure 4, displaying the observed states at each site on each survey date for the Ash. Whilst the lower half of the survey length is usually observed to be flowing, the upper half experiences frequent cycling between dry, ponded and flowing conditions. In the early part of the record, there are fewer observations of ponding; this may be an accurate record of the conditions in the 1997/1998 dry period, or reflect less robust standardisation in survey procedures.

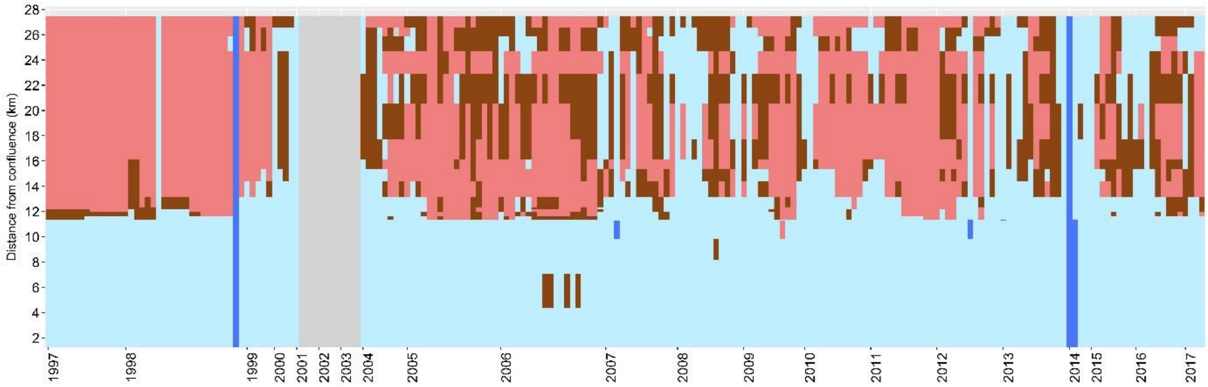


Figure 4 *Observation heat map for the River Ash*

Observation heat maps for all ten rivers are presented in Appendix B. Where there is a strong annual cycle of wetting and drying in the upper reaches, this is seen in the migration of the boundary between wet and dry, for example from 2007 until 2011 on the Chess and the Bulbourne. There is a marked difference in heat maps of the Colne and Lee catchments, with greater fragmentation and more ponding seen in the latter. This reflects the greater coverage of clay and drift deposits in the Lee, which provide a flashier response to rainfall and cause puddles to form on the river bed.

Temporal variation is also graphically displayed, with droughts such as 1997-1998 and 2005-2006 clearly seen in the Colne catchment with a greater proportion of the channel length shaded pink. Taking a horizontal slice along a heat map provides information on the frequency and duration of drying encountered at a given site. Many of the sites on the Gade, unlike the Ash, stay in the same hydrological state for years at a time. Hence the suitability of a site for a given species, or for the development of a food web is pictorially represented with potential for the overlaying of ecological data.

Similarly, taking a vertical slice through a heat map reveals the longitudinal connectivity of a river. On the Bulbourne, all reaches downstream of the source are usually flowing and connected, and all reaches upstream dry. On the Misbourne, the whole length of the river flows during wet years such as 2001 and 2014, but during more average conditions, the mid reaches dry, often bounded by ponding. Dry reaches may develop downstream of the source on a groundwater-fed river when a discontinuity between groundwater and river interrupts the supply of baseflow to the river. This can result from natural causes, such as infiltration through a permeable bed as the river flows over dry gravels or geological strata, or from artificial causes such as local drawdown of groundwater level in response to abstraction, or movement of the river away from the valley bottom. Ecologically, this phenomenon favours those taxa able to migrate, and there are implications for methods of recolonization, as flow returns both from upstream refuges and from perennial reaches downstream.

3.2.2 Monthly average heat maps

3.2.2.1 Median

The monthly average heat maps for the Chess, Bulbourne and Gade exhibit a pronounced seasonal cycle in the extent of flow intermittency (Figure 5a), with flowing patches progressing upstream through the winter and spring and tracking downstream during the summer and autumn. The intermittent behaviour of the Rib, Ash and Stort (Figure 5b) is perhaps less typical of Chalk streams. On these rivers there is no obvious seasonal cycle, though the monthly average heat maps highlight the occurrence of protracted summer and autumn drying through the upper reaches, though a return to flowing conditions of almost the entire river in the winter half-year.

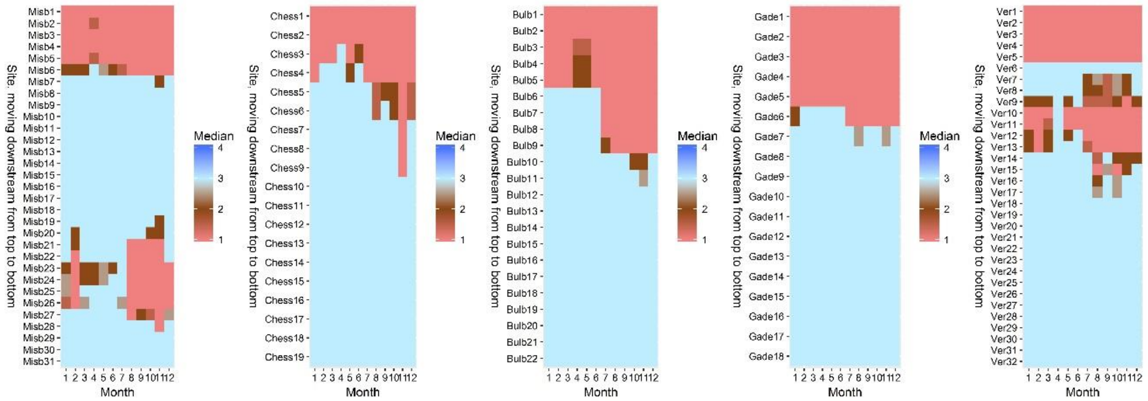


Figure 5a *Monthly median heat maps for the Colne catchments (left to right: Misbourne, Chess, Bulbourne, Gade and Ver)*

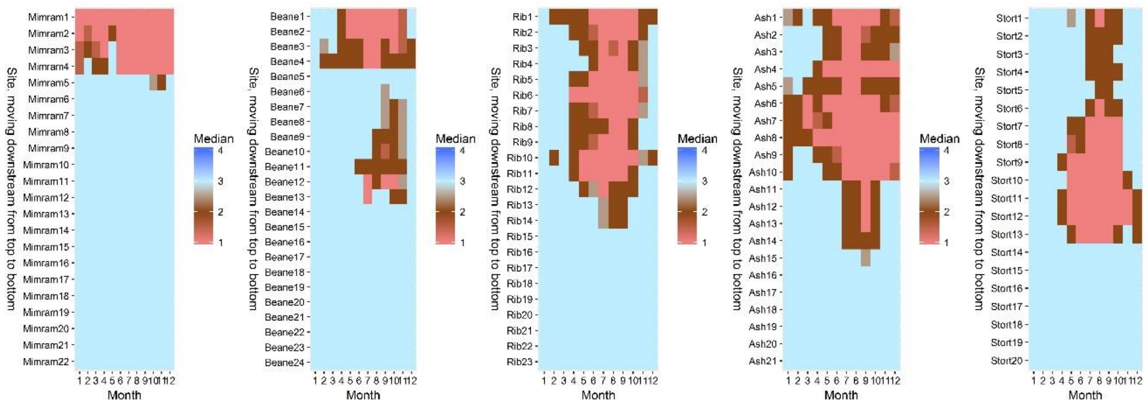


Figure 5b *Monthly median heat maps for the Lee catchments (left to right: Mimram, Beane, Rib, Ash and Stort)*

3.2.2.2 Mean and standard deviation

Whilst the seasonal cycle exhibited on the Chess, Bulbourne and Gade is still observed (Figure 6a), the annual variability in the downstream extent of ponding and drying is not as straightforward as indicated by the median graphs. Particularly for the summer months, there are few sharply defined horizons between ponding and flowing. Ponding in winter months downstream on the Misbourne is observed to be a much more common occurrence (Figure 6a), and the funnel shape illustrated suggests the expansion of this feature both upstream and downstream as the year progresses.

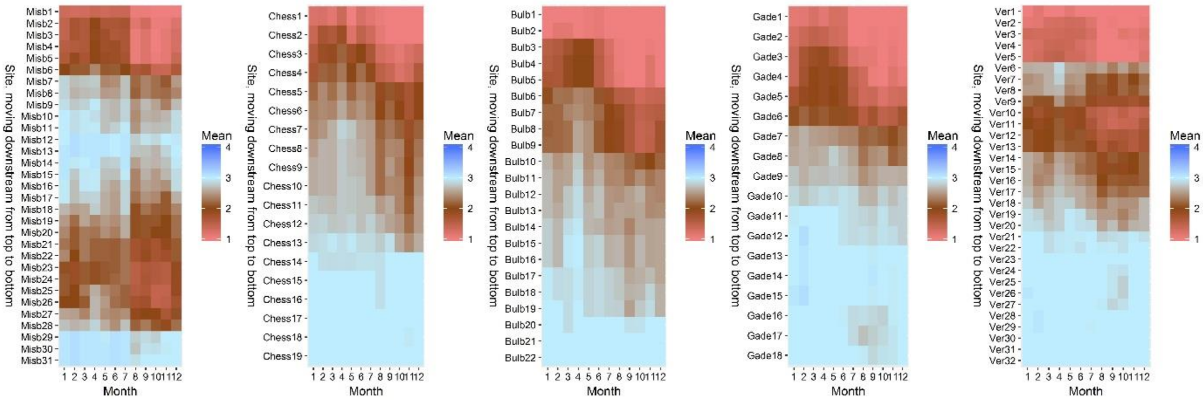


Figure 6a *Monthly mean heat maps for the Colne catchments (left to right: Misbourne, Chess, Bulbourne, Gade and Ver)*

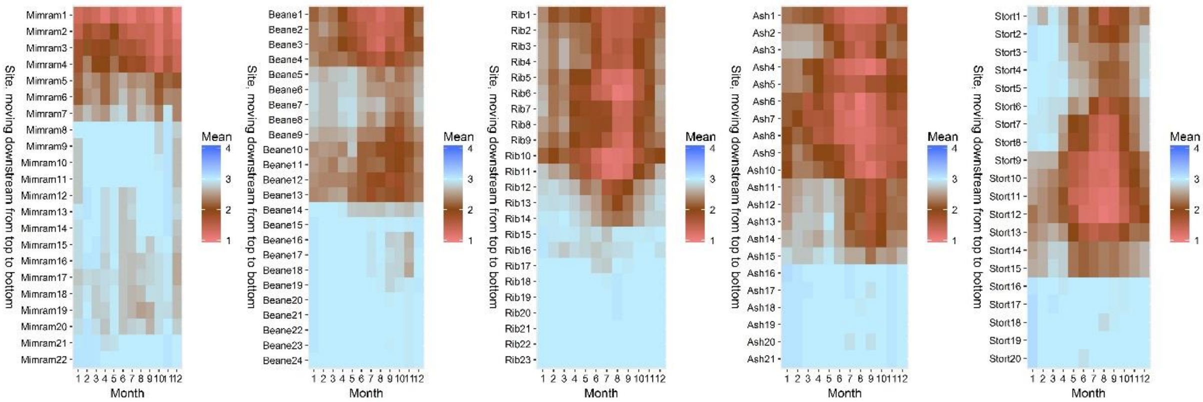


Figure 6b *Monthly mean heat maps for the Lee catchments (left to right: Mimram, Beane, Rib, Ash and Stort)*

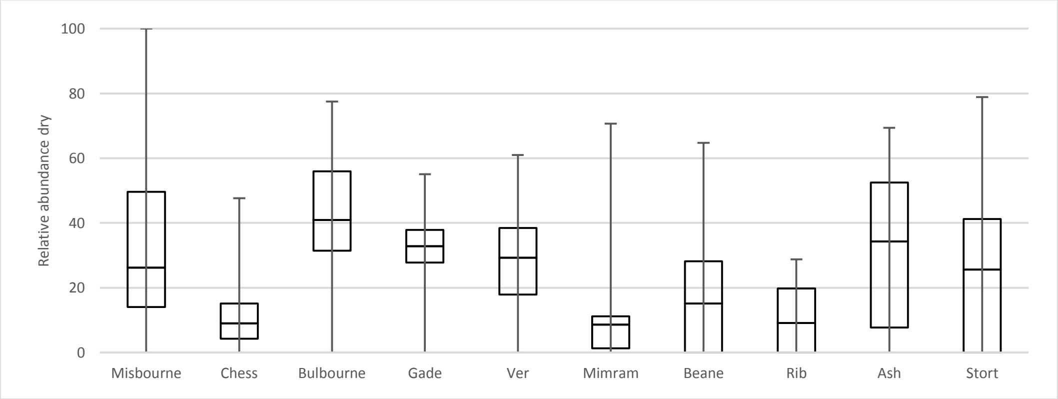
Similarly, the mean heat maps for the Rib, Ash and Stort are also more variable than first understood (Figure 6b). For example, on the Mimram, the median heat maps restricts drying to the upper reaches, whereas the mean reveals occasional observation of dry reaches along the length of the surveyed channel. The accompanying standard deviation heat maps (Appendix C) help to interpret such variability of the rivers in both space and time.

3.3 Quantifying drying/wetting patterns

3.3.1 Composition

The distributions of the selected composition metrics (Table 3) are summarised in Figure 7. On each of the ten rivers, the dry and moderate flow states dominate, and observations of high flow are rare but as visualised in the heat maps, may extend along 100% of the survey length (the Misbourne, Mimram and Ash). Ponding accounts for only 6.9% of the total number of observations (Table 2) and the abundance metric shows that these are predominantly on the Beane, the Rib, the Ash and the Stort.

a)



b)

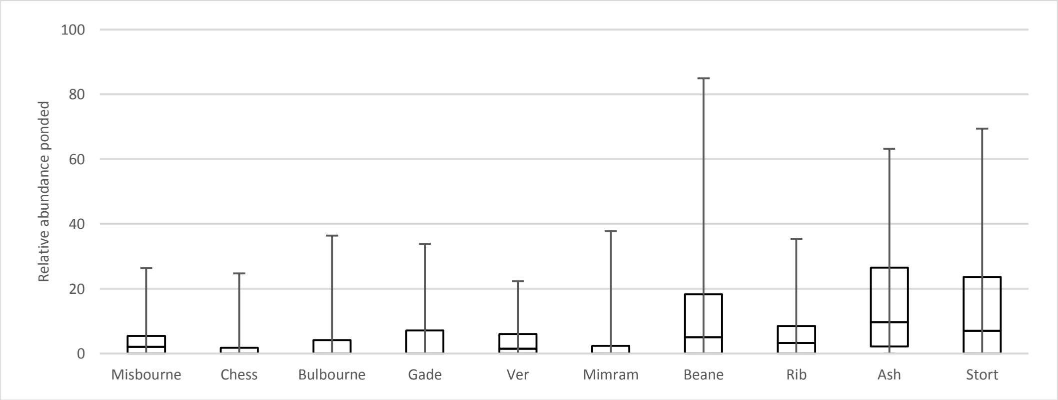
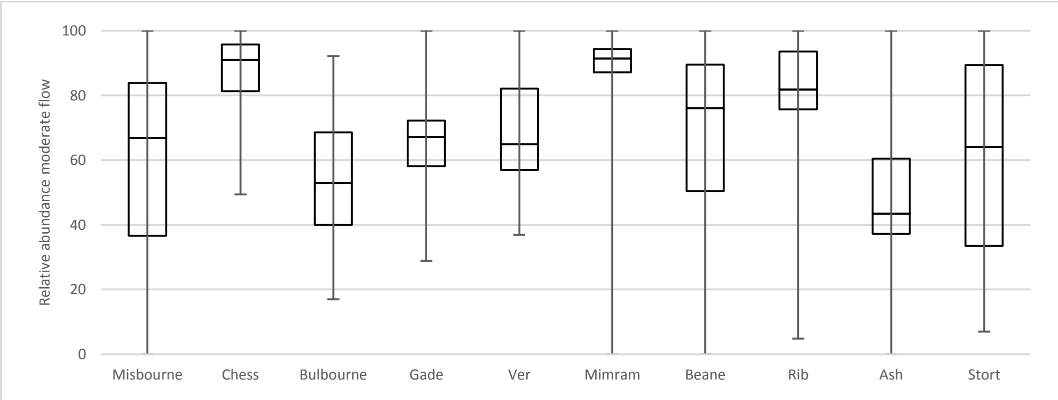
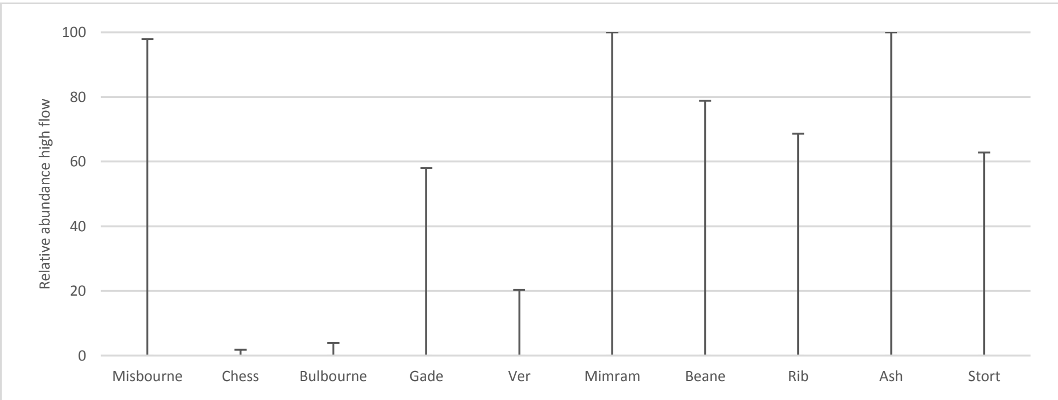


