

Cranfield University

Andrew Chiverton

The influence of catchment characteristics on river  
flow variability

School of Applied Sciences

PhD Thesis

Cranfield University

School of Applied Sciences

PhD thesis

Academic year: 2015

Andrew Chiverton

The influence of catchment characteristics on river  
flow variability

Supervisors: Jamie Hannaford, Ian Holman, Christel  
Prudhomme, Tim Hess and John Bloomfield.

Date of Presentation: 05/08/2015

© Cranfield University, 2015. All rights reserved. No part of this publication may  
be produced without written permission of the copyright holder.

## **Abstract**

Hydrology is yet to fully understand the role that catchment characteristics have in determining a river's response to precipitation variability. This thesis assesses the influence that catchment characteristics have on modulating a river's response to changes in precipitation throughout the UK. Central to this aim is the concept of the precipitation-to-flow relationship (the transformation of precipitation into river flow), which is characterised using the Variogram, a way of indexing temporal dependence (i.e. the average relationship between river flow on a given day and river flow on the previous days). Firstly, 116 catchments were grouped into four clusters, based on the shape of their variogram, which significantly differed in their catchment characteristics demonstrating that catchment characteristics control how, on average, precipitation is transformed into river flow. Furthermore, over 70% of un-gauged catchments could be clustered correctly using information about their soil type, slope and the percentage of arable land. Secondly, a new method which identifies the changes in the variogram parameters over 5-year overlapping moving windows was developed to investigate temporal changes in the variogram parameters. This method was successfully demonstrated to detect changes in multiple aspects of artificially perturbed river flow time series (e.g. seasonality, linear changes and variability). On average >70% of the variability in the catchment variogram parameters was explained by the precipitation characteristics, although there was large variability between catchments. Finally, the influence that the catchment characteristics have on the temporal changes in the variogram parameters was analysed, demonstrating that rivers in relatively impermeable upland catchments have a relationship with precipitation which is closer to linear and less variable than lowland, permeable catchments. This thesis contributes significant new knowledge that can be used for both assessing how individual catchments are likely to respond to projected changes in precipitation and in informing data transfer to un-gauged catchments.

Our greatest weakness lies in giving up. The most certain way to succeed is to try one more time - Thomas Edison

## **Acknowledgments**

This PhD research has been made possible by financial and personal support. I am grateful for the financial support from the United Kingdom Natural Environment Research Council and the supportive environment of the Centre for Ecology and Hydrology (CEH) Wallingford that made this work possible. In particular, I sincerely thank my supervisors, Jamie Hannaford, Prof Christel Prudhomme at CEH Wallingford, Dr John Bloomfield at the British Geological Survey (BGS) and Prof Ian Holman and Dr Tim Hess at Cranfield University, for their continual guidance and friendship throughout the PhD.

I would also like to thank Dr Ron Corstanje and Dr Ilaria Prosdocimi for their statistical advice, Oliver Swain for his assistance with data extraction and Sandie Clemas for her help with administrative tasks.

I am grateful to the National River Flow Archives (NRFA) for providing river flow, precipitation and catchment characteristic data as well as BGS for the hydrogeological information.

Finally I would like to thank my loving girlfriend and family who have supported me throughout the PhD.

# Contents page

<b>1</b>	<b>Introduction</b> .....	1
<b>1.1</b>	<b>Background and rationale</b> .....	1
1.1.1	Objectives .....	5
1.1.2	Thesis structure .....	7
<b>1.2</b>	<b>Literature review</b> .....	9
1.2.1	The influence of the catchment characteristics on the precipitation-to-river flow relationship .....	9
1.2.2	Understanding historical changes in the river flow time series .....	15
1.2.3	The stability of the precipitation-to-river flow relationship .....	21
<b>1.3</b>	<b>Characterising the precipitation-to-river flow relationship</b> .....	23
<b>1.4</b>	<b>References</b> .....	27
<b>2</b>	<b>Which catchment characteristics control the temporal dependence structure of daily river flows?</b> .....	36
<b>2.1</b>	<b>Introduction</b> .....	37
<b>2.2</b>	<b>Data</b> .....	39
2.2.1	Catchment selection .....	39
2.2.2	Catchment characteristics .....	42
<b>2.3</b>	<b>Method</b> .....	44
2.3.1	River flow data transformation .....	45
2.3.2	Semi-variograms .....	46
2.3.3	Clustering .....	47
2.3.4	Quadratic discriminant analysis (QDA) .....	48
<b>2.4</b>	<b>Results</b> .....	49
2.4.1	Clustering .....	49
2.4.2	Distinction between the clusters .....	49
2.4.3	Identify the catchment characteristics which differ between the clusters .....	51
2.4.4	Quadratic discriminant analysis .....	54
2.4.5	Validation .....	57
<b>2.5</b>	<b>Discussion</b> .....	59
<b>2.6</b>	<b>Conclusion</b> .....	64
<b>2.7</b>	<b>References</b> .....	65
<b>3</b>	<b>Using variograms to detect and attribute hydrological change</b> .....	69

<b>3.1</b>	<b>Introduction</b> .....	70
3.1.1	Review of previous approaches to change detection.....	71
3.1.2	The proposed new method .....	73
<b>3.2</b>	<b>Data</b> .....	75
3.2.1	Catchment selection .....	75
3.2.2	Precipitation characteristics.....	77
<b>3.3</b>	<b>The Temporally Shifting Variograms methodology</b> .....	77
3.3.1	Data transformation.....	78
3.3.2	Creating variograms .....	79
3.3.3	Detection of change in river flow using TSV .....	80
3.3.4	Relating change to the meteorological drivers .....	82
<b>3.4</b>	<b>Testing the TSV method using artificially perturbed time series</b> .....	83
<b>3.5</b>	<b>Application of the TSV method to Benchmark catchments</b> .....	86
3.5.1	Stability analysis .....	86
3.5.2	Identifying periods of change.....	88
3.5.3	Drivers behind the change.....	89
<b>3.6</b>	<b>Discussion</b> .....	92
<b>3.7</b>	<b>Conclusion</b> .....	95
<b>3.8</b>	<b>References</b> .....	96
<b>4</b>	<b>How do catchment characteristics influence a river’s response to temporal changes in precipitation?</b> .....	101
<b>4.1</b>	<b>Introduction</b> .....	102
<b>4.2</b>	<b>The variogram parameters</b> .....	107
<b>4.3</b>	<b>Data</b> .....	108
<b>4.4</b>	<b>Methods</b> .....	108
4.4.1	Investigating the effect of precipitation changes on the variogram parameters	108
4.4.2	Investigate the drivers behind temporal stability in the variogram parameters (questions 2 and 3) .....	112
<b>4.5</b>	<b>Results</b> .....	114
4.5.1	Correlation between the CV of the Sill and the Range, and the precipitation regime .....	114
4.5.2	Calculate the amount of temporal variability explained by the uncorrelated precipitation characteristics.....	115
4.5.3	Investigating the CV of the Range and the Sill for each catchment.....	116

4.5.4	The correlation between the CV and the potential drivers .....	117
4.5.5	The CV which can be explained by the potential driving characteristics .....	118
<b>4.6</b>	<b>Discussion</b> .....	119
4.6.1	The amount of temporal variability in the Range and Sill explained by precipitation characteristics.....	119
4.6.2	The drivers behind the amount of temporal variability (CV) of the variogram parameters .....	121
4.6.3	How do catchment characteristics influence a river's response to temporal changes in precipitation?.....	124
<b>4.7</b>	<b>Conclusion</b> .....	125
<b>4.8</b>	<b>References</b> .....	127
<b>5</b>	<b>Synthesis</b> .....	131
<b>5.1</b>	<b>Introduction</b> .....	131
<b>5.2</b>	<b>Summary of methods and key results</b> .....	132
5.2.1	Characterising the influence that the catchment characteristics have on the precipitation-to-river flow relationship .....	132
5.2.2	Which catchment characteristics control the temporal dependence structure of daily river flows? (Chapter 2) .....	133
5.2.3	Using variograms to detect and attribute hydrological change (Chapter 3) .....	134
5.2.4	How do the catchment characteristics influence the temporal variability in the river flow? (Chapter 4).....	134
<b>5.3</b>	<b>Discussion</b> .....	135
5.3.1	Integrated overview .....	141
<b>5.4</b>	<b>Recommendations for further work</b> .....	148
5.4.1	Analysing the influence of groundwater storage.....	148
5.4.2	Testing the methods in a different climate .....	148
5.4.3	Further evaluation of the relationships between the variogram properties and the potential drivers.....	148
5.4.4	Assessing the effects of artificial influences .....	149
5.4.5	The influence of changing land cover .....	149
<b>5.5</b>	<b>Conclusions</b> .....	150
<b>5.6</b>	<b>Final remarks</b> .....	153
<b>5.7</b>	<b>References</b> .....	153