Figure 7 *Distribution plots of composition metrics showing median, interquartile range, maximum and minimum of all observations during period of record for relative abundance of a) dry b) ponded (contd)*

c)



d)



e)

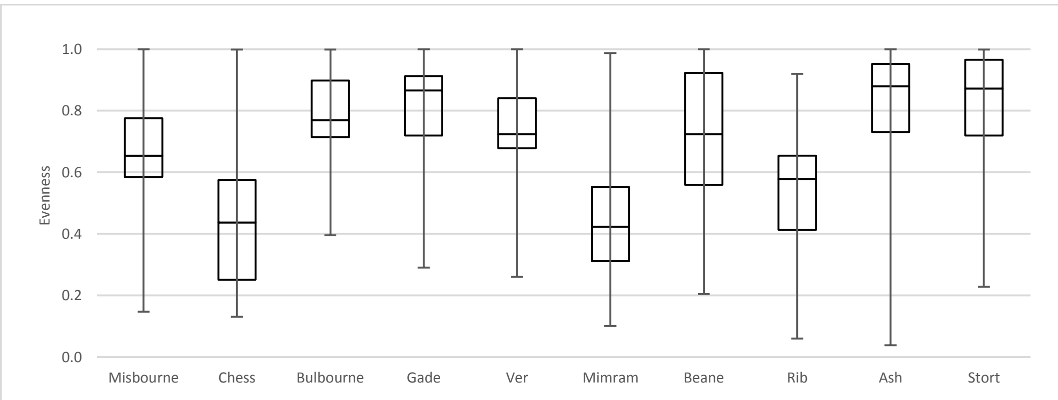


Figure 7 *(contd) Distribution plots of composition metrics showing median, interquartile range, maximum and minimum of all observations during period of record for relative abundance of c) moderate flow d) high flow states and e) evenness.*

The length of the box is an indication of the variability in the metrics and the less responsive rivers such as the Gade, Chess and Mimram can therefore be identified numerically in this way.

The relative abundance metrics of the states present on a given day (richness) are combined into a single measure in the evenness score. This is equal to one if the states are all equally present by distance, and approaches zero if one of the states is dominant. Richness scores on average over the period record are between 2.3 and 2.6 on all rivers. This means that there are between two and three of the four states possible represented at any one time. On the Chess and the Mimram, the boxes representing the interquartile range in evenness (from the 25th to the 75th percentile) sit lower than for the other rivers because they are often dominated by a single state (moderate flow, drying only rarely at the lowest sites). By contrast, the high position of the box for the Ash shows that it can be relied upon to provide a variety of habitats, whilst the Beane which has a larger evenness range, is more likely to flow along its length than the Ash.

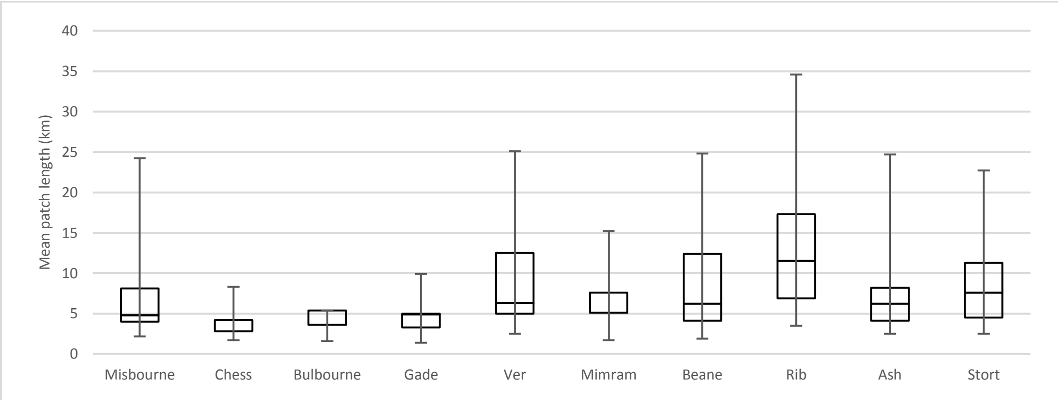
3.3.2 Configuration

The distributions of the selected configuration metrics (Table 4) are summarised in Figure 8.

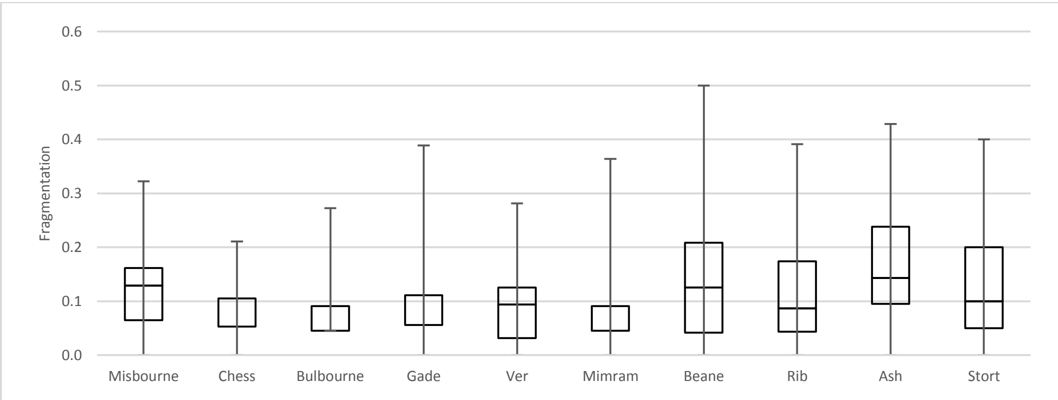
The average (median) fragmentation scores do not reveal as great a difference as might be expected between the clay-influenced and groundwater-dominated rivers. Each has a median fragmentation between 0.05 and 0.14, which means that between 5 and 14% of the sites have a different hydrological state to the neighbouring site downstream. The reason for this is seen in the marked difference in its interquartile range which is much greater for example on the Ash and Stort than on the Ver and Mimram. Where only one box is shown, this means that the variability is notably low as either the 75th or 25th percentile has the same value as the median.

The pattern in mean patch length is similar but includes the influence of survey length. The Ver, for example, has a large range in patch length despite its low fragmentation because it is one of the longest rivers in the survey. This is also a factor in the lotic connectivity where the Ver's high scores arise from its long length and low fragmentation. However, the influence of the location of the downstream observation site is also a strong influence on this metric (see Section 2.3.4) as seen on the Rib where the surveyed channel includes a significant section of perennial flow.

a)



b)



c)

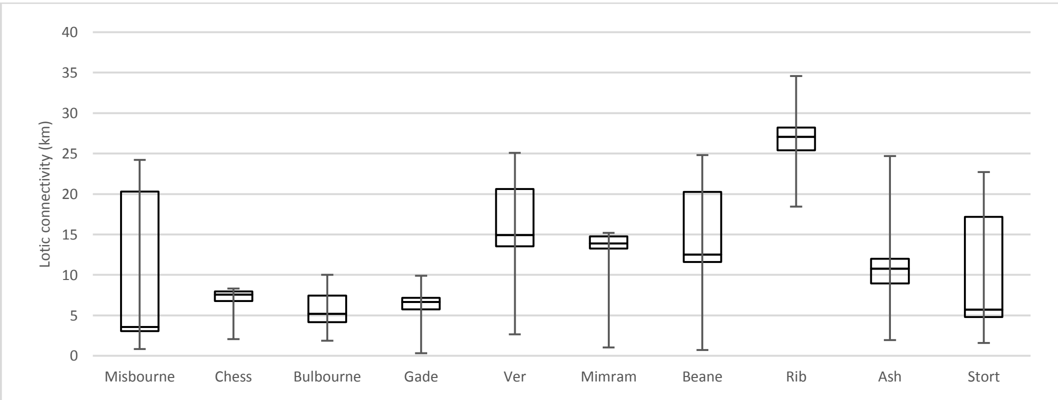


Figure 8 *Distribution plots of configuration metrics showing median, interquartile range, maximum and minimum of all observations during period of record for relative abundance of a) mean patch b) fragmentation and c) lotic connectivity.*

3.4 Temporal analysis

3.4.1 Long term average conditions

The overall balance of hydrological conditions along the total length of surveyed channel is roughly two-thirds flowing to one-third non-flowing; on average, 140km is flowing, 14km ponded and 47km dry (Table 5).

The long term fragmentation values range from 0.08 for the more groundwater-dominated rivers such as the Gade and Chess, to 0.16 for the highly fragmented Ash. A threshold of around 0.10, which means that on average 10% of the sites surveyed have a different hydrological state to the next site downstream, separates the Colne tributaries from the more clay-influenced tributaries of the Lee.

Limitations of the metrics in comparing rivers in this way and in the distribution plots of Section 3.3 arise from the differences in the location of the observation sites and dates. With respect to the sites, for example, where the farthest downstream observation point is located some distance into the perennial reach, as seen on the Rib, there is an over-representation of flowing conditions in comparison to other rivers. This is a result of the decision to focus on the intermittent reaches, as introduced in Section 2.3.4. and is therefore an issue implicit in the study of intermittent streams. With respect to the observation dates, since the metrics are calculated using the whole dataset, they contain a bias towards periods of more frequent observation. For example, the continuation of observations on the Beane during 2002 and into 2003 when no other rivers were surveyed (Section 2.3.4) will have biased the metrics towards normal hydrological conditions. Similarly, the increase in observation frequency during 1997 and 1998 will skew metrics calculated from the whole dataset towards dry conditions, in comparison to metrics if calculated from a monthly dataset. This illustrates the need for such a dataset, as raised in Section 2.2.4 which would remove such bias in comparing rivers, and in the dataset as a whole.

Table 5 *Long term average metrics over the whole observation period*

	Composition						Configuration			
	Total length (km)									
	High flow	Moderate flow	Ponded	Dry	Richness	Evenness	Patch length (km)	Edge density (km^{-1})	Fragmentation	Lotic connectivity (km)
Misbourne	0.9	14.5	0.8	7.9	2.6	0.6	7.4	0.13	0.11	9.4
Chess	0.0	7.3	0.1	0.9	2.3	0.4	3.7	0.18	0.08	7.3
Bulbourne	0.0	5.9	0.3	4.6	2.4	0.8	4.5	0.15	0.08	5.8
Gade	0.0	6.5	0.4	2.9	2.4	0.8	4.3	0.16	0.09	6.4
Ver	0.1	16.9	0.9	7.3	2.6	0.7	7.4	0.12	0.10	16.0
Mimram	0.2	13.0	0.4	1.6	2.3	0.4	6.6	0.12	0.08	12.3
Beane	0.2	17.6	2.6	4.3	2.5	0.7	9.3	0.12	0.13	15.8
Rib	0.1	28.9	1.9	3.6	2.5	0.5	13.1	0.08	0.12	27.9
Ash	0.3	13.0	3.7	7.7	2.6	0.8	7.7	0.14	0.16	11.8
Stort	0.2	14.0	2.9	5.6	2.4	0.8	9.6	0.11	0.12	9.9

3.4.2 Temporal dynamics

Figure 9 is a Summary Sheet of the key metrics for the Ver starting with a reproduction of the heat map to display the raw data (Figure 9a).

Composition is represented by relative abundance and evenness. The chart of relative abundance (Figure 9b) is similar to the heat map but presents a clearer snapshot of the hydrological states occurring on the river since they are no longer fragmented vertically, that is, along the river and are calculated for reach length rather than numbers of sites. The wet water years of (2000/2001 and 2013/2014) and dry years (1997/1998, 2005/2006, 2011/2012 and 2016/2017) are readily identified in the appearance of dark blue at the bottom of the chart and the dominance of pink at the top of the chart respectively.

Evenness (Figure 9c) is seen to approach its maximum value of 1 when the lengths of hydrological states observed on a given date are similar. This occurs during dry periods when the source has migrated half way down the surveyed channel of the Ver. The metric may be thought of as a standardised indicator of diversity of habitat. When it is low, for example in spring 2014 when the Ver had moderate flow along the majority of its length, there is less variability in the habitats available for mobile specialists to exploit.

The remaining three plots are configuration metrics. Mean patch length (Figure **9**d) and fragmentation (Figure 9e) show similarities in temporal dynamics to those of evenness with some periods of stability such as the autumn and winter of 2014/2015 when the source did not move and others of greater variability such as 2009 when the development of ponding in the dry upper reaches was intermittent. Both metrics are derived from changes in state along the channel, with mean patch length incorporating distance, and an inverse relationship therefore exists between them. For example in 2005, when the Ver was highly fragmented at 20%, mean patch length was at its lowest, at around 5km.

The lotic connectivity (Figure 9f) quantifies the flowing area under the relative abundance plot. On the Ver it was at its shortest of 2.7km in the summer of 1997 when a dry patch developed in the normally perennial reaches towards the bottom of the surveyed channel. The timing of variations in this metric may be critical for fish needing to reach a spawning ground at certain time of year.

The summary sheets can be used to explore the frequency and duration of drying/wetting at a given site with ecological relevance in the suitability for aquatic and terrestrial species and intermittent flow specialists. For example, at the top of the Ver, there are only three short periods of inundation during the period of record, of no more than six months each. This may provide a habitat for a resilient terrestrial species that can tolerate the inundation. Further downstream, many sites cease to flow during dry periods for months if not years at a time. Similarly, aquatic species that are able to tolerate the drying or quickly recolonise following a return of flowing water may thrive.

The development of a monthly dataset would allow further analysis of temporal dynamics and seasonality. The temporal equivalent of abundance, for example, is the proportion of time that a site is observed to have a given hydrological state. This is known as flow/dry/pooling permanence (Gallart et al., 2017). Seasonality could be explored by calculating long term monthly averages in any of the spatial composition or configuration metrics. This would allow exploration of unseasonal behaviour by comparison of the observations with the long term monthly averages. Without a monthly dataset, analysis of temporal cycling in the intermittency patterns is largely restricted to visual interpretation.

A full set of summary sheets is presented in Appendix E and drivers of changes in metrics with time, both natural and artificial, are further explored in Section 3.5.

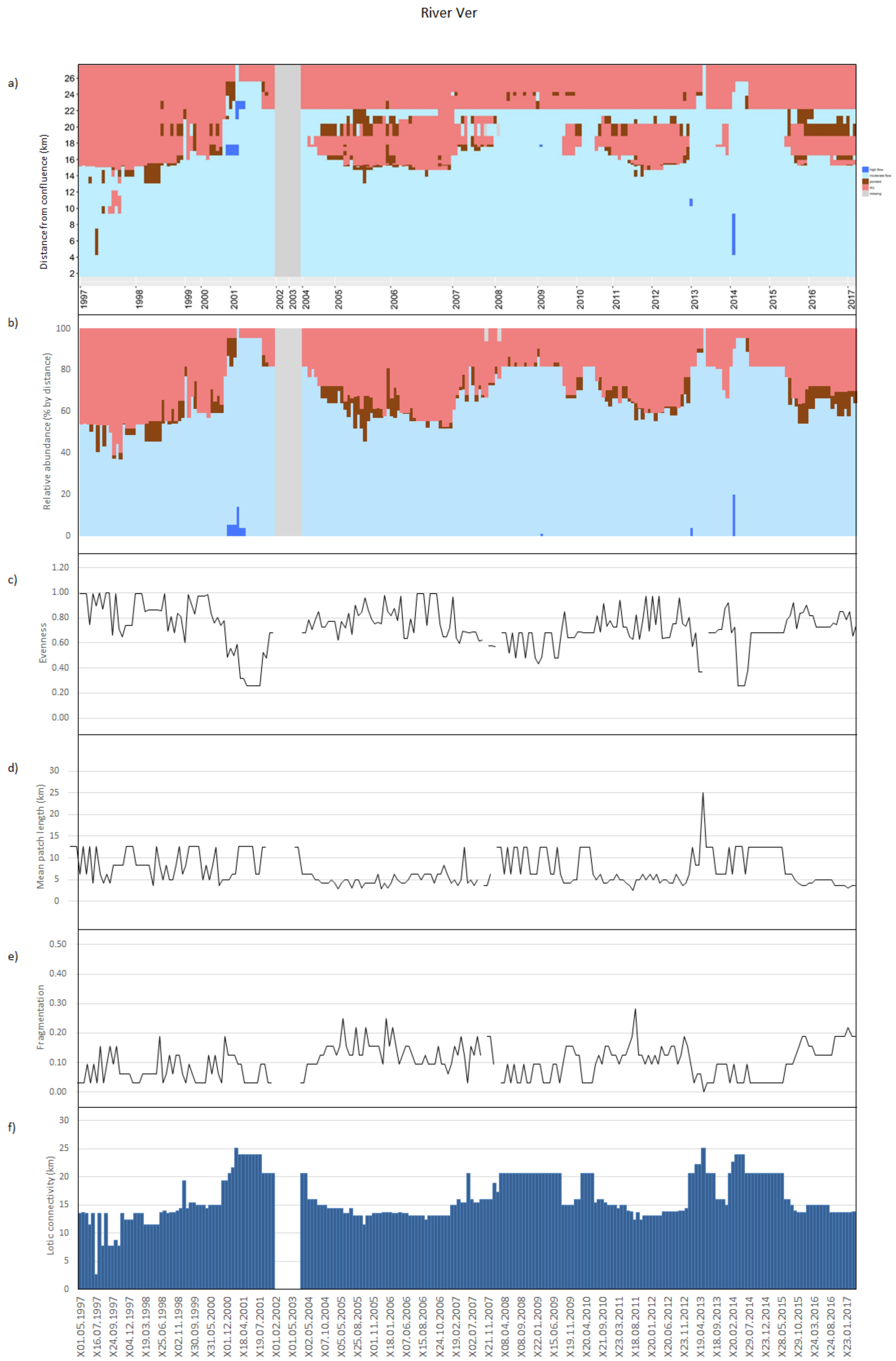


Figure 9 *Summary Sheet for the River Ver*

3.5 Response to drought and drivers

3.5.1 Drought

The use of metrics in quantifying the response of intermittent rivers to drought is demonstrated by comparing the relative abundance of hydrological states on all ten of the surveyed rivers during the dry winter of 2016/2017 to the previous dry period of 2005/2006 (Figure 10).

At the start of the winter recharge period, in October, the abundance patterns in the Lee tributaries such as the Ash and the Stort were similar in 2005 and 2017. In the Colne, by contrast, the rivers in October 2005 were already showing the effects of the previous dry winter (2004/2005), most notably on the Misbourne and the Chess which were dry along at least 40% of their survey length, in comparison to 20% in October 2017. As the dry winters continued with scant recharge of groundwater resources, there was little improvement in the Colne tributaries by the Januaries of 2006 or 2017. However, in the clay-influenced Lee tributaries, rainfall in January 2017 brought a marked reduction in the proportion of dry channel and concomitant increase in pooling. By March, whilst the occurrence of pooling was less in 2017 than in 2006, the differences in channel dryness between the two events are less marked. The suggestion is that conditions following the dry winter of 2016/2017 are not as severe as they were in March 2006 although it is likely that the impact of a second dry winter in 2017/2018 would be similarly, if not more significant.

***Figure 10** Response of relative abundance to drought, comparing 2005/2006 with 2016/2017*

3.5.2 Natural drivers

Figure 11 shows the proportion of flowing channel of the Misbourne plotted with rainfall, effective rainfall, groundwater level measured at a nearby observation borehole and gauged river flow.

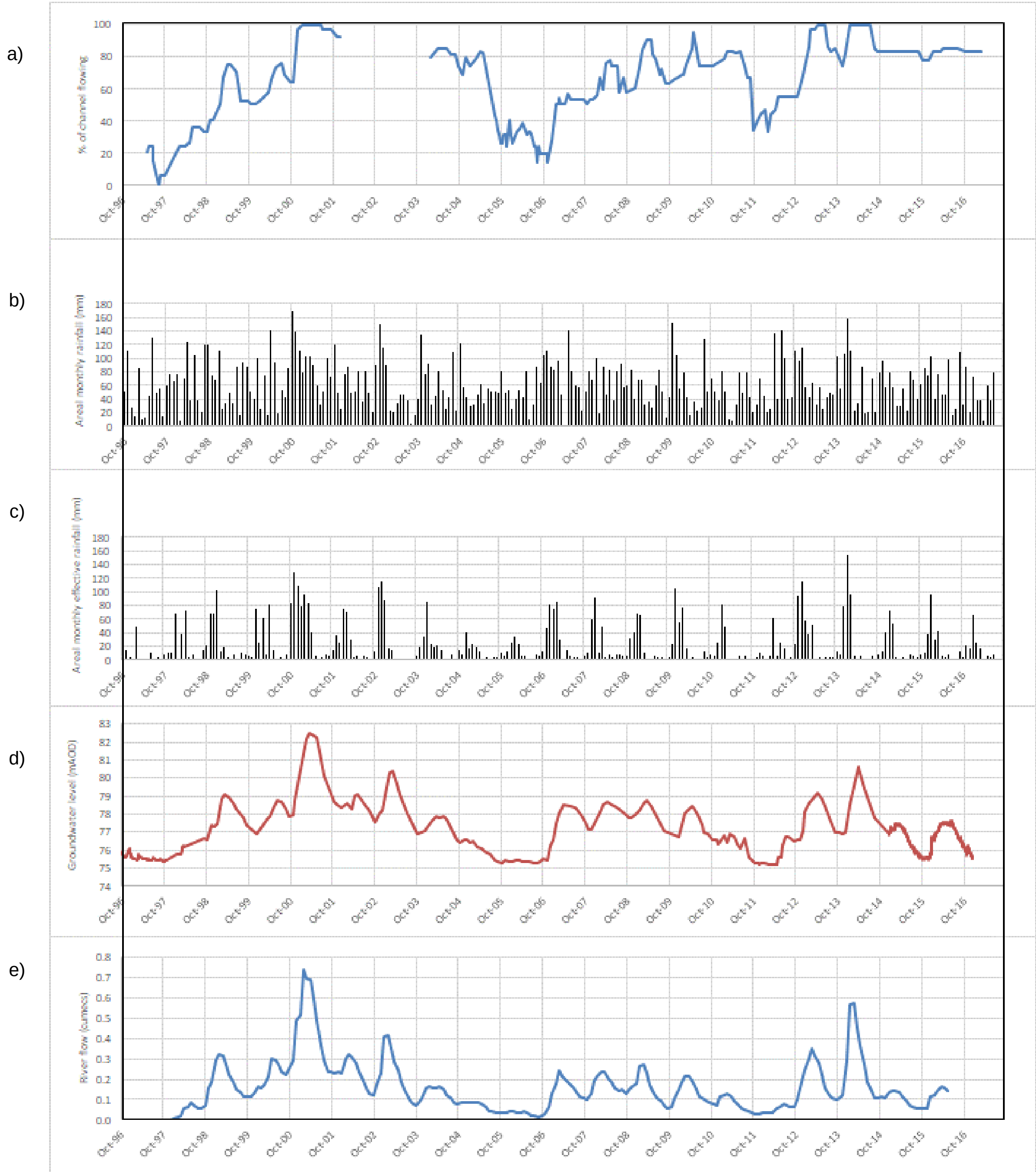


***Figure 11** Misbourne catchment a) relative abundance of flowing river channel, b) daily and c) effective rainfall for Chilterns East Colne rainfall unit, d) groundwater level at borehole Amersham Road (SU99/67) and e) river flow gauged at Little Missenden (local number 2873TH, NRFA number 39127).*

During periods when the rainfall is effective in recharging groundwater resources, the groundwater level responds, and river flows in turn increase. Whilst the proportion of flowing channel increases during these same recharge periods, the correlation is not as marked, and there are clearly other drivers having an influence. Statistical analysis would be required to assess the amount of the variability accounted for by changes in monthly rainfall. However, it may be anticipated that the rate of change during dry periods is not simply a function of natural drivers, but is also affected by the movement of the parts of the channel away from the valley bottom for mill workings affecting the continuity between the river and its source of baseflow.

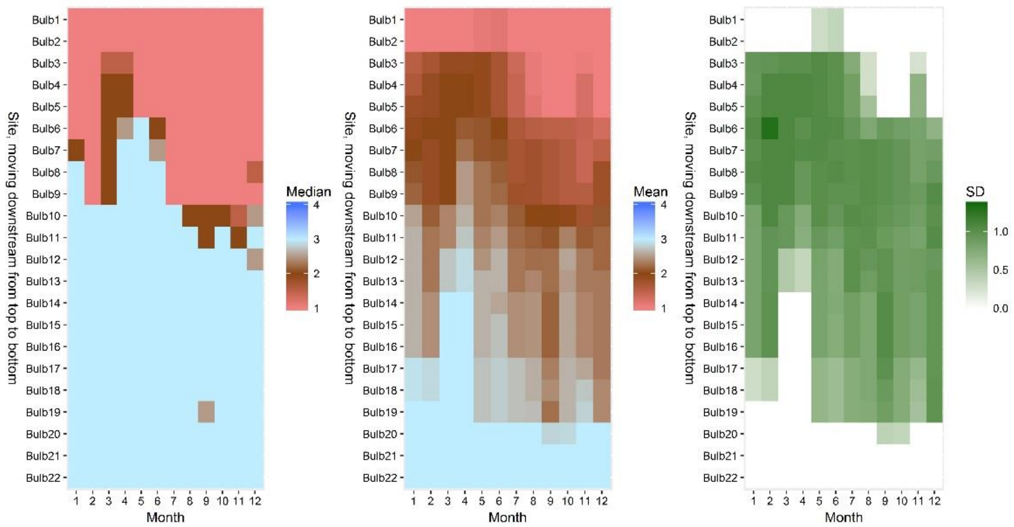
It should be noted that the availability of both gauged river flows and observations of hydrological state has been noted as rare and desirable (Gallart et al., 2017) and it is recommended that further analysis is conducted using this study area to investigate the relationship between the two.

3.5.3 Artificial influence

Since there has been no attempt to remove artificial influences in the recording of observations, the heat maps include the impact of abstractions and discharges as well as historical alterations for mill workings as suggested on the Misbourne. Continuous discharges such as those from a sewage treatment works may be readily identified by a lack of temporal variation in the location of an edge (boundary between two hydrological states), with dry conditions upstream and flow downstream. A good example is on the Ver (Appendix B), where flow continues in the upper reaches even after the natural source has migrated well downstream. This creates an artificially perennial reach.

The impacts of groundwater abstraction are harder to identify as they are usually more distributed in time and space. Furthermore, there is only one instance in the dataset of a large change in abstraction with sufficient periods both before and after the change for analysis. This is on the Bulbourne where a large abstraction at the top of the catchment was switched off in 2010. Monthly average heat maps using the observations before and after this date (Figure 12) show that the numerical value of the mean hydrological state (Section 2.4) is lower and with more variability in the mid reaches before 2010 than after 2010. However, since the period prior to 2010 is both longer, and contains more dry events than the period since 2010, it is not possible to identify whether these effects are the result of a reduction in abstraction. The selection of hydrologically similar periods of the same length would reduce this impact of the natural drivers. There are currently significant changes in abstractions underway in the catchments of the Misbourne and the Ver, and it is recommended that the surveys continue to allow analysis of the natural and artificial causes of drying in this way.

a)



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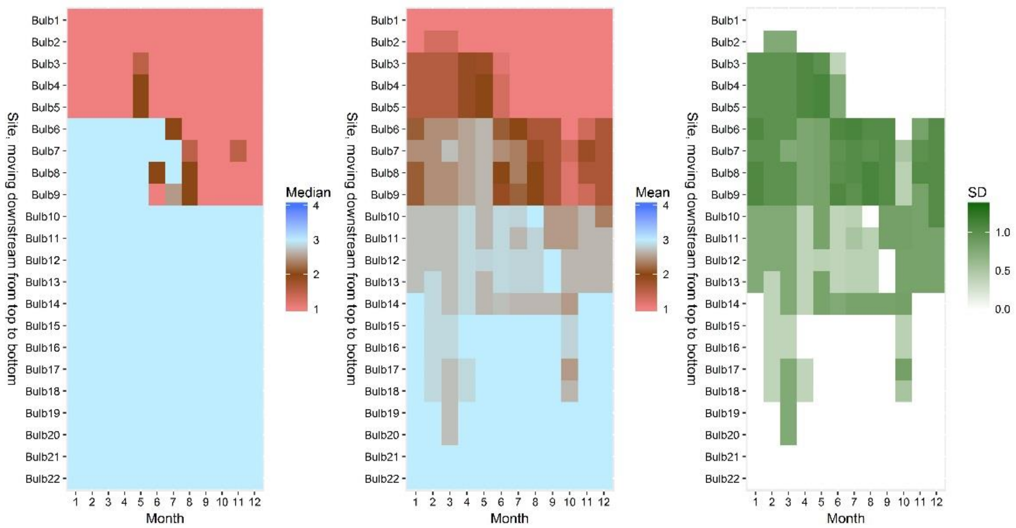

Figure 12 *Monthly average heat maps a) before and b) after abstraction reduction in the Bulbourne catchment*

4 Conclusions

The Springs and Sources dataset, notwithstanding its qualitative nature, is uniquely valuable in the UK, and even in an international context. No other published monitoring programmes of IRES can match its spatial extent longitudinally over ten rivers, its temporal extent from 1997 to date, or its continuity, covering all twelve months of the year. These features provide a rare opportunity that should be exploited to explore both the temporal and spatial variability in flow intermittence patterns and to contribute to the scientific study of these neglected watercourses that comprise more than half of the world's river network.