**APPENDIX I:** *Hydrological Processes* paper

**APPENDIX II:** *Hydrology and Earth Systems Science* paper



## List of Tables

Table 2.1: Summary of the catchment characteristics investigated. ....	43
Table 2.2: Characteristics of the variogram models fitted to the mean semi-variogram of each cluster. ....	51
Table 2.3: Transformations applied to each catchment characteristic in order to create a normal distribution. ....	56
Table 2.4 Different discriminant models and the percentage of catchments which were correctly classified by using the catchment characteristics. Shaded cells show the catchment characteristics included in the model. ....	56
Table 2.5: Variables and associated coefficients used in Model 5 to classify the catchments based on their catchment characteristics. ....	57
Table 2.6: Confusion matrix showing Benchmark and validation (in brackets) catchments in each cluster after clustering using the catchment characteristics in model 5. ....	58
Table 2.7: Discriminant models and the percentage of catchments which were correctly classified, shaded cells show the catchment characteristics which were included in the model. ....	59
Table 3.1: Daily precipitation characteristics. ....	77
Table 3.2: Change in the median value of the potential driving characteristics for 1995 – 2001 and 2004 - 2012, compared to 1980 – 1994. The median value (taken from all the 91 catchments) is presented along with the significance level (if significantly different from 1980 – 1994 at or above the 95% CI). ....	90
Table 3.3: Percentage of catchments with significant (at the 95% CL) correlation between the 5-year precipitation and variogram characteristics. The average correlation (for catchments with significant correlations) is in brackets. The darker the colour, the larger the absolute average correlation. ....	90
Table 4.1: Correlation coefficients for the characteristics which have a significant correlation (>95% CI) with the CV for the Range and the Sill. ....	118
Table 4.2: The P values for each of the characteristics which are included in each model to describe the differences in the CV between each catchment and the resulting R <sup>2</sup> value. ....	119
Table 5.1: Description of the influence that the characteristics have on the precipitation-to-river flow relationship. ....	136

## List of figures

Figure 1.1: Schematic diagram of the thesis. ....	8
Figure 1.2: The major controls on the processes within a catchment which are responsible for transforming precipitation into river flow. The catchment average precipitation and river flow data are from the river Foston Beck (station number 26003).....	10
Figure 1.3: The variogram parameters for a theoretical variogram.....	25
Figure 1.4: From top left to bottom right the figure shows the following standardised river flow time series: original daily river flow time series, smoothed river flow time series (smoothed using locally weighted scatter plot smoothing), river flow time series divided by 1.5, smoothed river flow time series divided by 1.5.....	26
Figure 2.1: Location of the 116 Benchmark catchments (black) and the 49 validation catchments (grey) used in this chapter. ....	41
Figure 2.2: The variogram parameters for a theoretical semi-variogram.....	46
Figure 2.3: Semi-variograms from daily river flow for the four identified clusters with the 95% confidence intervals (dark shaded area) and the upper and lower bounds of each cluster (light shaded area).....	50
Figure 2.4: Location of the catchments coloured by cluster. ....	50
Figure 2.5: Semi-variograms from daily precipitation data for the four identified clusters with the mean of each cluster (line) and the 95% confidence intervals (shaded area). ....	51
Figure 2.6: Box plots of characteristics which differ between all four clusters. Thick black line is the median value. Box shows the inter-quartile range. Black whiskers represent 1.5 times the inter-quartile range. Blue and red lines show the upper and lower 90% confidence intervals respectively and the circles show outliers. ....	52
Figure 2.7: Box plots of characteristics which differ between two or three clusters, as in Figure 2.6.....	53
Figure 2.8: Box plots of characteristics which do not differ between clusters, as in Figure 2.6. 54	
Figure 2.9: Relationship between the catchment characteristics shown as scatter plots with locally weighted smoothed red line and histograms. Correlation values are calculated using Spearman's rank.....	55
Figure 3.1: Locations of the catchments used in this chapter.....	76
Figure 3.2: Theoretical variogram.....	79
Figure 3.3: The time series resulting from the addition of artificial changes between 1987 and 1994 (shaded area) to normalised river flows for the South Tyne river.....	84
Figure 3.4: Changes in the variogram parameters resulting from the artificial changes to the time series for the South Tyne.....	85
Figure 3.5: Relationship between the variogram parameters when calculated using all the available data and the parameters using 90 % of the data. The red lines show the range of acceptable values. Any catchments with points outside the red lines were removed. ....	87
Figure 3.6: Percentage of catchments which exceed thresholds through time. ....	89
Figure 3.7: The average variance in 5-year variogram characteristics explained (adjusted R <sup>2</sup> ) by meteorological characteristics, calculated using the variables in the model with the lowest AIC value (calculated using IT) for each catchment.....	91
Figure 4.1: Flow diagram of the layout of this chapter. ....	107

Figure 4.2: Correlation of the Range and the Sill with different precipitation characteristics, the grey dashed line shows the zero line. ....	115
Figure 4.3: The amount of temporal variability explained for the Range and the Sill by the six uncorrelated precipitation characteristics (adjusted $R^2$ value). ....	115
Figure 4.4: The CV of the Range and Sill for each catchment respectively, grouped by cluster. ....	117
Figure 4.5: Scatter plot between the CV of the Sill and the CV of the Range. ....	117

# 1 Introduction

## 1.1 Background and rationale

River flow is the result of the complex relationship between climatic variability and the processes which occur within a catchment (Wagener et al., 2007). The processes within a catchment will control the pathway water takes through the catchment, influencing the proportion of water which travels via runoff, interflow or groundwater. The pathway water takes controls the lag between a precipitation event and the river's response, and therefore the dynamics of the river flow regime. Understanding the role catchment characteristics play in influencing the transformation from precipitation into river flow is a key aspect of hydrology which requires further research (Bloschl et al., 2013).

River flow is highly variable with several recent notable floods and droughts across the globe. Examples of flooding include: 2010 and 2013 in China and Pakistan; 2013 and 2014 in India; 2005, 2009 and 2015 across multiple countries in Africa; 1997, 2002, 2009 and 2010 across central Europe and 2010, 2013 and 2014 in the USA. Examples of drought include: 2010 – 2011 in China; 2012 - 2015 in the USA, 2006 in Australia and 2011 in East Africa. There have also been notable flood and drought events in the UK (e.g. 2004 – 2006 (Marsh et al., 2007), summer 2007 (Marsh, 2008), 2010 - 2012 (Kendon et al., 2013) and 2013 – 2014 (Muchan et al., 2015)). There is still a debate in the literature as to the relative impacts of different potential drivers on these extreme events. The drivers of river flow variability can be grouped into two groups: external factors (occur outside of the catchment) and internal (occur within the catchment). The external factors include meteorological variations which result in periods of increased extreme events or climatic non-stationarity which results in a change in the mean, variability or autocorrelation over time. The internal factors include abstractions and discharges in the river, land use change and modification of the river flow channel.

It is widely accepted that anthropogenic greenhouse emissions are already exerting a detectable influence on many climate variables, and it is expected that this will continue in future, with potentially profound implications for river flows. For example, the UK climate projections (UKCP09, Murphy et al. (2009)) show that by 2080 summers are

likely to be warmer and drier and winters will be wetter (Murphy et al., 2010); a number of studies have demonstrated such changes could modify future river flow regimes (e.g. Prudhomme et al., 2011; von Christerson et al., 2012). However, the predicted climate changes are highly uncertain due to: internal variability in the climate system, model uncertainty and emissions uncertainty (Hawkins and Sutton, 2009). Moreover, the large number of complex processes involved in determining the response of the river to precipitation variability means that the effects on hydrology will vary both spatially and temporally (i.e. throughout the year).

If realised, these changes could cause problems for water resource management. The changing precipitation dynamics (Environment Agency, 2008) along with an increasing population (ONS, 2008) and other social-economic drivers are likely to result in increased pressure on water resources even under lower emission scenarios (Arnell et al., 2013), especially for the driest parts of the UK (Hess et al., 2010). Furthermore, changes in flood or drought magnitude or frequency could have major economic and societal impacts (Rojas et al., 2013) as well as indirect health effects (Stanke et al., 2013). Several scenario-based modelling studies (e.g. Reynard et al. (2009) and Prudhomme et al. (2013b)) have shown that catchment characteristics are likely to influence a river's response to future changes in meteorological conditions. Thus, headline future projections of 'wetter winters, drier summers' are widely assumed to hold for large regions, with obvious impacts on hydrology, but the actual effect of future climate change will vary strongly in space, according to catchment properties (Bloschl et al., 2013). Therefore, it is important to understand how catchment characteristics influence the transformation of precipitation into river flow.

In order to identify the influence that catchment characteristics may have on how future climatic changes manifest themselves in river flows, it is necessary to investigate the precipitation-to-river flow relationship in historical river flow records using a sufficiently large set of catchments with diverse characteristics. The impact of the catchment characteristics should be investigated throughout the range of the river flow regime and not just the extremes. The catchment characteristics are key because, although the amount of water that enters the catchment is controlled by precipitation, catchments act to transform meteorological inputs into river flow outputs – this simple fact is the basis of

much of hydrology. The amount and rate at which water reaches the catchment outlet is influenced by a range of catchment characteristics, including:

- **Topography and soil type** affects the velocity of water through the system and the amount of infiltration.
- **Land cover** influences the amount of interception, infiltration and the macropores in the soil which will affect the lag time.
- **Rock and soil type** determines whether water can enter the rock unit. Rock type constrains the productivity of the aquifers; driving the amount of base flow.
- **Channel density** determines the average distance water has to travel to reach the channel and hence the lag time.
- **Catchment area and shape**, along with other factors, influence the shape of the hydrograph and the volume of water in the river.

Catchment characteristics influence four broad catchment processes: 1) partitioning– separation of water between horizontal and vertical pathways, 2) topology – connectivity (and hence efficiency) of the drainage network, 3) topography – hydraulic gradients controlled by elevation differences, and 4) release - the release of water either back to the atmosphere (evapotranspiration) or along the river channel and through the catchment outlet (Wagener et al., 2007). However, while much is understood about the processes involved in this translation (McDonnell, 2013), and decades of research (Beven, 2012) has advanced our capacity to model the phenomenon, there is still generally a lack of appreciation of the importance of the role of catchment properties in influencing observed hydrological variability, as typically reported in long-term studies of river flow.

Countless papers have looked at the relationship between catchment characteristics and river flow. These papers can be grouped into two broad categories: process based studies (investigate the catchment processes which occur in a small number of catchments) and regionalisation studies (identify similarities in numerous catchments). An overview of the literature and the limitations is given below, before section 1.2 provides the literature review from which the research gaps were identified.

Hrachowitz et al. (2013) provides a review of process based studies which were carried out during the prediction in un-gauged catchments decade (2003 to 2012). The review highlights advances in the understanding of the processes which are involved in

transforming precipitation into river flow as well as the need for further work investigating how un-gauged catchments are likely to be influenced by climate variability.

Numerous other papers have investigated similarities in river flow regimes with the aim of transferring data from gauged to un-gauged catchments through a statistical, data-driven approach. For example, Young (2006) and Merz and Blöschl (2009), who assess the benefit of including catchment characteristics (in addition to geographical location) when transferring river flow data to un-gauged catchments. However, there are disagreements in the benefit of including the catchment characteristics between these papers. In addition, there are studies which have grouped catchments based on one or more aspect of the river flow time series. For example, floods (Robson and Reed, 1999); low flows and flow duration curves (Holmes et al., 2005); seasonal flow indicators (Laizé and Hannah, 2010) and long-term average annual flow regimes (Bower et al., 2004). Although these studies highlight groups of catchments which have similarities in specific parts of the river flow regime, there is still a gap in the literature with no study grouping catchments based on how the catchment characteristics filter precipitation into river flow.

Other techniques have been developed for estimating the pathway water takes through the catchment, based on catchment characteristics, for example Hydrology Of Soil Types (HOST, Boorman et al. (1995)) which provides an estimate of the base flow index and standard percentage runoff based on the soil type in the catchment. The limitation to using HOST to provide an indication as to the dominant pathway water is taking through the catchments is that HOST will only capture differences which are implicit in the soil classification. Furthermore, HOST only provides an indication as to the percentage of water which comes from storage and runoff, hence will not capture the difference in the river flow dynamics.

As well as identifying homogeneous groups of catchments which have a similar precipitation-to-river flow relationship, it is crucial to assess how the catchment characteristics have influenced a river's response to historic climate variability. Numerous studies have investigated historical changes in the river flow regime across many parts of the world (e.g. Burn and Hag Elnur (2002), Canada; Stahl et al. (2010), Europe; for a review of research on past changes in Europe see Madsen et al. (2014)). However, these studies typically assess a specific aspect of the river flow regime (e.g.

mean or maximum flow) and none have assessed how the catchment characteristics modulate a river's response to meteorological variability. Therefore, there is no indication as to how the catchment characteristics influence temporal changes in the precipitation-to-river flow relationship. This overview of the literature has shown that there are still clear gaps in the literature:

- 1) None of the regionalisation techniques captures how the catchment characteristics transform precipitation into river flow.
- 2) Existing change detection techniques are not able to investigate how the precipitation-to-river flow relationship varies through time.
- 3) There are no published studies which analyse the influence that catchment characteristics have on how a river responds to meteorological variability.

The aim of this thesis is to evaluate the influence that the catchment characteristics have on a river's response to climate variability. Understanding the relationship between catchment characteristics and variability in the river flow is also fundamental to hydrology and key to data transfer between gauged and un-gauged catchments. In addition, this knowledge will provide more detail as to how the catchment characteristics are likely to modulate future changes in meteorological conditions. Finally, this knowledge will improve the ability to translate coarse scale meteorological projections to finer scale hydrological responses, which will be vital for informing plans for adaptation at the catchment scale. The aim will be addressed by answering three key objectives.

### **1.1.1 Objectives**

Throughout this thesis, the precipitation-to-river flow relationship is characterised by using temporal dependence; this term is used to describe the average relationship between river flow on a given day and river flow on the previous days. From a hydrological perspective, the temporal dependence characterises the variability and 'smoothness' of the river flow time series which are driven by the processes which occur within the catchment. In order to address each of the identified gaps, the three objectives of this thesis are:

- 1) Identify the role that catchment characteristics have on the temporal dependence structure of the river flow time series.



The temporal dependence structure will be calculated for each catchment and be used to divide the catchments into groups. For a given rainfall event it would be expected that the catchments in each group would respond in a similar way. Although these groups will be derived from the river flow data, differences in the catchment characteristics should be evident between the groups of catchments. The differences in catchment characteristics should make it possible to assign un-gauged catchments to a cluster with relative confidence. This will therefore provide: a) information as to the influence individual catchment characteristics are having on the precipitation-to-river flow relationship and b) an indication as to the precipitation-to-river flow relationship in un-gauged catchments. This research is presented in Chapter 2.

- 2) Detect changes in the temporal dependence structure over multi-decadal periods, and relate them to the potential meteorological drivers.

The second objective is to develop a new method which enables change in the temporal dependence structure (which characterises the precipitation-to-river flow relationship) (objective 1) to be detected and attributed to potential drivers. The attribution should identify the proportion of the changes which can be related to changes in precipitation characteristics. This will show how aspects of the river flow regime (e.g. variability or ‘smoothness’) are driven by different precipitation characteristics and hence different processes within the catchment. Therefore, the new change detection method should: utilise as much of the information available in the daily river flow data as possible; enable the change in each catchment to be captured; allow attribution of the changes and use a method which characterises the influence catchment characteristics have on the precipitation-to-river flow relationship. This research is presented in Chapter 3.

- 3) Assess the influence that the catchment characteristics have on how a river responds to meteorological variability.

The third objective is to investigate how the catchment characteristics influence the amount of temporal change which is detected in objective 2. The catchment characteristics will influence the resilience (stability of the precipitation-to-river flow relationship) and resistance (the amount of change in river flow per unit change in precipitation) of the catchment. The resilience of a catchment characterises the magnitude and time for which the precipitation-to-river flow relationship will deviate from the

average, following a precipitation anomaly. Therefore, throughout this thesis, a resilient catchment will have a relatively consistent precipitation-to-river flow relationship (i.e. the propagation of precipitation anomalies through the catchment is relatively constant). A catchment which is resistant but not resilient will have a non-linear precipitation-to-river flow relationship as the river's response will be modulated by the processes within the catchment. Identifying how the catchment characteristics influence a river's response to changes in meteorological variability will assist in making catchment specific management plans which can deal with a changing climate. This research is presented in Chapter 4.

### **1.1.2 Thesis structure**

The thesis layout is described below and an illustration of the thesis structure is shown in Figure 1.1. Chapter 1 reviews the literature used to identify the research gaps (section 1.2). Chapter 1 also introduces the indicators which are used throughout this thesis to characterise the precipitation-to-river flow relationship (section 1.3). Chapter 2 develops a method for investigating the average precipitation-to-river flow relationship and groups the catchments into similar clusters based on this relationship (published in Chiverton et al. (2015a)). Chapter 3 develops a new method for looking at temporal changes in the precipitation-to-river flow relationship (published in Chiverton et al. (2015b)). Chapter 4 investigates the relationship between the catchment characteristics (investigated in Chapter 2) and the temporal variability of the variogram parameters (investigated in Chapter 3). Chapter 5 discusses the findings in chapters 2 to 4, highlights the major findings and suggests areas for future research.