Methods of visualising and quantifying the drying and wetting patterns of the rivers have been presented with results that demonstrate the utility of the dataset. However, these methods are only a first step in assessing the challenge presented by IRES, and of water resource activities upon them. For example, monthly heat maps presented for the Bulbourne before and after a change in abstraction highlight the challenge of accounting for the compounding effect of natural drying, and charted metrics for the Misbourne alongside the natural drivers of groundwater level and effective rainfall visually indicate but do not quantify the interference of artificial influence. The separation of natural and artificial causes of drying is complex, not least in systems influenced by historical mill workings. The application of regional groundwater models, although capturing the timing and seasonality of source migration and accounting for artificial influences (Atkins, 2007), is limited by the small size of the headwater streams and their sensitivity to changes in groundwater level that are within the calibration tolerance of the model (Sefton, 2013). The further development of tools is needed that will separate and quantify the natural and artificial drying of these watercourses.

An additional challenge in the assessment of water resource activities is that flow compliance with the Water Framework Directive is currently defined at Q95, the flow that is exceeded 95% of the time, which is often zero on an intermittent river or ephemeral stream. A scientifically robust definition that is tailored to IRES is required, to support area water resources hydrologists in assessing the impact of abstraction. The overlaying of ecological monitoring data with the Springs and Sources dataset is a first step in the development of such standards and the assessment of the impact of artificial influences upon IRES ecology.

Further research questions that can be addressed using this dataset include the relationship between hydrological state and gauged flows. The opportunity is presented to derive statistical models for the study catchments and investigate the feasibility of estimating intermittency metrics from gauged or estimated flows. It may be anticipated that geological and meteorological information would also be required in the regionalisation of this approach which, although challenging, has the potential to address the question of the scale of the challenge presented by IRES. Another research topic that could be addressed is the occurrence of unseasonal hydrological behaviour which has implications for the timing of habitats made available to the stream ecology (Westwood, 2013). The extraction of a monthly time series from the Springs and Sources dataset would be required, allowing numerical assessment of seasonality in the wetting and drying patterns.

Operationally, the foresight and dedication of the area hydrologists and decision-makers in collecting this dataset is commended. The value of observations of this type which are new to many hydrologists has been demonstrated, and it is recommended that the surveys continue, and procedures reviewed with a view to training hydrologists and collecting these data in other parts of the country where water resource assessments on IRES are required.

5 Recommendations

1. The extraction of a monthly time series from the Springs and Sources data, for example by selecting from or by weighting observations, would remove the implicit bias that exists in the data because of irregular survey frequency. The bias is unavoidable in an operational monitoring programme that must respond to drought, groundwater flooding and resources pressures. A monthly time series would be a valuable development as it would allow quantitative analysis of spatial variability in the temporal permanence of flowing, pooled and dry states. An alternative approach would be through statistical modelling that accounts for the irregular frequency of the data.

2. The co-location in chalk catchments of Springs and Sources surveys collating observations of hydrological state and gauging stations monitoring river flow presents a rare opportunity to investigate the relationship between the two types of data. There are gauging stations on all of the HNL Area survey rivers except the Bulbourne, and here it is likely that one of the two gauging stations on the Gade would be a suitable analogue. At the local scale, this research would provide a robust means of validation and infilling, reducing the uncertainty that inevitably accompanies subjective observations of this nature and increasing confidence in the Springs and Sources dataset. More importantly, the development of statistical models of this type would faciliate estimation of the occurrence of hydrological states more widely, in other similar IRES where gauged or modelled flows are available.

3. Springs and Sources surveys should continue following the proposed reductions in abstraction in the catchments of the Misbourne and the Ver so that pre- and post-change data may be compared with a view to visualising the natural and artificial causes of drying.

4. The classification of hydrological states should be reviewed in consultation with ecologists, for example, to separate the ponded category into impounded water, connected pools and disconnected pools, with more robust definitions in order to standardise the data. Photographs taken as part of the HNL Springs and Sources survey would inform this task, and improve the ecological relevance of the existing dataset. This would supersede the approach taken in this report of grouping hydrological states in order to reduce uncertainty.

5. The visualisations and metrics of the drying and wetting patterns present an opportunity to investigate the hydroecology of IRES by the overlaying of ecological monitoring data. This research would be an important step towards a robust scientific basis for regulatory thresholds.

6. To improve the regulation of water resource activities on IRES, an alternative to the current Water Framework Directive flow compliance threshold is required along with guidance on suitable quantification of the

impacts of abstraction, for example the change in the duration, extent and timing of drying caused by the artificial influence.

7. Consideration should be given to establishing Springs and Sources surveys conducted by hydrologists in other Areas in which assessment of the impact of water resource activities upon IRES is required.

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7 Appendices

Appendix A Raw data

The tables of raw data following the quality control procedures described in Section 2.3 are provided in electronic format, and are summarised in the table below. One spreadsheet is provided for each river containing two versions of the dataset:

- S&S_8State – eightfold classification of hydrological state, following infilling and data cleaning measures as described in Section 2.3.1 and 2.3.2. This is project data Deliverable D1.1;
- S&S_4State – fourfold classification of hydrological state, with the missing period of 2002/2003 represented to aid intuitive interpretation of the visualisations (see Section 2.3.3).

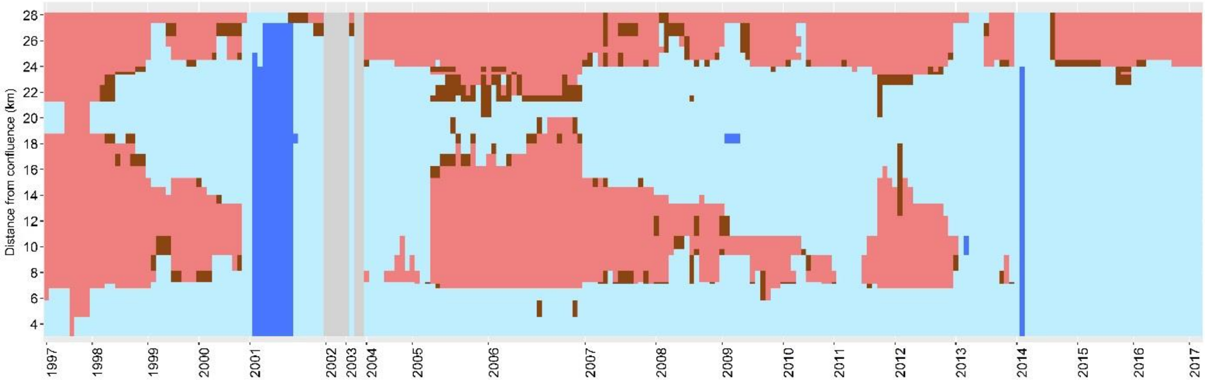
River	Start date	End date	Number of observations	Number of sites
Misbourne	08/05/1997	16/03/2017	221	31
Chess	16/05/1997	16/03/2017	220	19
Bulbourne	04/05/1997	16/03/2017	225	22
Gade	22/04/1997	16/03/2017	227	18
Ver	01/05/1997	16/03/2017	230	32
Mimram	30/04/1997	25/04/2017	203	22
Beane	20/05/1997	25/04/2017	233	24
Rib	14/05/1997	25/04/2017	200	23
Ash	21/05/1997	25/04/2017	198	21
Stort	11/05/1997	25/04/2017	207	20

Appendix B Observation heat maps

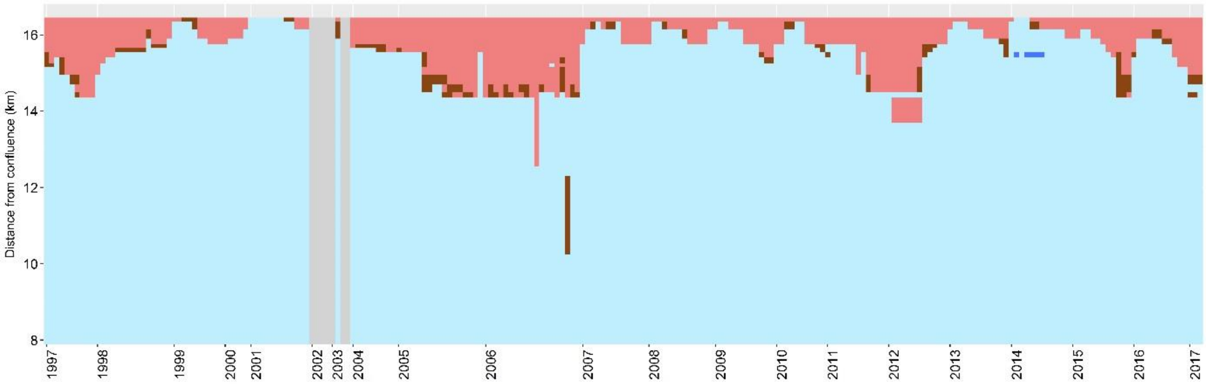
The observation heat maps are produced using the fourfold classification of hydrological state (see Appendix A).