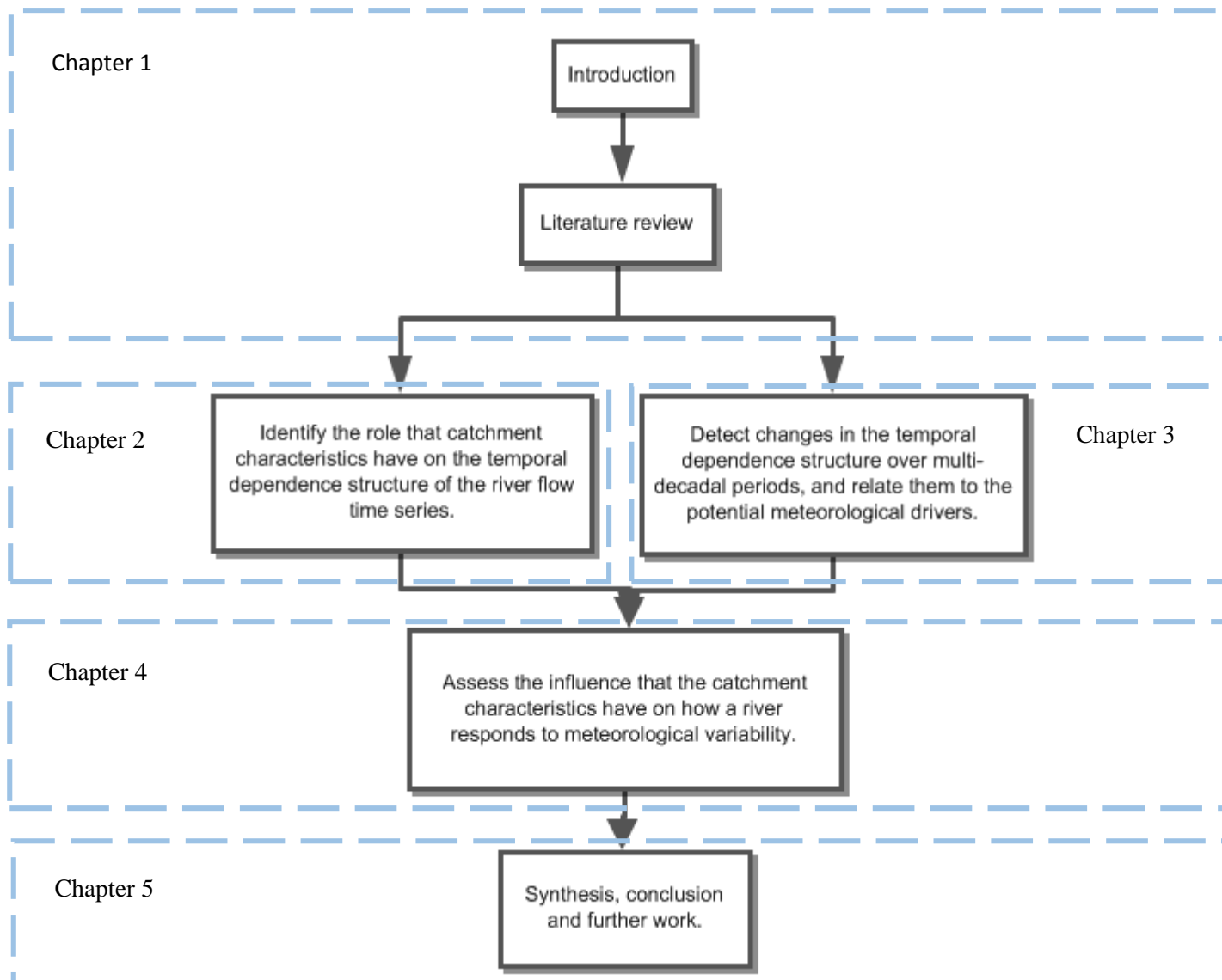


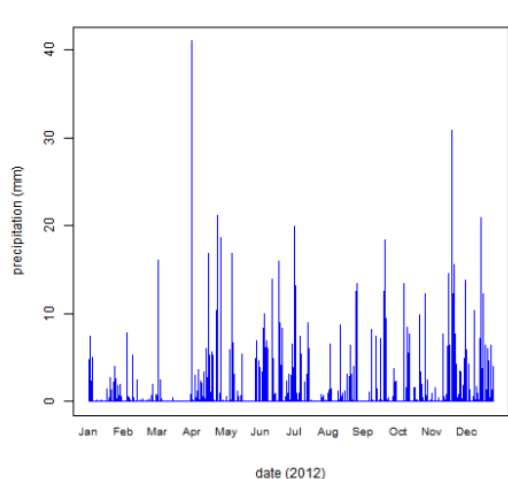
Figure 1.1: Schematic diagram of the thesis.

## **1.2 Literature review**

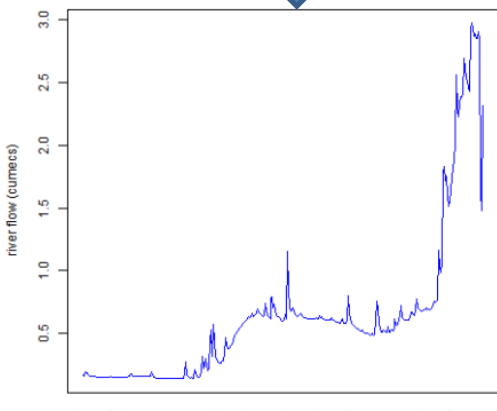
This section identifies research gaps for investigation. The review is split into three parts. Firstly, the influence that catchment characteristics have on the precipitation-to-river flow relationship is analysed (section 1.2.1). Secondly, the evidence for change in river flow is reviewed (section 1.2.2). Thirdly, the influence that catchment characteristics have on the stability of the precipitation-to-river flow relationship is discussed (section 1.2.3). This chapter then describes the indicators which are used to characterise the precipitation-to-flow relationship throughout the thesis (section 1.3).

### **1.2.1 The influence of the catchment characteristics on the precipitation-to-river flow relationship**

A river's response to changes in atmospheric conditions is not simple; the processes which occur within a catchment form a complex system (Kumar, 2007) due to the multiple interacting processes (Bloschl et al., 2013). A schematic of some of the processes along with the catchment characteristics which influence them is shown in Figure 1.2. These complex interactions will vary between catchments and through time depending on the antecedent conditions.



date (2012)



date (2012)

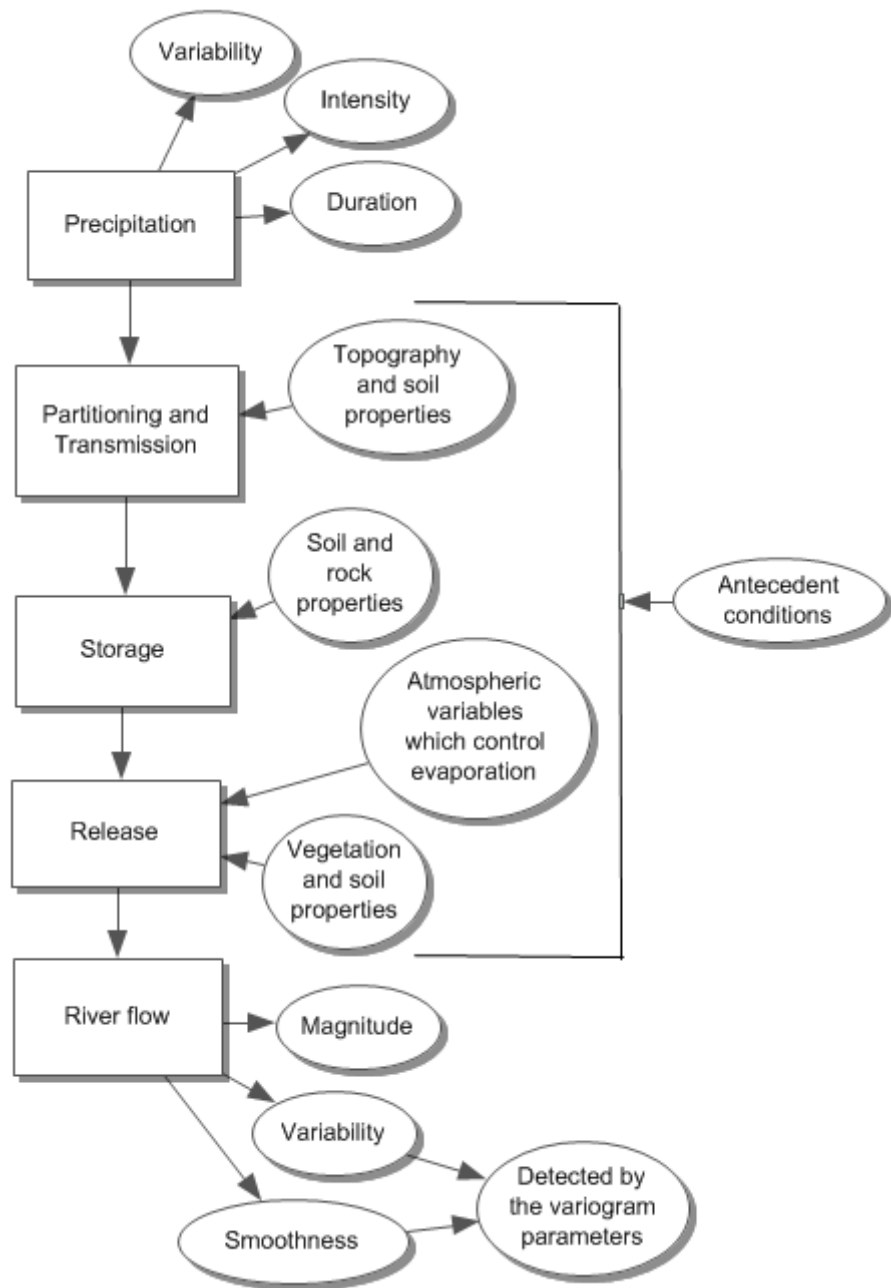


Figure 1.2: The major controls on the processes within a catchment which are responsible for transforming precipitation into river flow. The catchment average precipitation and river flow data are from the river Foston Beck (station number 26003).

There have been several studies which have assessed the influence of catchment characteristics. These studies can be grouped into two broad categories (process based studies and regionalisation studies).

#### **1.2.1.1 Process based studies**

Process based studies incorporates research which uses either detailed catchment measurements or physically based models to investigate the detailed processes which occur within a catchment. Research on the processes which occur within a catchment was particularly prominent during the IAHS Prediction in Un-gauged Basins decade (PUB), 2003 – 2012. The PUB decade provided new information on the processes which occur within a catchment. These highlighted the spatial and temporally varying processes which create the complexity in the precipitation-to-river flow relationship. For example: runoff generation (Anderson et al. (2009), McGlynn et al. (2004), and McGlynn and McDonnell (2003)); the influence of soil moisture deficits (McNamara et al. (2005) and Tromp-van Meerveld and McDonnell (2006)); preferential flow paths (Zehe et al. (2007), Vogel et al. (2005) and Weiler and Naef (2003)); antecedent wetness (Uchida et al. (2005) and Buttle and McDonald (2002)). A detailed review of the findings from the PUB decade can be found in Hrachowitz et al. (2013).