Colne catchment

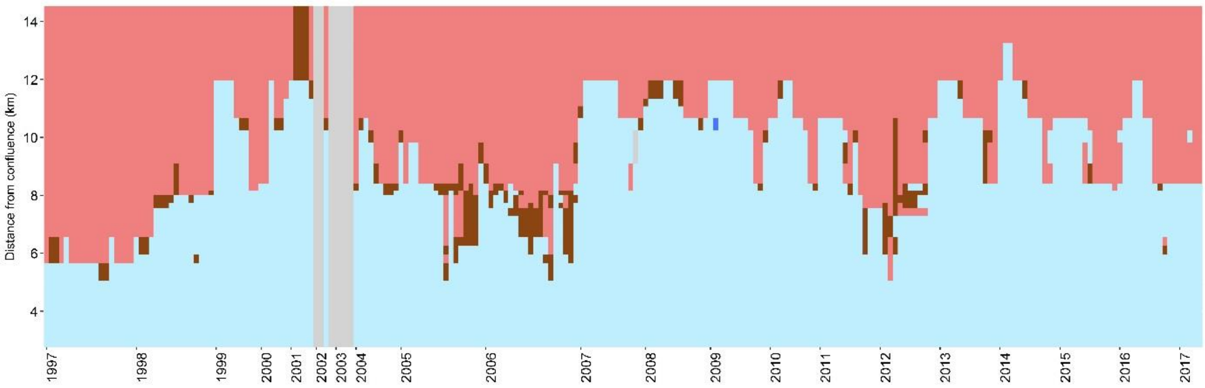
River Misbourne



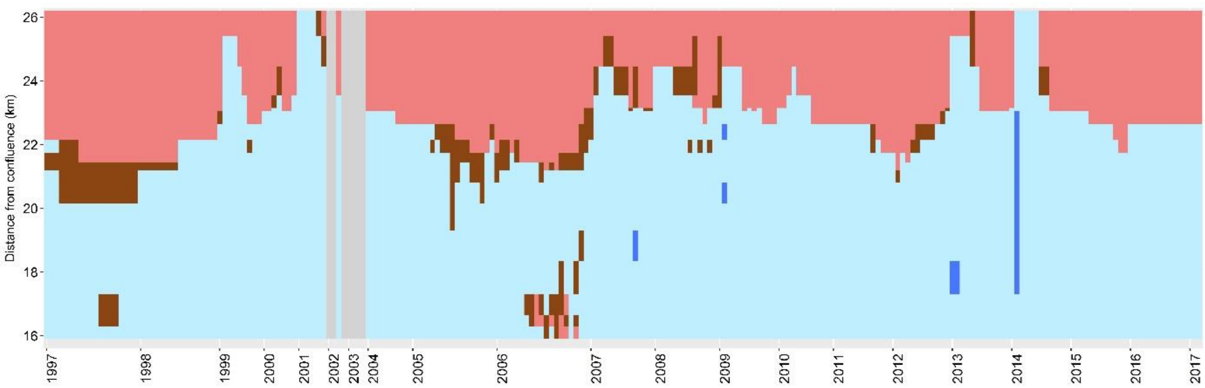
River Chess



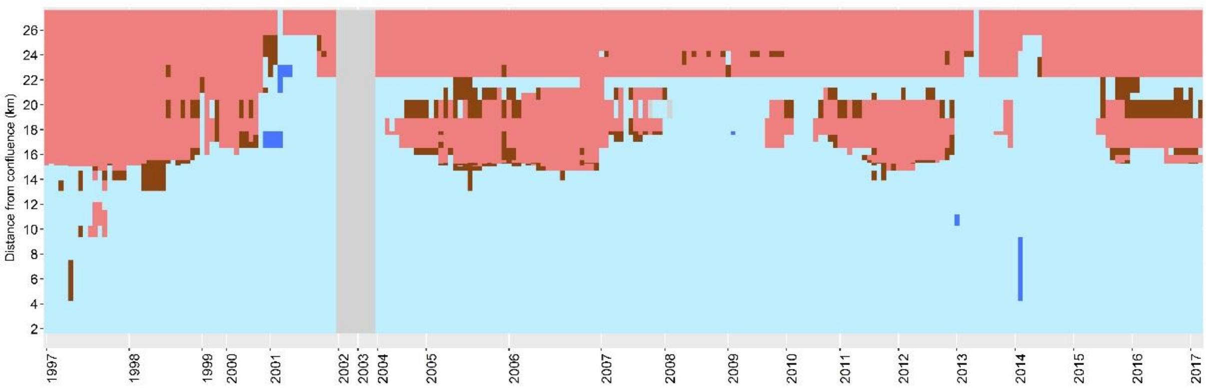
River Bulbourne



River Gade

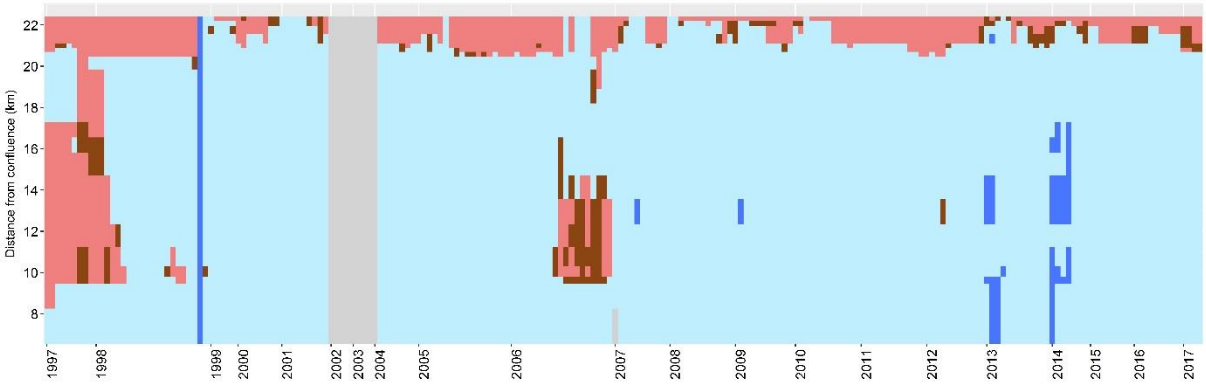


River Ver

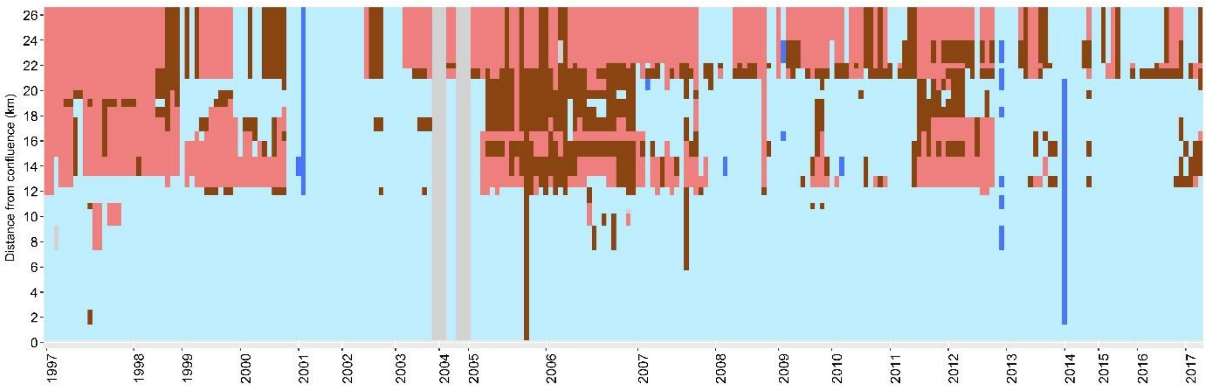


Upper Lee catchment

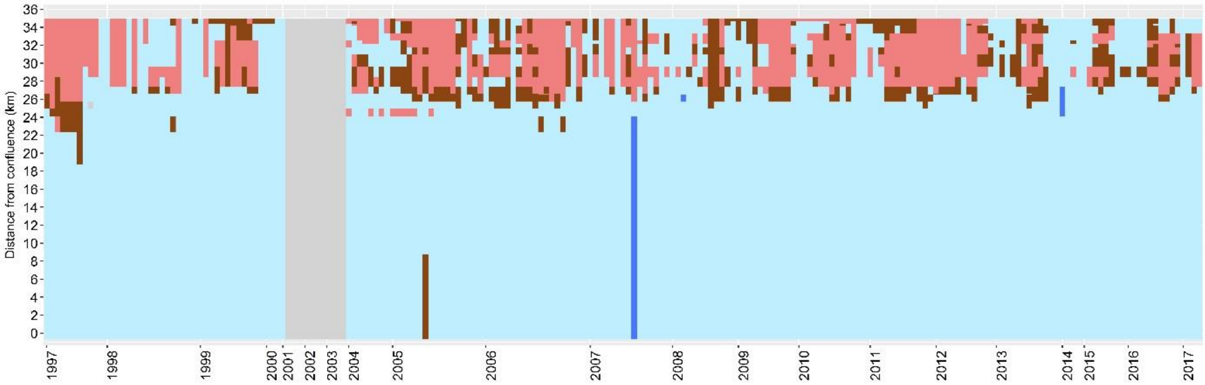
River Mimram



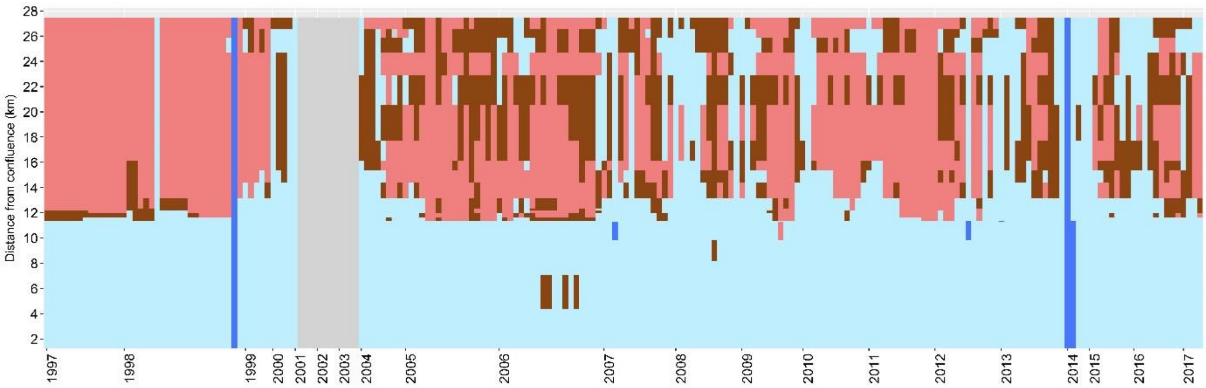
River Beane



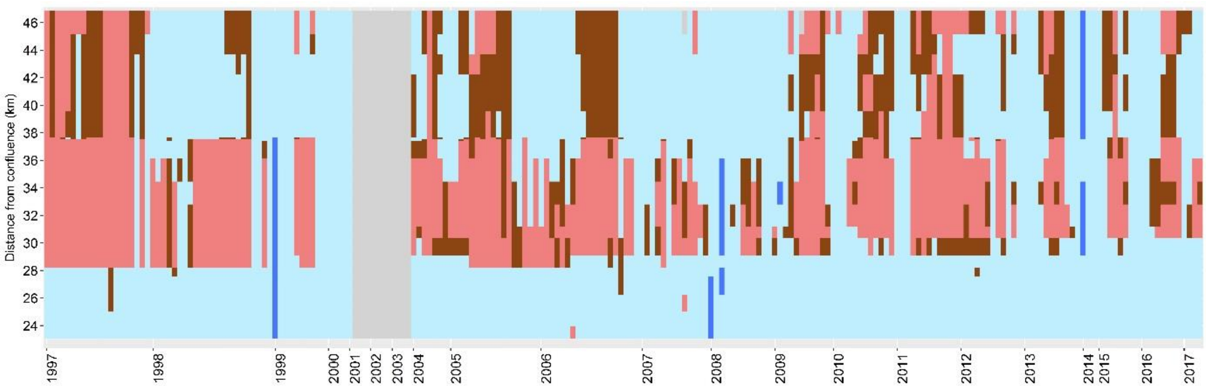
River Rib



River Ash



River Stort

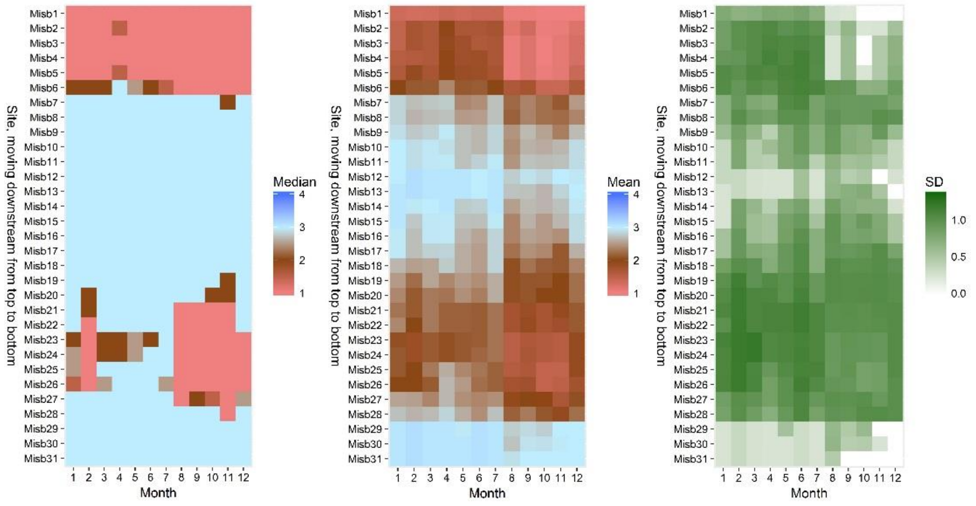


Appendix C Monthly average heat maps

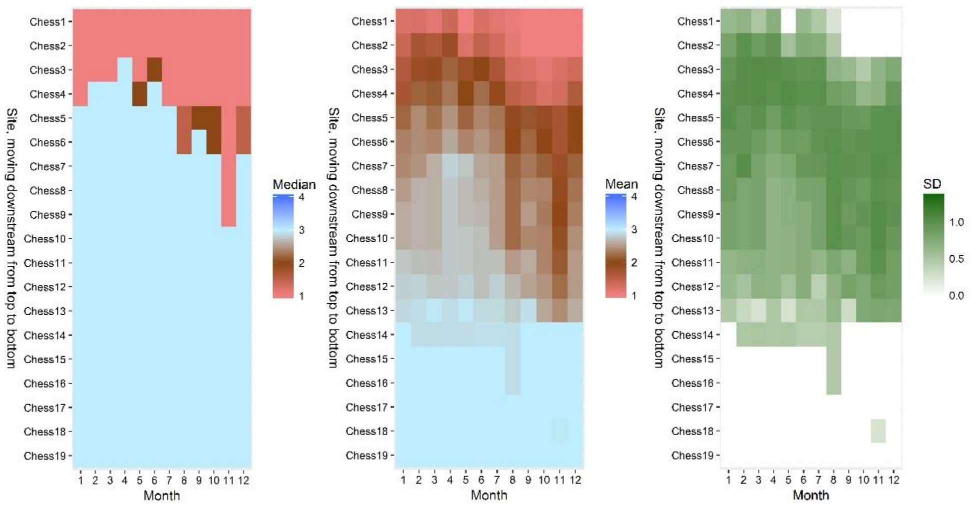
The monthly average heat maps are produced using the fourfold classification of hydrological state (see Appendix A).

Colne catchment

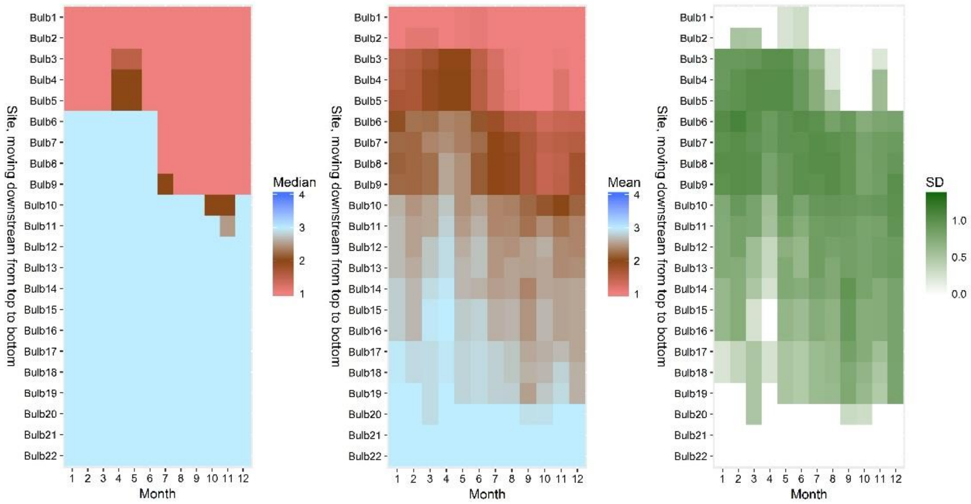
River Misbourne (median, mean and standard deviation)



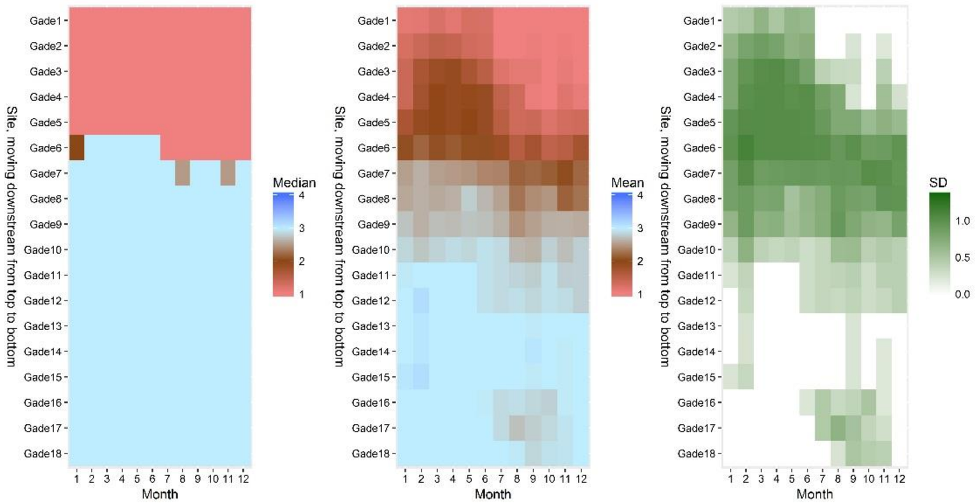
River Chess (median, mean and standard deviation)



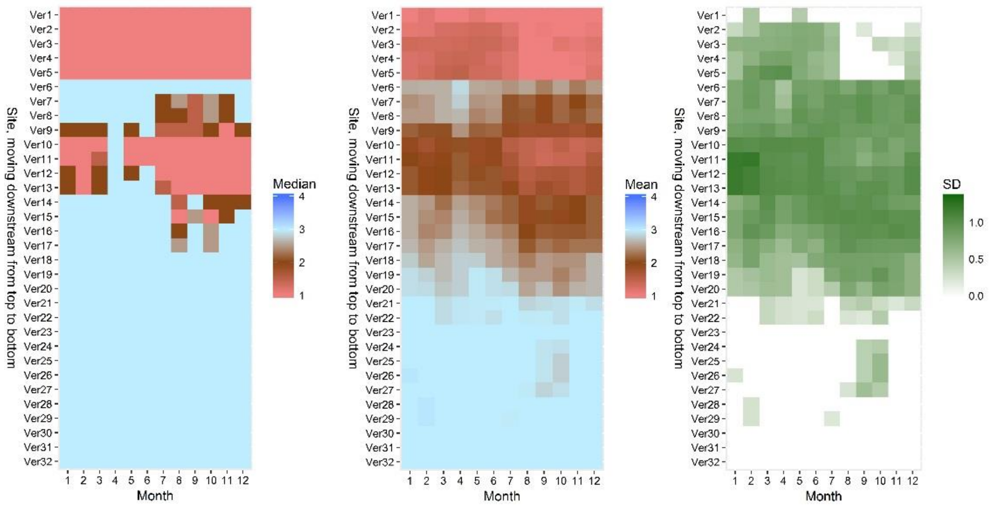
River Bulbourne (median, mean and standard deviation)



River Gade (median, mean and standard deviation)

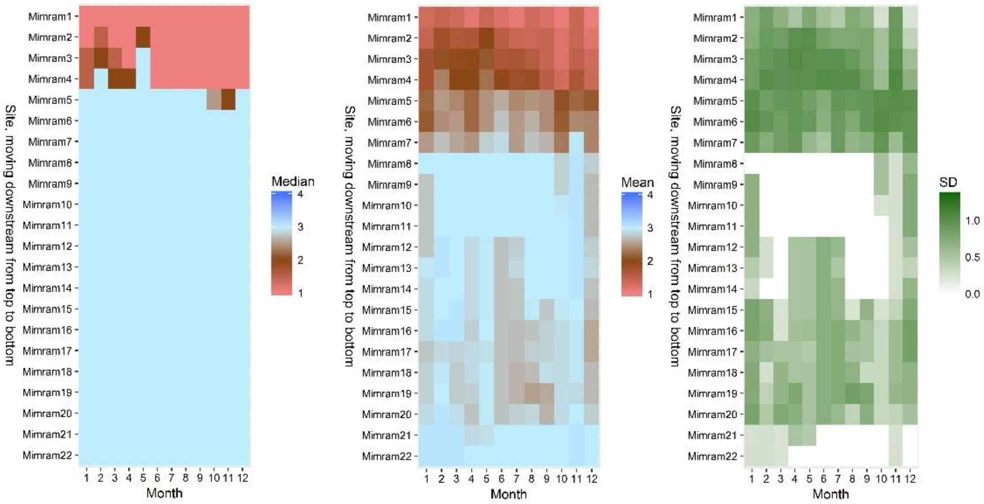


River Ver (median, mean and standard deviation)