In principle, the most accurate way to characterise how the processes within the catchment influence the precipitation-to-river flow relationship would be to use tracer experiments (e.g. McGuire et al. (2005), Broxton et al. (2009) and Tetzlaff et al. (2009)). However, tracer studies are generally undertaken in experimental catchments, and data are not available at large spatial and temporal scales. Therefore, the vast majority of studies examining the precipitation-to-flow relationship have used hydrological models in order to model the processes which occur within the catchment. There have been several reviews of hydrological modelling (e.g. Wagener et al. (2004), Pechlivanidis et al. (2011) and Beven (2012)). While rainfall-runoff models provide a valid conceptual tool for understanding key processes in catchment-based studies, there are several limitations with hydrological models (Beven, 2001), particularly when applying them to a large range of catchments:

- **Uncertainty:** each additional parameter in a model increases the uncertainty (Beven, 1993).
- **Parameter estimation:** the use of uncertain data for calibration will lead to uncertainty in the parameter estimation (McIntyre et al., 2002).
- **Model structure assumptions:** It is assumed that the model parameters which are calibrated subsequently are reflecting the true processes. For example, the calibration process may change the lag time between precipitation and river flow, however the shorter lag time could be due to a number of processes.
- **Assume stationary:** The model may not perform well if the precipitation-to-river flow relationship is non-stationary as the calibration period will not represent the rest of the time series.
- **Mathematical approximations:** models are only approximating the processes which are occurring in the catchment and therefore cannot be relied upon to accurately capture the precipitation-to-river flow relationship all the time.

Due to the limitations associated with hydrological modelling and the limited amount of tracer data available it is advantageous to use data driven regionalisation techniques to investigate similarities in the precipitation-to-river flow relationship between catchments when good quality hydrometric data are available. In the UK there is good quality, validated, daily river flow data for many catchments as well as catchment averaged daily precipitation data. In addition, the UK has detailed descriptors of the catchments physical attributes (catchment characteristics). Using the observed data has the advantage of being readily available and eliminates the uncertainties that arise from calibrating models.

### 1.2.1.2 Regionalisation studies

In terms of hydrology, regionalisation is grouping catchments based on similarities in one or more aspect of the hydrological regime. There have been countless regionalisation studies which can be grouped into three broad categories based on how hydrological similarity is quantified: climate similarity, catchment similarity and runoff similarity. This section focuses on catchment and runoff similarity.

The desire to use similarities between catchments to transfer information from gauged to un-gauged catchments is not new. The flood studies report (NERC, 1975) set out detailed methods for estimating river flows at un-gauged catchments which was later superseded by Institute of Hydrology (1999). Even though every catchment is unique (Beven, 2000) regionalisation should be possible based on the theory that catchments with similar

catchment characteristics and climatic conditions will have similar river flow regimes. The desire to group catchments based on hydrological similarities has led to numerous studies which cluster catchments based on one or more aspect of the hydrological regime, some examples are presented below:

- High flows: Burn et al. (1997) cluster catchments based on the mean date of the annual flood and a catchment similarity measure using L-moment ratios calculated from the magnitude of the peak flows, proposed by Hosking and Wallis (1993) for 217 catchments in Canada. Ramachandra Rao and Srinivas (2006) investigated several clustering methods for grouping 245 catchments based on the magnitude and date of occurrence of peak flows in the USA. Srinivas et al. (2008) groups the same 245 catchments in the USA based using the linear self-organising feature maps which are clustered using Fuzzy c-means clustering.
- Low flows: Laaha and Blöschl (2006) compares four methods for grouping catchments based on their performance in predicting low flow discharges ( $q_{95}$ ) for 325 catchments in Austria. Dodangeh et al. (2014) clustered 26 catchments in Iran based on their 7 day minimum flow series.
- Flow Duration Curves (FDCs): Mendicino and Senatore (2013) produce regional estimates of FDCs for 19 catchments in southern Italy. Sauquet and Catalogne (2011) use FDCs amongst other physical and hydrological characteristics in order to obtain homogeneous regions in France.
- Soil type: Boorman et al. (1995) (UK) and Bormann (2010) (Australia, USA, Canada and Germany) group soil into homogeneous classes based on hydrological properties.
- Mean Transit Time (MTT): Hrachowitz et al. (2009) analysed MTT for 20 catchments in Scotland and identified the catchment controls on the MTT.
- Climate: Unal et al. (2003) and Wigley et al. (1984) identify regions which have similar atmospheric characteristics for Turkey and the UK respectively.
- Catchment function: Sawicz et al. (2011) used six characteristics calculated from precipitation and river flow data for 280 catchments in the USA.
- Identifying and characterising the dominant catchment function through assessing the hydrological regime (Oudin et al., 2008, Lyon and Troch, 2010, Haltas and Kavvas, 2011).
- As well as clustering catchments for hydrological purposes, catchments have been grouped for other purposes. For example, ecology, where the river flow conditions are important for aquatic habitats (e.g. Olden and Poff (2003) and Monk et al. (2007)).

The aforementioned studies provide detailed information about the similarities in catchments for a range of aspects of the river flow regime, but there are shortcomings in



existing approaches. Firstly, most classification techniques use a limited aspect of the river flow regime (e.g. annual or seasonal averages, minimum or maximum data). Therefore, a lot of information in the daily river flow data is discarded before the catchments are grouped, and the catchment characteristics may not have a large influence on the aspect of the river flow regime which is being analysed. Secondly, at the catchment scale there are still often disparities between studies in the importance given to catchment characteristics in transferring information from gauged to un-gauged catchments (i.e. whether the catchment characteristics add information rather than just using location) (e.g. Young (2006) and Merz and Blöschl (2009)). Disparities between studies in the importance of catchment characteristics was also shown by Salinas et al. (2013) who carried out an assessment of different methods used to regionalise both floods and droughts across multiple climatic regions.

Studies investigating aspects of the hydrological regime which are controlled by the catchment characteristics (e.g. mean transit time and catchment function) found a limited relationship between the groups obtained from river flow and precipitation characteristics, and the catchment characteristics. This is demonstrated by Oudin et al. (2010) who shows that the overlap between catchment characteristics and response is only significant for 60% of catchments; the paper attributes this to some of the catchments having specific hydrological behaviour and the role of the subsurface processes not being accurately described by the catchment characteristics. This is also supported by Ali et al. (2012) who identified that the catchments grouped by their characteristics did not match those which are grouped by flow indicators, mean transit times or storage estimates.

Therefore, there is a need for further research into the influence that catchment characteristics have on the precipitation-to-river flow relationship throughout the river flow regime. A general classification process should be possible based on similarities in catchment function (i.e. the translation of precipitation into river flow, (Black (1997), Blöschl et al. (2013)). Wagener et al. (2007) and Wagener et al. (2010) expanded this idea by thinking of catchments as non-linear space-time filters which control a number of processes, broadly consisting of: partitioning, storage and release of water. The broad similarities in catchment function may be a result of the co-evolution between climate, soils, vegetation and topography (Sivapalan, 2006). Therefore, if the catchment

characteristics in the catchment are similar between catchments, they should also exhibit a similar catchment function (Winter, 2001). Understanding how a catchment function occurs in a given catchment would shed new light on the reasons behind the similarity or dissimilarity that is exhibited between catchments (Gottschalk, 1985, Dooge, 1986) and the influence of catchment characteristics on the dominant pathway water takes through the catchment.

### **1.2.2 Understanding historical changes in the river flow time series**

Increased greenhouse gas emissions have led to a rise in radiative forcing which has increased more rapidly since 1970 (IPCC, 2014). Recent studies have shown that, in the UK, there is likely to be an increase in the length of dry spells in the future as well as increases in rainfall intensity (e.g. Watts et al., 2015). However, the impact of climate change on the river flow regime is still unclear (Bloschl and Montanari (2010), Sun et al. (2012)). When projections are downscaled to the regional scale then there is considerable variability and disagreement in the sign of the change with some variables (e.g. precipitation) in some regions and seasons (Bates et al., 2008). This is true for the UK, where weather patterns are influenced by the North Atlantic Oscillation (fluctuations in the gradient of atmospheric pressure at sea level which influence the strength of westerly winds and storm tracks), storm tracks and blocking (Murphy et al., 2009). Furthermore, predicting the response of an individual river to future changes in meteorological conditions is likely to be further complicated by the influence of the catchment characteristics, as indicated by scenario-based projection studies (e.g. Capell et al. (2014), Prudhomme et al. (2013a)).

The increase in greenhouse gas emissions and recognition of non-stationarity has resulted in a lot of work investigating non-stationarity in hydrological regimes. The non-stationarity in the hydrological data can be caused by several factors:

**Climate conditions:** drive the input of water into the system and hence drive the temporal variability exhibited in a river flow time series. Precipitation is highly spatially and temporally variable in the UK. It varies spatially due to the prevailing westerly airflow interacting orographically with the western upland chain, leading to a gradient in annual rainfall of an order of magnitude between the wettest parts of the North West and the

driest parts of the South East. Temporal variability occurs over a range of time scales (e.g. the event scale driven by local atmospheric conditions, seasonal cycle driven by the earth's orbit around the sun, inter-annual scale driven by changes in atmospheric circulation (e.g. via the North Atlantic Oscillation, NAO)). Temporal variability in precipitation is demonstrated by Osborn et al. (2000) who describes how the intensity and distribution of daily precipitation amounts in the UK has changed between 1961 and 1995, becoming on average more intense in winter and less intense in summer. Osborn and Hulme (2002) analysed daily rainfall data between 1961 and 2000 identifying an increase in multi-day sequences of heavy precipitation events for the winter and a decrease for summer. Furthermore, New et al. (2001) show mix trends in annual precipitation for the UK depending on the part of the UK and the length of the record being analysed. These are highly variable, temporally and spatially, controlled by many factors including: temperature, surface topography, ocean circulation and land cover.

**Direct human influences:** encompasses a wide range of changes. For example, urbanisation (Martin et al., 2012), deforestation (Andréassian, 2004), and changes in agricultural practices (Mahmood et al., 2006, Parton et al., 2005). Land use change will influence: evapotranspiration, infiltration, macropores in the soil and surface roughness. The influence of land use change is discussed by O'Connell et al. (2007) who highlight that, from a flooding perspective, there is substantial evidence that modern land-use management practices have enhanced surface runoff generation at the local scale. However, there is limited evidence of the influence of land use change at the larger catchment scale (>10km<sup>2</sup>). In addition, Climent-Soler et al. (2009) and Archer et al. (2010) identified evidence that land cover change influences the river flow dynamics for two UK catchments. Finally, Prosdocimi et al. (2015) found that urbanisation influences high flows for two catchments in northern England. In addition, changes in abstractions (ground and surface water) and the building of reservoirs will alter the magnitude and variability of the river flow.

**Hydrometric influences:** these cause artificial changes (i.e. present because the true conditions are not being recorded accurately). A degree of uncertainty in the data is created from temporal changes in gauge type and alteration of structures (Beven et al. (2008)).

### 1.2.2.1 Previous change detection studies

There has been lots of discussion and investigations regarding the potential non-stationarity in the hydrological regime (e.g. Koutsoyiannis (2013)) resulting in fluctuations to river flow and groundwater levels. Non-stationarity could be present in several different aspects of the hydrological regime: magnitude (e.g. changes in the maximum, minimum, mean, median, x day min / max); frequency of events / variability (e.g. frequency and duration of peaks over and under thresholds, standard deviation); timing of events (e.g. summer to winter ratio, timing of the start of recharge for groundwater, timing of large / small events) and relationships (e.g. correlation between two measured variables, propagation of a rainfall anomaly through surface flow and groundwater levels). Below is a selection from the vast amount of literature demonstrating that it is possible to detect non-stationarity in the aforementioned aspects of the hydrological regime.

**Magnitude:** Hannaford and Marsh (2006) and Hannaford and Marsh (2008) investigated monotonic changes in low and high river flows respectively. Both studies showed that in general stronger changes were found in maritime-influenced upland catchments in the North and West of the UK. This was shown to coincide with a (then) shift towards a positive phase of the North Atlantic Oscillation. A detailed review of papers assessing changes in the magnitude in the UK can be found in Hannaford (2015). Stahl et al. (2010) carried out a similar investigation for catchments across Europe. They found regional patterns of trends in the annual flow with negative patterns in the South and East of Europe. In addition the study identified that there are positive trends in the winter flows and negative trends in the catchments which have their low flows in summer.

**Frequency and duration:** Archer and Newson (2002) developed the ‘pulse’ methodology which identifies change in the frequency or duration of a pulse of water above pre-defined thresholds. Archer (2003) used this method to investigate river flow changes in a large (335 km<sup>2</sup>) and small (1.5 km<sup>2</sup>) catchment. The results showed considerable variability in the number of pulses above thresholds. Archer (2007) used the same method on two further small catchments again demonstrating non-stationarity in the river flow time series.

**Timing of events and seasonality:** Morris et al. (2012) developed indicators designed to detect changes in the timing, frequency and duration of river flow events. The report described 10 different indicators which can be used to assess changes in the hydrological regime between two time periods (1961 – 1990) and (1990 – 2007). Out of the 10 indicators, 8 were shown to detect a difference between the two time periods, the ones specifically designed for assessing a change in the timings include: ratio between different seasons; highest and lowest n days; day of the year when p% of flow is reached and day of the year with the maximum flow. In an extension to the pulse method, Archer et al. (2010) investigated the rate of increase for a pulse in the river flow time series and found statistical changes to the hydrological time series. Macdonald et al. (2010) counted peaks over a threshold, using the method outlined in Bayliss and Jones (1993), as well as the mean day of flood for several catchments in Wales over a 30-year time period.

**Precipitation-to-river flow relationship:** Lavers et al. (2010) investigated the relationship between the large scale drivers, precipitation and river flow and found stronger relationships between the atmospheric drivers and precipitation than between the atmospheric drivers and river flow. The weaker relationship with the river flow identifies the importance of the catchment characteristics in modulating the climatic inputs. Laizé and Hannah (2010) investigated the influence that catchment characteristics have on modulating seasonal flows. The paper demonstrates that the upland, impermeable catchments have a stronger relationship with regional climate characteristics (e.g. catchment scale precipitation) and that the influence of the catchment characteristics on the precipitation-to-river flow relationship varies between seasons. Both these studies found weaker relationships in lowland catchments in the South East due to substantial lag times between precipitation and the river flow signal caused by storage in groundwater, a finding also borne out in drought studies (e.g. Fleig et al. (2011)). Sawicz et al. (2014) investigated how their classifications of catchments based on catchment function in Sawicz et al. (2011) varied between decades. As their classes were based on the catchment function (i.e. the precipitation-to-river flow relationship), this identified how the catchment function changes through time. Van Loon and Laaha (2014) assessed the role catchment characteristics have on controlling drought characteristics, identifying that both drought duration and deficit are influenced by the catchment characteristics.

As well as looking at the precipitation-to-river flow relationship, several studies have looked at the relationship between other aspects of the hydrological regime and precipitation. Boutt and Smoth (2011) compared anomalies in the groundwater to anomalies in precipitation temperature and river flow in order to understand the sensitivity of the ground water to change. The report found the groundwater regime to be non-stationary with no significant correlation between precipitation and groundwater level. Eltahir and Yeh (1999) investigate the propagation of hydrological anomalies through the hydrological cycle (looking at the flux of atmospheric water vapour, incoming solar radiation, precipitation, soil moisture content, aquifer water levels and river flow); concluding that seasonal variability in evaporation, soil moisture, aquifer level and river flow is driven by changes in incoming solar radiation. Whereas precipitation is the major driving force in the inter-annual variability expressed in the system.

#### **1.2.2.2 Comparing results between studies**

Although the studies in section 1.2.2.1 demonstrated non-stationarity, the type of statistical change (e.g. change in mean or variance, gradual or step change) and direction (e.g. increase or decrease) of change are often not comparable between studies as they depend on many factors:

**Statistical technique:** The statistical technique can impact on the findings because changes in the observed hydrological time series can be in different forms: magnitude versus variance around the mean, short-term versus long-term, gradual versus abrupt and periodic versus episodic (Merz et al., 2012). As demonstrated in Shao et al. (1999) a hydrological time series will often exhibit several different statistical changes through time. Each statistical technique will be able to detect different types of change e.g. the Mann Kendall test (used to investigate monotonic changes through time) is employed to detect gradual long-term change in magnitude.

**Chosen indicator:** Indicators will be influenced by certain physical changes in the catchment, some of which may have changed more than others.

**Time period:** Several studies have highlighted the dependency on the time period investigated. Chen and Grasby (2009) investigated the time delay between climate variables and groundwater, the paper shows that the start and end dates of the record affected the time delay calculated. This is likely caused by the location of wet and dry periods and the asymmetric response of ground water level to floods and droughts identified in Eltahir and Yeh (1999). Further to the above Baggaley et al. (2009) carried out a monotonic trend test on a long record (1929 – 2004) demonstrating that monotonic trend tests are sensitive to the start and end date of the record. More recently this was also demonstrated by Stahl et al. (2010) and a follow up paper (Hannaford et al., 2013).

**Catchment:** The choice of catchment could also influence the findings due to two factors. Firstly, the location may have an influence because precipitation changes may not be uniform across the UK (Osborn et al., 2000). Secondly, different catchments will have different characteristics; these characteristics could influence what change is seen in the indicators. Hannaford et al. (2013) showed that at a national scale there are spatial patterns, likely to be caused by unequal changes in atmospheric conditions (e.g. driven by the North Atlantic Oscillation). However, there are also variations at a local scale, potentially caused by different catchment characteristics moderating changes to the flow regime.

With regards to identifying the influence that catchment characteristics have on how a river responds to temporal changes in precipitation, the previous trend detection studies have several limitations. Firstly, the results from previous studies which look at changes in different aspects of the river flow regime cannot be compared to give a holistic indication as to how the catchment characteristics are influencing a river's response to changes in precipitation. Furthermore, the majority of trend detection papers use the Mann-Kendall trend test which will show the presence of monotonic trends. These tests are influenced by the presence of autocorrelation in the data as well as the start and end dates. In addition, monotonic trend tests do not provide information as to when in the time series change occurred. A further limitation in many of the trend detection studies is that only a specific part of the river flow regime is investigated (e.g. minimum, maximum or frequency of peaks over / under a threshold). This means that only a small amount of the information in the daily river flow data is used. Furthermore, these studies were not able

to show how the catchment characteristics are influencing the temporal stability in the precipitation-to-river flow relationship. Finally, there are a lack of studies which attribute the detected changes to meteorological drivers. Most studies either make inferences about the potential drivers or link the changes to large scale atmospheric drivers (e.g. the North Atlantic Oscillation) in a rather qualitative way, rather than quantifying relationships between changes in climate drivers and river flow. Attribution is an important step as it will show if there is a different relationship between the drivers and aspects of the river flow in different catchments.