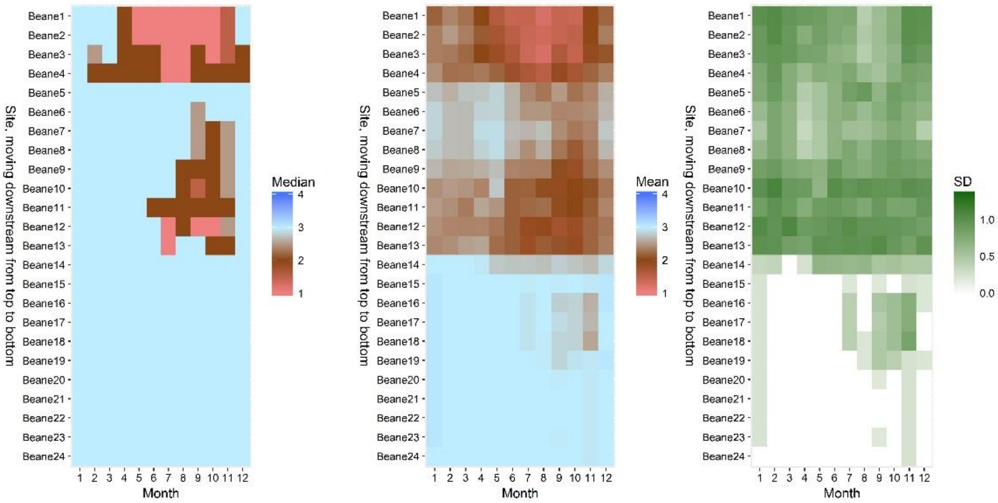


Upper Lee catchment

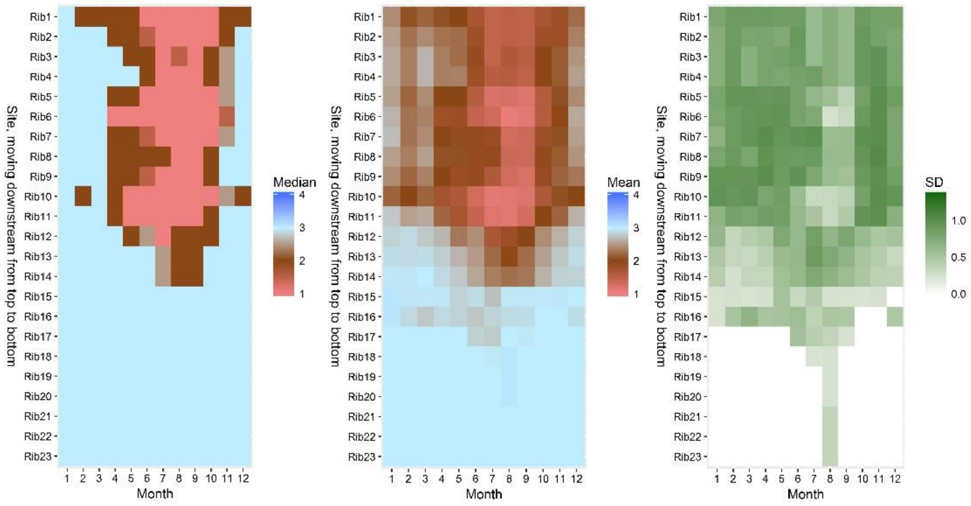
River Mimram (median, mean and standard deviation)



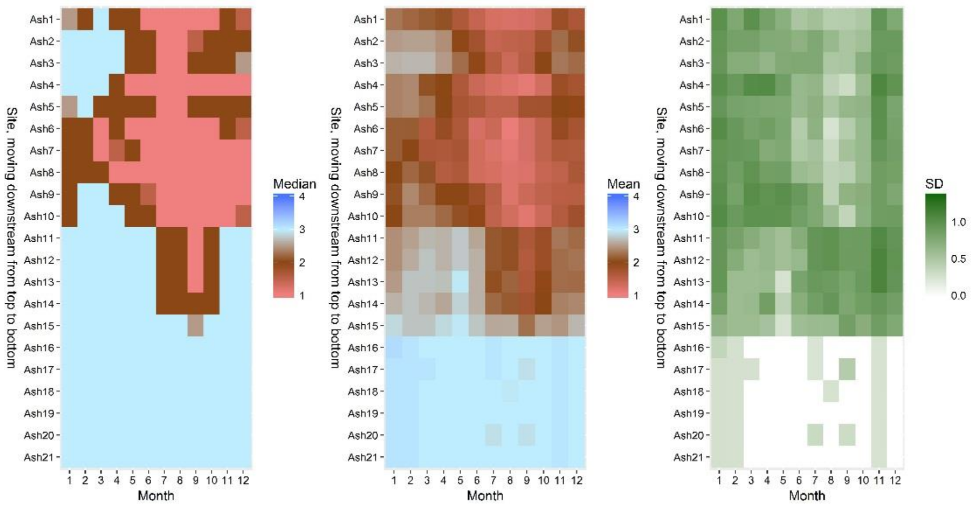
River Beane (median, mean and standard deviation)



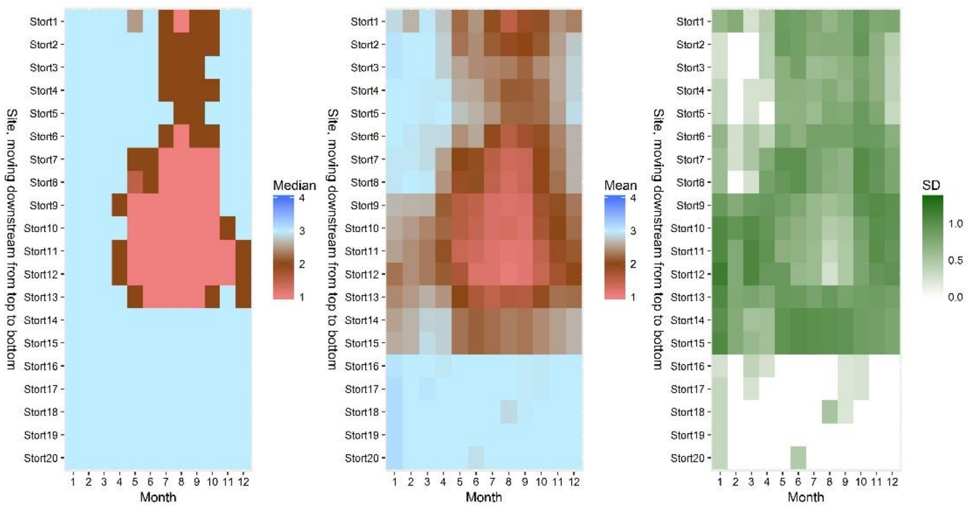
River Rib (median, mean and standard deviation)



River Ash (median, mean and standard deviation)



River Stort (median, mean and standard deviation)



Appendix D Composition and configuration metrics

The composition and configuration metrics described in Section 4 are provided in electronic format for each of the ten rivers on the S&S_Metrics tab in the datafiles, and are summarised in the table below. This is project data deliverable D2.1.

Deliverable D2.1a *Composition metrics*

Tab name	Metric	Units	Description (calculated at each time step)
AbundanceDistance	Abundance	km	Total length of surveyed channel of each hydrological state
RelativeAbundanceDistance	Relative abundance	Dimensionless Ranges from 0 to 1	Proportion of surveyed channel length of each hydrological state
AbundanceSites	Abundance	Dimensionless Ranges from 0 to max no of sites	Total number of sites having each hydrological state
RelativeAbundanceSites	Relative abundance	Dimensionless Ranges from 0 to 1	Proportion of total number of sites having each hydrological state
Richness	Richness	Dimensionless Ranges from 1 to 4	Number of hydrological states present along the surveyed channel length
Evenness	Relative evenness	Dimensionless Ranges from 0 to 1	Diversity of hydrological states present along the surveyed channel length

Deliverable D2.1b *Configuration metrics*

Tab name	Metric	Units	Description (calculated at each time step)
EdgeDensity	Edge density	km^{-1}	Number of changes of state per km
Fragmentation	Relative edge density	Dimensionless Ranges from 0 to 1	Number of changes of state as a proportion of the total number of reach boundaries
LoticConnectivity	Lotic connectivity	km	Total length of flowing surveyed channel that is connected to the farthest downstream site
MeanPatchLength	Mean patch length	km	Average length of consecutive reaches having the same state

Appendix E Summary sheets

A Summary Sheet of key metrics is presented for each river showing:

a) heat map of observations;

Composition metrics

b) relative abundance;

c) evenness;

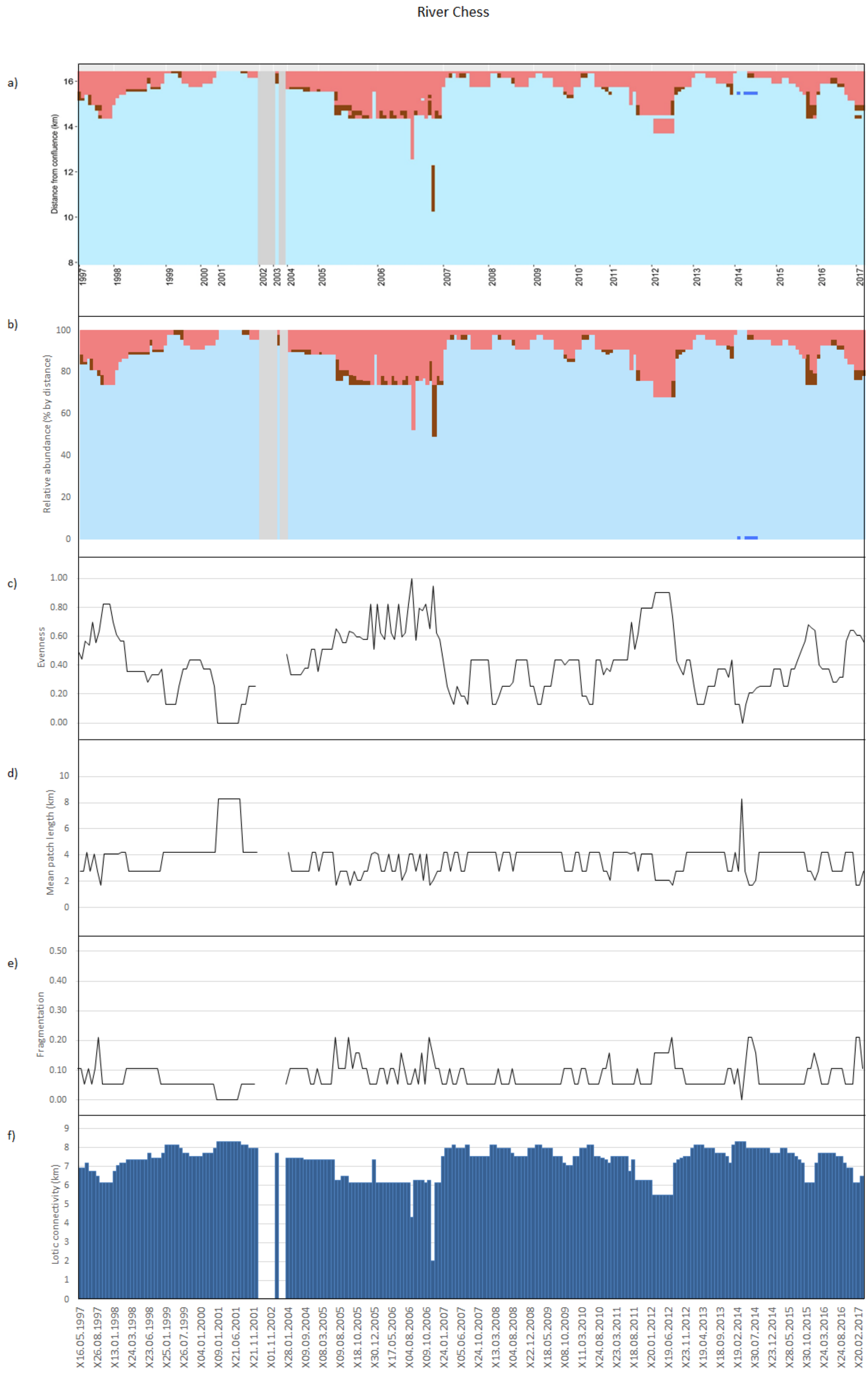
Configuration metrics

d) mean patch length (km);

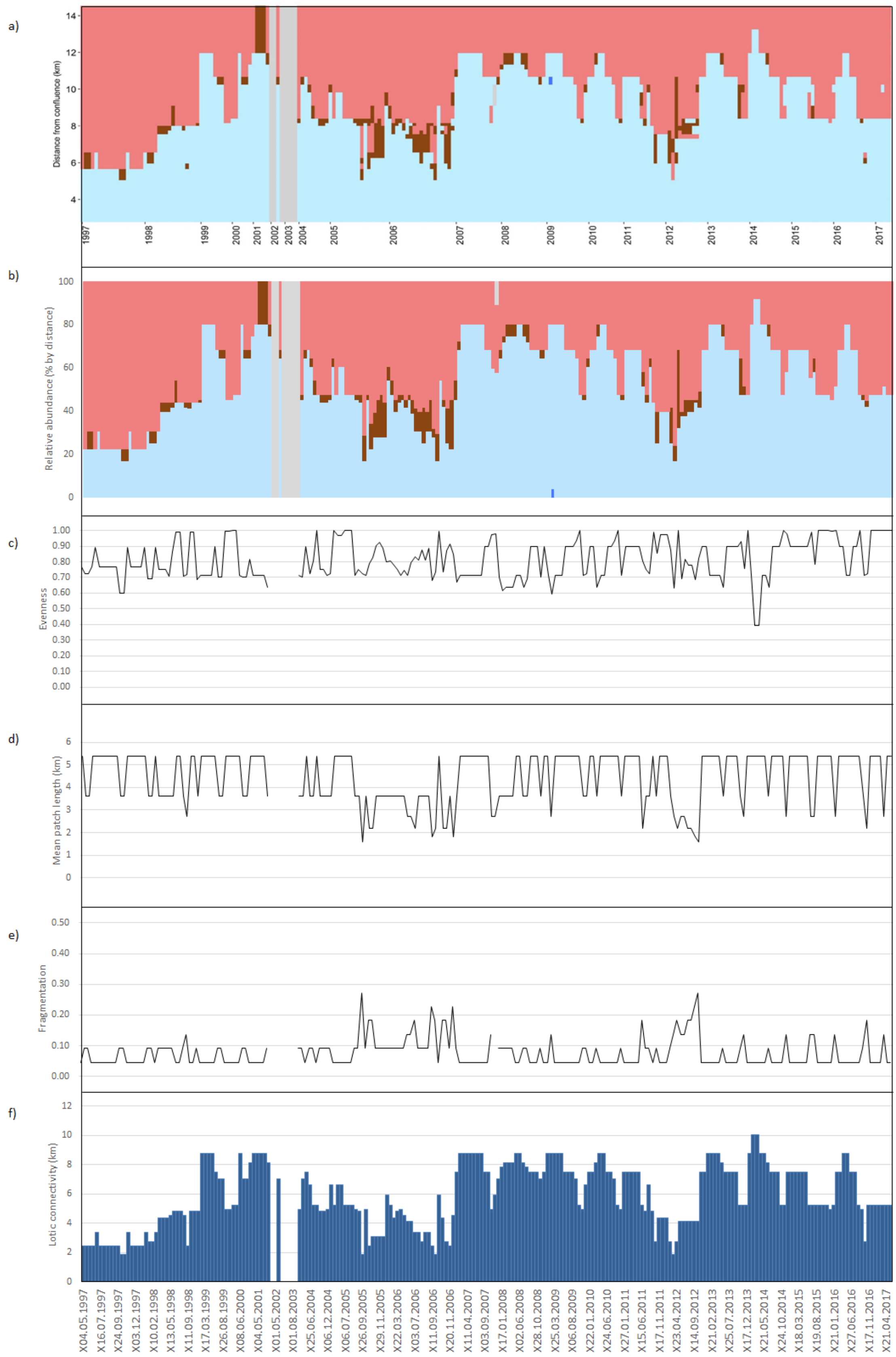
e) fragmentation;

f) lotic connectivity (km).