### **1.2.3 The stability of the precipitation-to-river flow relationship**

This thesis is primarily investigating how the catchment characteristics influence how a river responds to meteorological variability (section 1.2.2). However, it is also important to look at how temporally stable the precipitation-to-river flow relationship is. This will provide information about the range of pathways which water takes through the catchment as well as the behaviour of the catchment (i.e. whether the propagation of precipitation signals through the catchment are dependent on thresholds). This information is important because a lot of hydrological predictions assume that the precipitation-to-river flow relationship is temporally stationary. However, changing climate may result in a different precipitation-to-river flow relationship (Blöschl and Montanari, 2010) which would have implications for the prediction of river flows (Peel and Blöschl, 2011) and catchment specific management plans.

The stability (i.e. the magnitude and duration of deviations in the precipitation-to-river flow relationship from the average values) of the precipitation-to-river flow relationship will depend both on the meteorological changes and the catchment characteristics (Buttle, 2006). There have been multiple studies which have assessed the stability of the precipitation-to-river flow relationship. For example, Carey et al. (2010) investigated the stability of the precipitation-to-river flow relationship for catchments in Sweden, Scotland, the United States and Canada, identifying that upland catchments have the most stable precipitation-to-river flow relationship. In addition Saft et al. (2015) investigates temporal changes in the precipitation-to-river flow relationship for catchments in



Australia finding that long-term drought is more likely to influence the precipitation-to-river flow relationship in drier and flatter catchments.

The precipitation-to-river flow relationship represents a range of catchment responses from wet through to dry periods. The precipitation-to-river flow relationship can be changed by factors within a catchment (land management change, precipitation properties, temperature, etc) or outside the catchment (climate forcing) (Saft et al., 2015). If the precipitation-to-river flow changes, it means that there has been a change in the partitioning, transmission, storage or release of water in the catchment.

There are several reasons why a change in the precipitation-to-river flow relationship would occur. For example: a change in the precipitation regime, which results in more intense rainfall events, would increase the proportion of river flow which travels via a fast pathway through the catchment. In addition, a change in the evapotranspiration will influence the antecedent conditions of the catchment including the soil moisture. Therefore, a proportion of the next precipitation event will fill the storage before water starts moving towards the channel (Tromp-van Meerveld and McDonnell, 2006). However, it has been noted that during extreme droughts soil crusting may occur which would increase the amount of runoff for subsequent rainfall (Descroix et al., 2009). Finally, a change in land use could alter the pathway water takes through the catchment (Peel et al., 2001).

There have only been a small number of studies which have assessed the relationship between the stability of the precipitation-to-river flow relationship and the catchment characteristics. Moreover, none of these studies have linked individual catchment characteristics to the stability of the precipitation-to-river flow relationship. Some papers, such as Carey et al. (2010), assess the stability in the raw river flow data (e.g. average monthly values). However, there are two limitations with this study. Firstly, only upland catchments were investigated meaning that the influence of groundwater cannot be assessed. Secondly, the relationship between mean monthly river flow and the catchment characteristics has not been established, meaning that precipitation or evapotranspiration could be causing the difference in stability between the catchments rather than the catchment characteristics. Sawicz et al. (2014) assessed temporal changes in catchment function which had previously been shown to be related to the catchment characteristics

(Sawicz et al., 2011). However, the study was unable to relate the identified changes to the catchment characteristics, this is likely to be at least partly caused by the clustering which was used to detect decadal changes.

### **1.3 Characterising the precipitation-to-river flow relationship**

The multiple interactions (over space and time) between the processes which occur within a catchment result in a complex system. The catchment filters rainfall into runoff and hence alters the dynamics of the river flow time series. Despite much detailed experimental and modelling work on individual catchments, there is a lack of understanding of how the catchment characteristics influence the precipitation-to-river flow relationship, and particularly how the effects of catchment properties combine with one other. In order to tackle the central aim of this thesis (to understand the effect of catchment characteristics on the river flow response to climate variability) there is firstly a pressing need to understand how catchment characteristics affect the precipitation-to-river flow relationship in a wide diversity of catchments representative of the heterogeneous climate and landscape of the UK. It is also clear that this should be done in a multivariate setting, bringing together numerous catchment characteristics.

There are several different indicators which provide information about aspects of the river flow time series (e.g. seasonality, peaks over thresholds, variability, periodicities, maximum flows). However, hydrology is yet to develop a process for characterising the hydrological differences between catchments. Wagener et al. (2007) suggested that the hydrological response (e.g. river flow characteristics and soil moisture patterns) should provide an indication of the hydrological functions (partitioning, transmission, storage and release) which occur in the catchment. The response of certain hydrological variables will provide an indication as to how the catchment characteristics have influenced the filtering of precipitation into river flow. The degree to which a catchment's function is characterised by the hydrological response will be dependent on both the time period investigated and the hydrological responses investigated. Certain aspects of the hydrological response will be more dependent on the processes within the catchment which are controlled by the catchment characteristics. For example, peak annual river flows are more dependent on the magnitude of the precipitation than the processes within

the catchment, whereas low flows depend more on release from stored sources. The rate at which water travels through the catchment (which depends on the partitioning, transmission, storage and release) will determine the amount of short-term variability in the precipitation which reaches the river.

The river flow time series has less short-term variability than the precipitation time series and has a larger amount of temporal dependence (i.e. river flow on a particular day is at least partly dependent on the river flow on the previous days). Therefore, short-term variability and the temporal dependence structure are dependent on the precipitation-to-river flow relationship which is influenced by the processes which occur within a catchment. An indicator is needed which will be able to capture the temporal dependence structure which will be related to the short-term variability and ‘smoothness’ of the river flow time series.

The temporal dependence structure is often characterised using autocorrelation. However, when applied to hydrological data autocorrelation has limitations. Firstly, multiple pairs of observations (in a time series a pair refers to data separated by the same lag, e.g. 1 day) are required in order to calculate autocorrelations. However, many observational records are incomplete. Secondly, the autocorrelation function is only defined for a stationary processes which may not hold true for a hydrological time series. In order to overcome these limitations the temporal dependence structure can be calculated using the squared difference between paired observations, an idea often used in geostatistics. The function based on squared differences is called the (semi-)variogram and has the advantage of being defined for a wider range of processes (intrinsic processes).

Variograms have been widely used in spatial hydrology (e.g. Skøien et al. (2006) and Bhowmik and Cabral (2015)). Skøien et al. (2006) use variograms to capture the processes which occur in the catchment and use this information along with catchment boundaries to estimate river flow-related variables at un-gauged catchments. Bhowmik and Cabral (2015) used variograms to spatially in-fill precipitation data in a data-scarce region. However, variograms are rarely used in a time series context. Skøien et al. (2003) is the only paper to use variograms to investigate the influence of space and time scales in hydrology. They show that precipitation has the shortest amount of temporal dependence followed by river flow then soil moisture and groundwater, this is driven by

water moving into the sub-surface which removes some of the short-term fluctuations and imposes a longer memory. De Iaco et al. (2013) discusses the differences between the spatial and temporal approaches and demonstrates an application for the variogram in time series analysis.

The variogram is the best way of calculating the temporal dependence structure in hydrological data and hence characterising a river's response to variability in the precipitation. Being able to characterise this relationship thus potentially enables regionalisation based on the precipitation-to-river flow relationship to be carried out, and temporal variability in the precipitation-to-river flow relationship to be analysed.

A variogram is created by calculating the difference between the values of river flow in the same time series which are separated by the same time interval. A variogram has several parameters, shown in Figure 1.3:

- **Sill:** semi-variance where the gradient of the variogram is zero.
- **Range:** the lag time at which the variogram reaches the Sill Temporal dependence is essentially zero beyond the Range.
- **Nugget:** the variability which occurs at the sub-daily time scale plus measurement error.
- **Partial Sill:** the Sill minus the Nugget

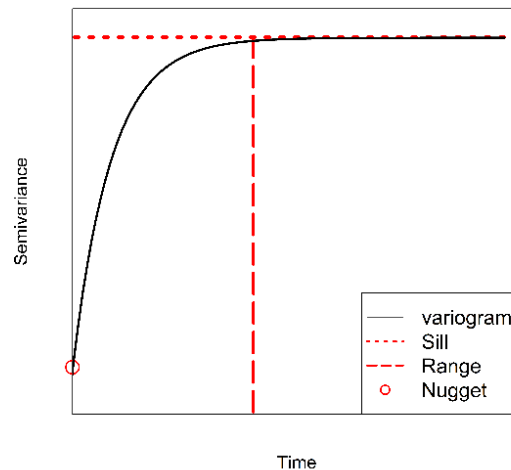


Figure 1.3: The variogram parameters for a theoretical variogram.

The variogram parameters characterise different parts of the river flow regime and therefore will depend on different processes within the catchment. The Sill is best thought of as capturing the total amount of variability (i.e. difference between largest and smallest values). A large Sill will represent a river which has a large amount of variability on a scale of days to months. The Range is best thought of as the 'smoothness' (i.e. whether the river flow time series is dominated by high or low frequency components) of the river flow time series. A large Range is indicative of a river for which change happens gradually and therefore there is not often a large difference between river flow on successive days. The Nugget will also be affected by the smoothness and the amount of variability in the river flow time series. A river which has good quality river flow data

(i.e. collected with little or no error over the full range of flows) and little variability at the sub 24 hour time scale will have the smallest Nugget.

The relationship between the variogram parameters and the river flow time series is demonstrated in Figure 1.4. The figure shows four plots of a 1-year section taken from a 30-year time series (the original and three manipulated time series). The variogram parameters for each variation of the time series were calculated using the full 30-year record. The figure demonstrates that the smoother time series (top and bottom right) have the longer Range and that the time series with the smallest difference between the largest and the smallest values (bottom left and right) have the smallest Sill.