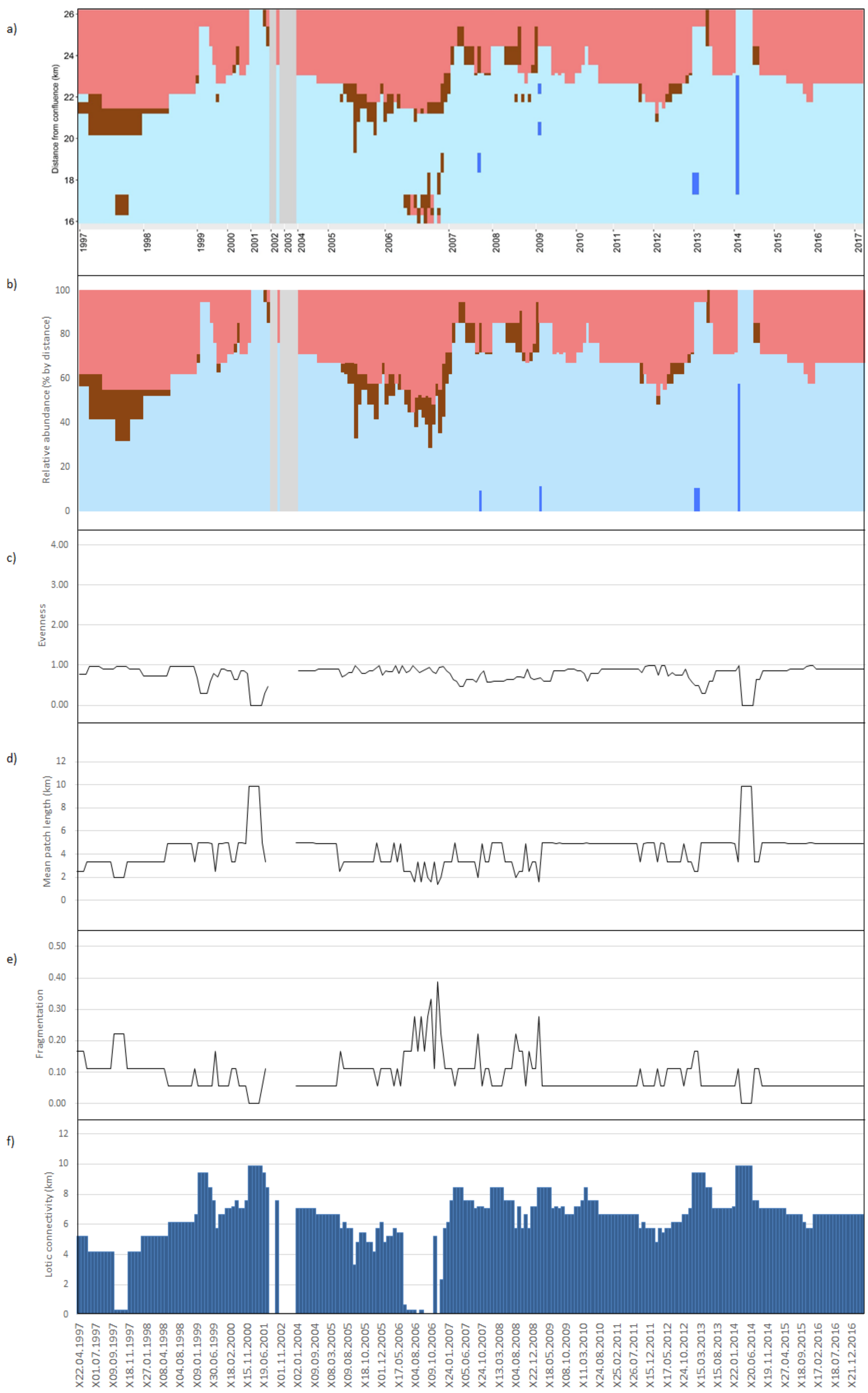
River Misbourne

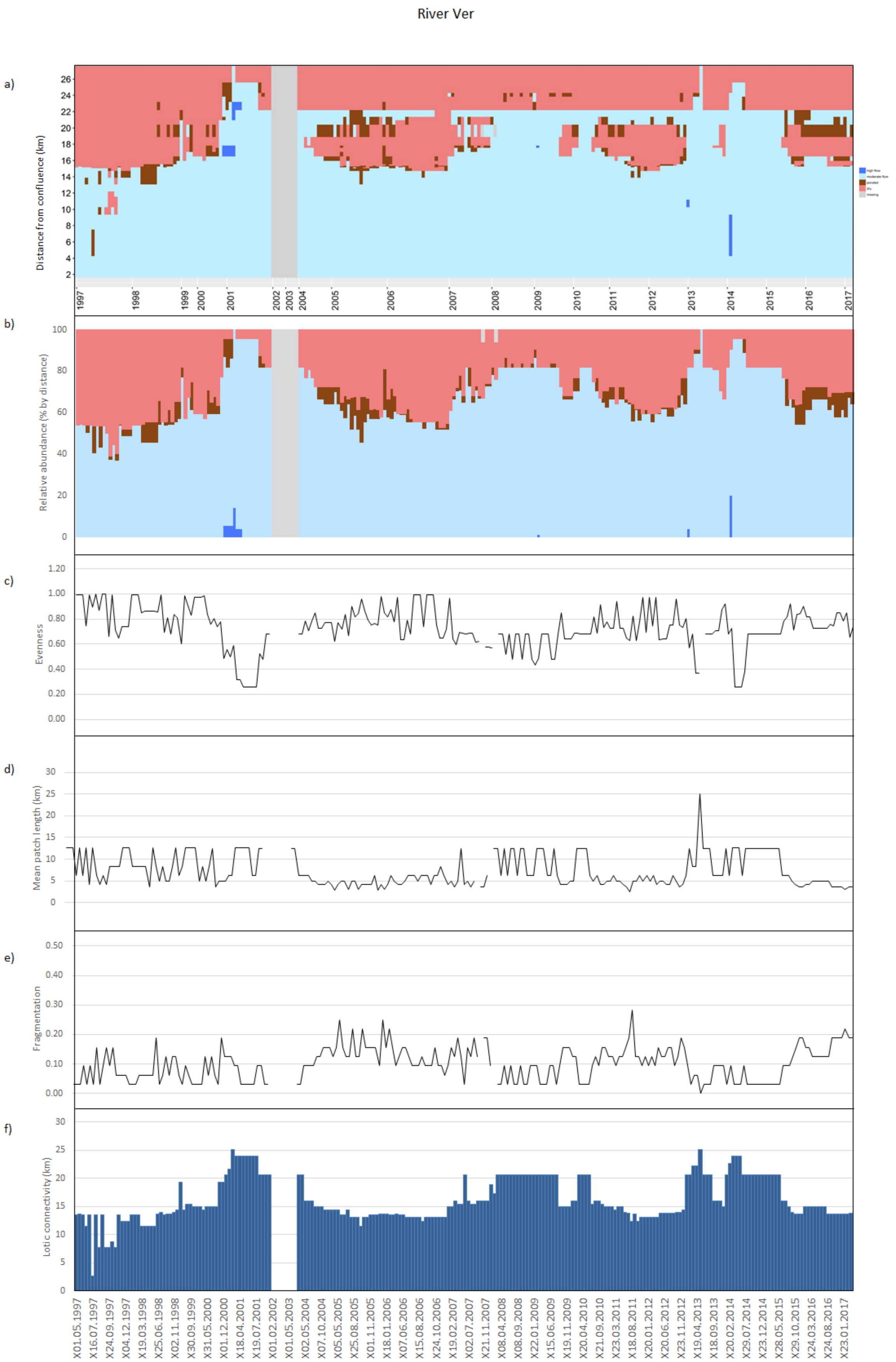

River Chess
a)
Distance from confluence (km)
8
10
12
14
16
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
b)
Relative abundance (% by distance)
0
20
40
60
80
100
c)
Evenness
0.00
0.20
0.40
0.60
0.80
1.00
d)
Mean patch length (km)
0
2
4
6
8
10
e)
Fragmentation
0.00
0.10
0.20
0.30
0.40
0.50
f)
Lotic connectivity (km)
0
1
2
3
4
5
6
7
8
9
X16.05.1997
X26.08.1997
X13.01.1998
X24.03.1998
X23.06.1998
X25.01.1999
X26.07.1999
X04.01.2000
X09.01.2001
X21.06.2001
X21.11.2001
X01.11.2002
X28.01.2004
X09.09.2004
X08.03.2005
X09.08.2005
X18.10.2005
X30.12.2005
X17.05.2006
X04.08.2006
X09.10.2006
X24.01.2007
X05.06.2007
X24.10.2007
X13.03.2008
X04.08.2008
X22.12.2008
X18.05.2009
X08.10.2009
X11.03.2010
X24.08.2010
X23.03.2011
X18.08.2011
X20.01.2012
X19.06.2012
X23.11.2012
X19.04.2013
X18.09.2013
X19.02.2014
X30.07.2014
X23.12.2014
X28.05.2015
X30.10.2015
X24.03.2016
X24.08.2016
X20.02.2017

River Bulbourne

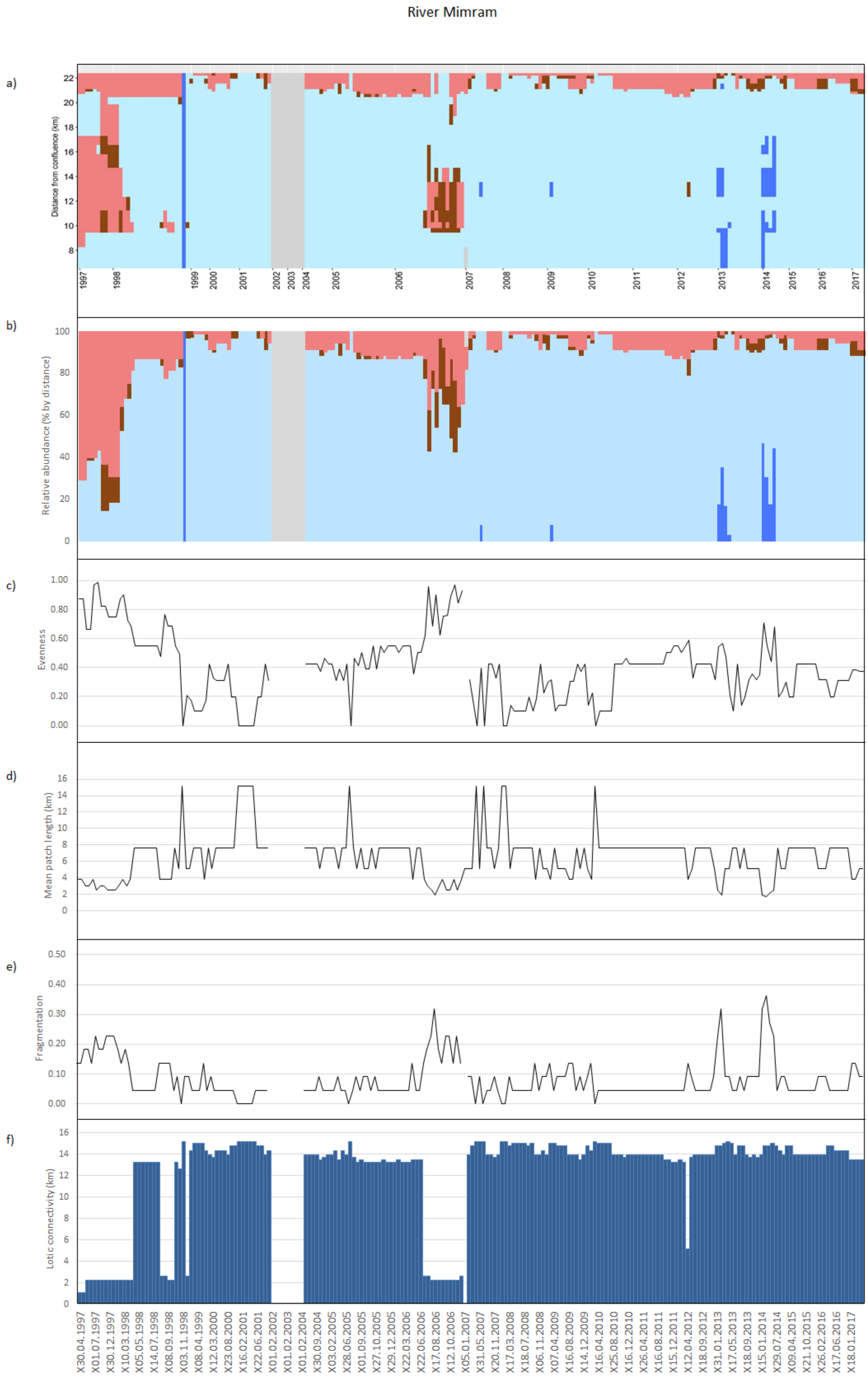


River Gade

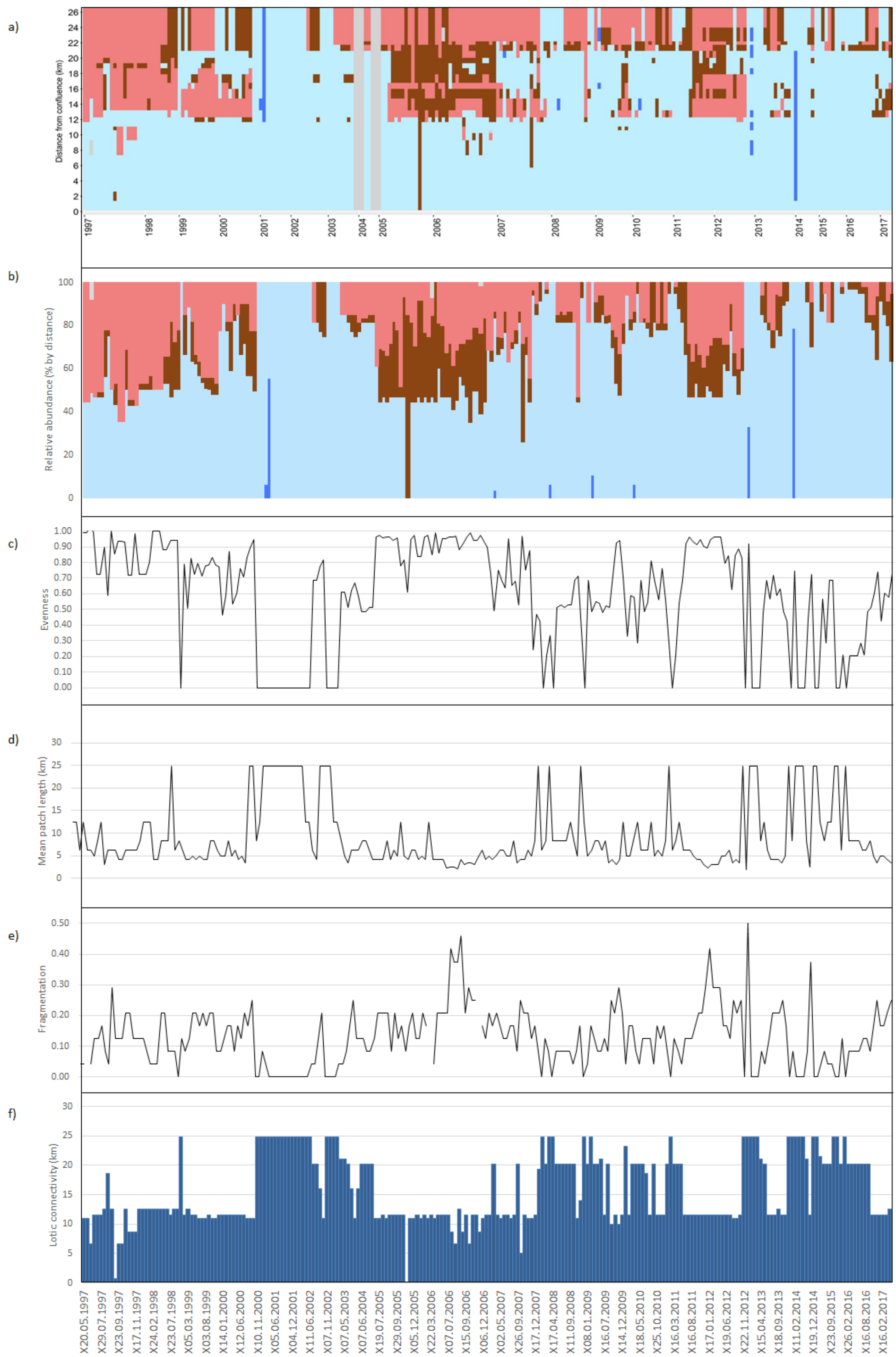

a)
b)
c)
d)
e)
f)
Distance from confluence (km)
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Relative abundance (% by distance)
Evenness
Mean patch length (km)
Fragmentation
Lotic connectivity (km)
X22.04.1997
X01.07.1997
X09.09.1997
X18.11.1997
X27.01.1998
X08.04.1998
X04.08.1998
X09.01.1999
X30.06.1999
X18.02.2000
X15.11.2000
X19.06.2001
X01.11.2002
X02.01.2004
X09.09.2004
X08.03.2005
X09.08.2005
X18.10.2005
X01.12.2005
X17.05.2006
X04.08.2006
X09.10.2006
X24.01.2007
X05.06.2007
X24.10.2007
X13.03.2008
X04.08.2008
X22.12.2008
X18.05.2009
X08.10.2009
X11.03.2010
X24.08.2010
X25.02.2011
X26.07.2011
X15.12.2011
X17.05.2012
X24.10.2012
X15.03.2013
X15.08.2013
X22.01.2014
X20.06.2014
X19.11.2014
X27.04.2015
X18.09.2015
X17.02.2016
X18.07.2016
X21.12.2016



River Ver
a)
b)
c)
d)
e)
f)
Distance from confluence (km)
Relative abundance (% by distance)
Evenness
Mean patch length (km)
Fragmentation
Lotic connectivity (km)

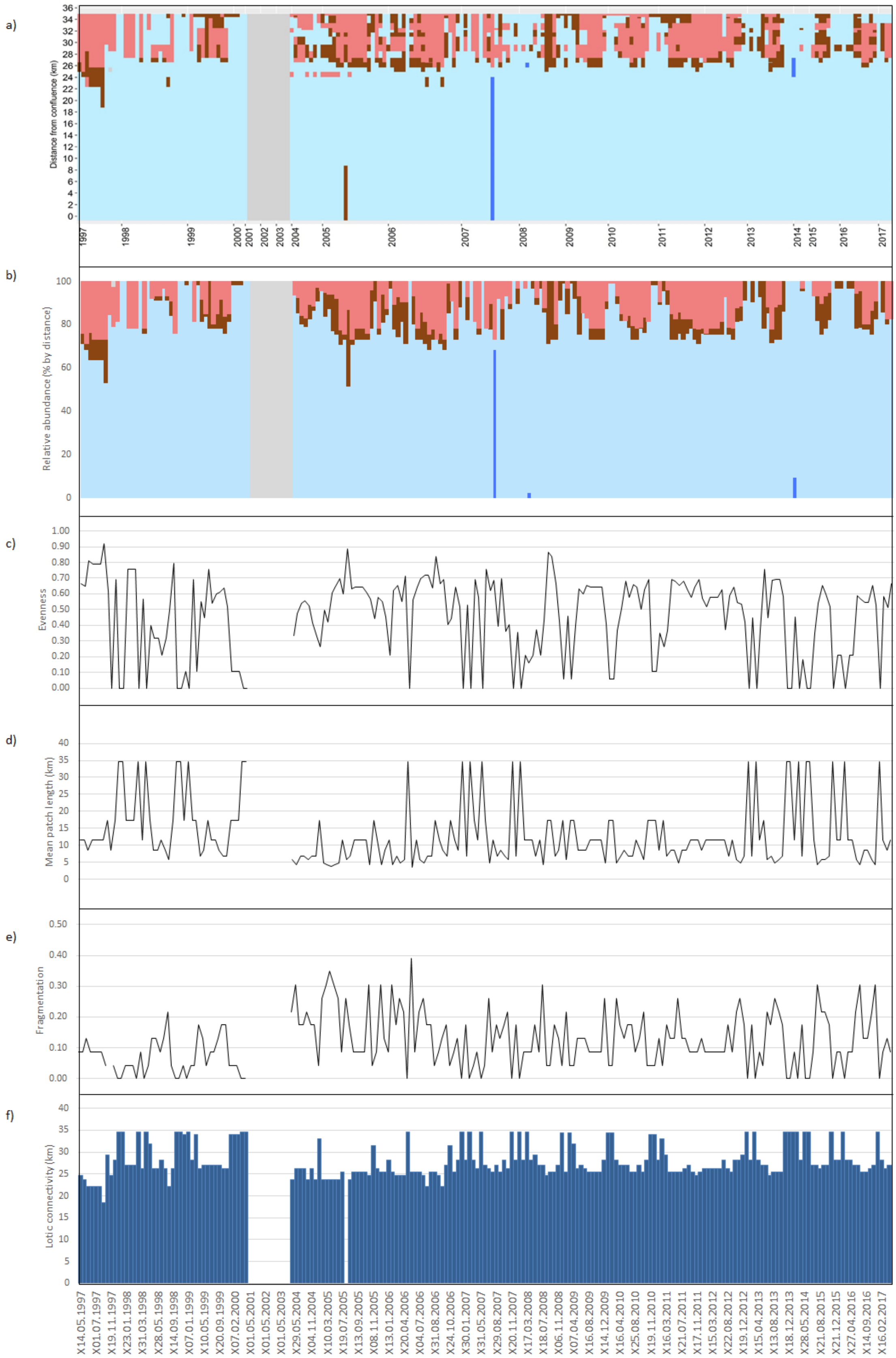

River Mimram
a)
b)
c)
d)
e)
f)
Distance from confluence (km)
Relative abundance (% by distance)
Evenness
Mean patch length (km)
Fragmentation
Lotic connectivity (km)
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
X30.04.1997
X01.07.1997
X30.12.1997
X10.03.1998
X05.05.1998
X14.07.1998
X08.09.1998
X03.11.1998
X08.04.1999
X12.03.2000
X23.08.2000
X16.02.2001
X22.06.2001
X01.02.2002
X01.02.2003
X01.02.2004
X30.09.2004
X03.02.2005
X28.06.2005
X01.09.2005
X27.10.2005
X29.12.2005
X22.03.2006
X22.06.2006
X17.08.2006
X12.10.2006
X05.01.2007
X31.05.2007
X20.11.2007
X17.03.2008
X18.07.2008
X06.11.2008
X07.04.2009
X16.08.2009
X14.12.2009
X16.04.2010
X25.08.2010
X16.12.2010
X26.04.2011
X16.08.2011
X15.12.2011
X12.04.2012
X18.09.2012
X31.01.2013
X17.05.2013
X18.09.2013
X15.01.2014
X29.07.2014
X09.04.2015
X21.10.2015
X26.02.2016
X17.06.2016
X18.01.2017

River Beane



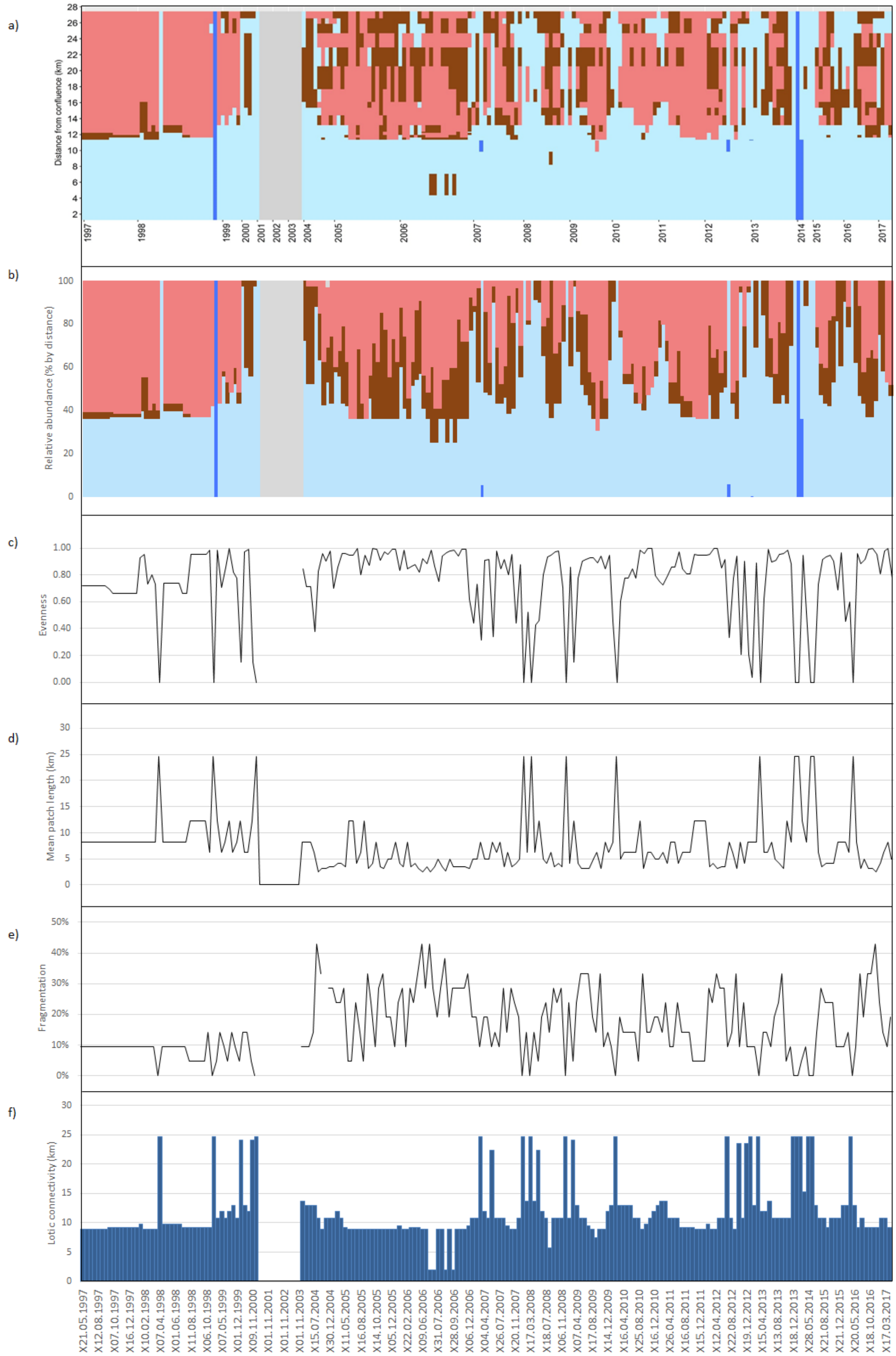
a)
Distance from confluence (km)
0 2 4 6 8 10 12 14 16 18 20 22 24 26
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017
b)
Relative abundance (% by distance)
0 20 40 60 80 100
c)
Evenness
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00
d)
Mean patch length (km)
0 5 10 15 20 25 30
e)
Fragmentation
0.00 0.10 0.20 0.30 0.40 0.50
f)
Lotic connectivity (km)
0 5 10 15 20 25 30
X20.05.1997 X29.07.1997 X23.09.1997 X17.11.1997 X24.02.1998 X23.07.1998 X05.03.1999 X03.08.1999 X14.01.2000 X12.06.2000 X10.11.2000 X05.06.2001 X04.12.2001 X11.06.2002 X07.11.2002 X07.05.2003 X07.06.2004 X19.07.2005 X29.09.2005 X05.12.2005 X22.03.2006 X07.07.2006 X15.09.2006 X06.12.2006 X02.05.2007 X26.09.2007 X17.12.2007 X17.04.2008 X11.09.2008 X08.01.2009 X16.07.2009 X14.12.2009 X18.05.2010 X25.10.2010 X16.03.2011 X16.08.2011 X17.01.2012 X19.06.2012 X22.11.2012 X15.04.2013 X18.09.2013 X11.02.2014 X19.12.2014 X23.09.2015 X26.02.2016 X16.08.2016 X16.02.2017

River Rib

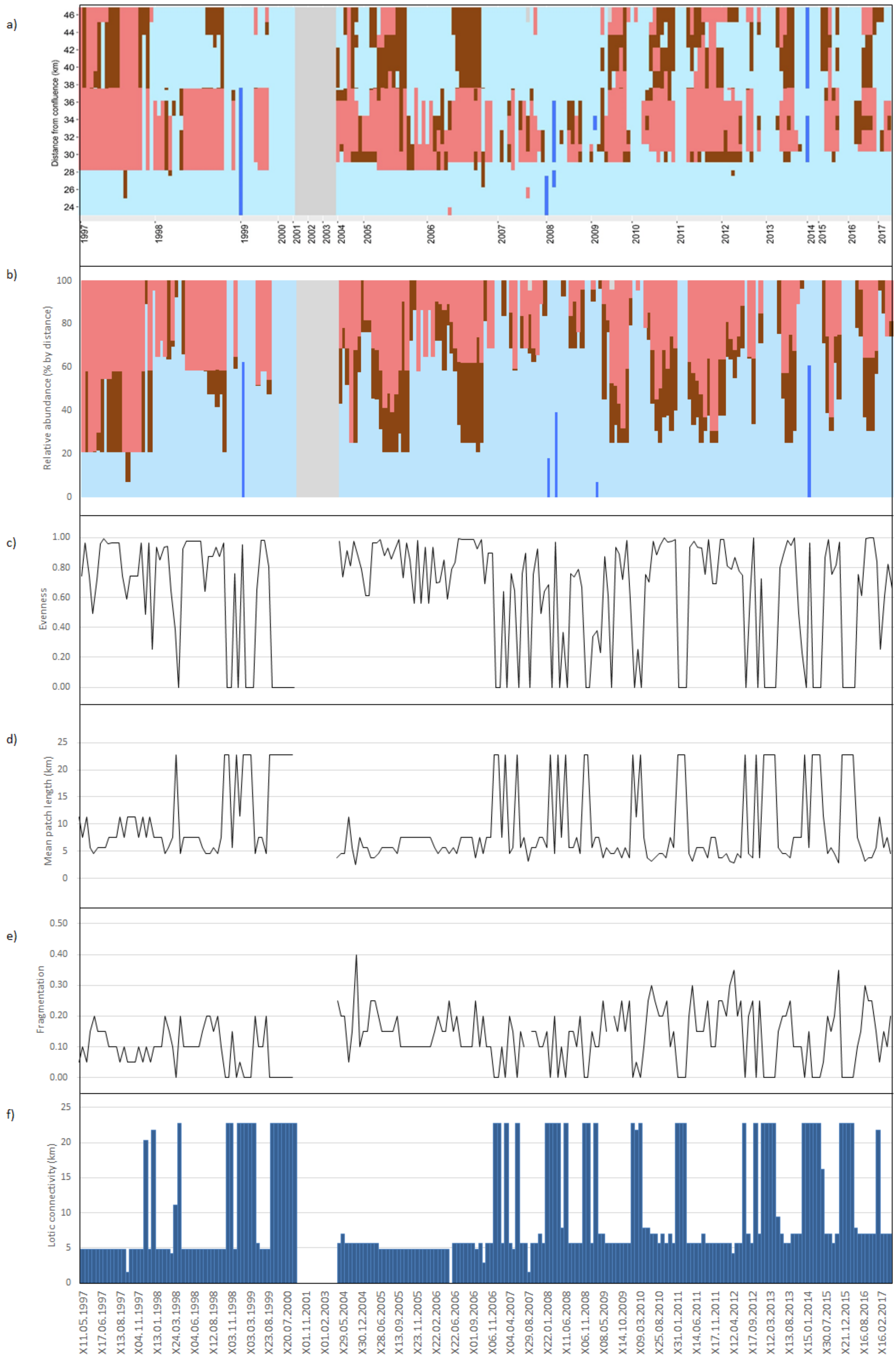


a)
Distance from confluence (km)
b)
Relative abundance (% by distance)
c)
Evenness
d)
Mean patch length (km)
e)
Fragmentation
f)
Lotic connectivity (km)

River Ash


a)
b)
c)
d)
e)
f)
Distance from confluence (km)
Relative abundance (% by distance)
Evenness
Mean patch length (km)
Fragmentation
Lotic connectivity (km)

River Stort



a)
b)
c)
d)
e)
f)
Distance from confluence (km)
Relative abundance (% by distance)
Evenness
Mean patch length (km)
Fragmentation
Lotic connectivity (km)

NERC SCIENCE OF THE ENVIRONMENT

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