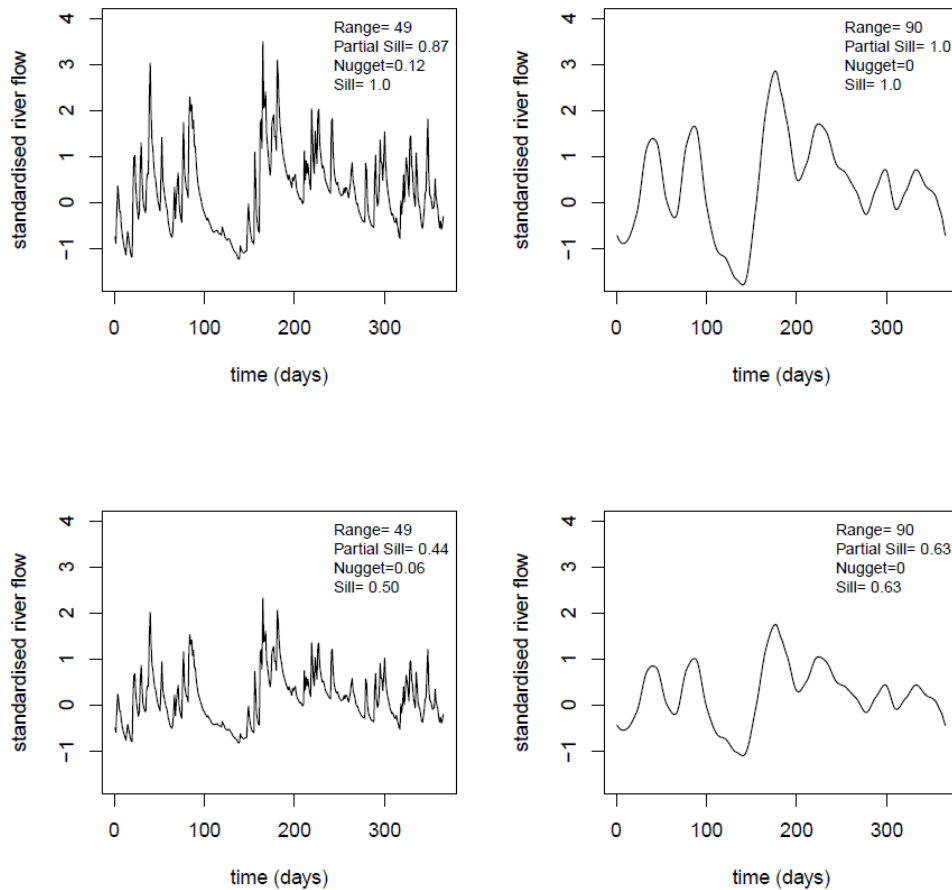


Figure 1.4: From top left to bottom right the figure shows the following standardised river flow time series: original daily river flow time series, smoothed river flow time series (smoothed using locally weighted scatter plot smoothing), river flow time series divided by 1.5, smoothed river flow time series divided by 1.5.

## 1.4 References

- ALI, G., TETZLAFF, D., SOULSBY, C., MCDONNELL, J. J. & CAPELL, R. 2012. A comparison of similarity indices for catchment classification using a cross-regional dataset. *Advances in Water Resources*, 40, 11-22.
- ANDERSON, A. E., WEILER, M., ALILA, Y. & HUDSON, R. O. 2009. Subsurface flow velocities in a hillslope with lateral preferential flow. *Water Resources Research*, 45.
- ANDRÉASSIAN, V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*, 291, 1-27.
- ARCHER, D. 2003. Scale effects on the hydrological impact of upland afforestation and drainage using indices of flow variability: the River Irthing, England. *Hydrology and Earth System Sciences*, 7, 325-338.
- ARCHER, D. & NEWSON, M. 2002. The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. *Journal of Hydrology*, 268, 244-258.
- ARCHER, D. R. 2007. The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales. *Journal of Hydrology*, 347, 487-496.
- ARCHER, D. R., CLIMENT-SOLER, D. & HOLMAN, I. P. 2010. Changes in discharge rise and fall rates applied to impact assessment of catchment land use. *Hydrology Research*, 41, 13-26.
- ARNELL, N. W., LOWE, J. A., BROWN, S., GOSLING, S. N., GOTTSCHALK, P., HINKEL, J., LLOYD-HUGHES, B., NICHOLLS, R. J., OSBORN, T. J., OSBORNE, T. M., ROSE, G. A., SMITH, P. & WARREN, R. F. 2013. A global assessment of the effects of climate policy on the impacts of climate change. *Nature Clim. Change*, 3, 512-519.
- BAGGALEY, N. J., LANGAN, S. J., FUTTER, M. N., POTTS, J. M. & DUNN, S. M. 2009. Long-term trends in hydro-climatology of a major Scottish mountain river. *Sci Total Environ*, 407, 4633-41.
- BATES, B. C., KUNDZEWICZ, Z. W., WU, S. & PALUTIKOF, J. P. 2008. Climate change and water. Geneva: IPCC Secretariat.
- BAYLISS, A. C. & JONES, R. J. 1993. *Peaks-over-threshold flood database: Summary statistics and seasonality*, Institute of Hydrology, UK, Institute of Hydrology.
- BEVEN, K. 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. *Advances in Water Resources*, 16, 41-51.
- BEVEN, K. 2001. How far can we go in distributed hydrological modelling? *Hydrol. Earth Syst. Sci.*, 5, 1-12.
- BEVEN, K. 2012. *Rainfall-Runoff Modelling: The Primer, 2nd Edition*, Wiley-Blackwell.
- BEVEN, K., YOUNG, P., ROMANOWICZ, R., O'CONNELL, E., EWEN, J., O'DONNELL, G., HOLMAN, I., POSTHUMUS, H., MORRIS, J., HOLLIS, J., ROSE, S., LAMB, R. & ARCHER, D. 2008. Analysis of historical data sets to look for impacts of land use and management change on flood generation In: Final Report for Defra Project FD2120.
- BEVEN, K. J. 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrol. Earth Syst. Sci.*, 4, 203-213.

- BHOWMIK, A. K. & CABRAL, P. 2015. Spatially shifting temporal points: estimating pooled within-time series variograms for scarce hydrological data. *Hydrol. Earth Syst. Sci. Discuss.*, 12, 2243-2265.
- BLACK, P. E. 1997. WATERSHED FUNCTIONS. *JAWRA Journal of the American Water Resources Association*, 33, 1-11.
- BLÖSCHL, G. & MONTANARI, A. 2010. Climate change impacts—throwing the dice? *Hydrological Processes*, 24, 374-381.
- BLOSCHL, G., SIVAPALAN, M., WAGENER, T., VIGLIONE, A. & SAVENIJE, H. 2013. *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales*, Cambridge, UK, Cambridge University Press.
- BOORMAN, D., HOLLIS, J. & LILLY, A. 1995. *Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Report No 126.*, UK, Institute of Hydrology.
- BORMANN, H. 2010. Towards a hydrologically motivated soil texture classification. *Geoderma*, 157, 142-153.
- BOUTT, D. & SMOTH, Z. 2011. Long-term Fluctuations of the Elevation of the Water Table in the Northeast US: Climate Variability, Land-Use and Hydrogeology. *AGU Fall 2011 Meeting*.
- BOWER, D., HANNAH, D. M. & MCGREGOR, G. R. 2004. Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrological Processes*, 18, 2515-2543.
- BROXTON, P. D., TROCH, P. A. & LYON, S. W. 2009. On the role of aspect to quantify water transit times in small mountainous catchments. *Water Resources Research*, 45.
- BURN, D., ZRINJI, Z. & KOWALCHUK, M. 1997. Regionalization of Catchments for Regional Flood Frequency Analysis. *Journal of Hydrologic Engineering*, 2, 76-82.
- BURN, D. H. & HAG ELNUR, M. A. 2002. Detection of hydrologic trends and variability. *Journal of Hydrology*, 255, 107-122.
- BUTTLE, J. 2006. Mapping first-order controls on streamflow from drainage basins: the T3 template. *Hydrological Processes*, 20, 3415-3422.
- BUTTLE, J. M. & MCDONALD, D. J. 2002. Coupled vertical and lateral preferential flow on a forested slope. *Water Resources Research*, 38, 18-1-18-16.
- CAPELL, R., TETZLAFF, D., ESSERY, R. & SOULSBY, C. 2014. Projecting climate change impacts on stream flow regimes with tracer-aided runoff models - preliminary assessment of heterogeneity at the mesoscale. *Hydrological Processes*, 28, 545-558.
- CAREY, S. K., TETZLAFF, D., SEIBERT, J., SOULSBY, C., BUTTLE, J., LAUDON, H., MCDONNELL, J., MCGUIRE, K., CAISSIE, D., SHANLEY, J., KENNEDY, M., DEVITO, K. & POMEROY, J. W. 2010. Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience. *Hydrological Processes*, 24, 3591-3602.
- CHEN, Z. & GRASBY, S. E. 2009. Impact of decadal and century-scale oscillations on hydroclimate trend analyses. *Journal of Hydrology*, 365, 122-133.
- CHIVERTON, A., HANNAFORD, J., HOLMAN, I., CORSTANJE, R., PRUDHOMME, C., BLOOMFIELD, J. & HESS, T. M. 2015a. Which



- catchment characteristics control the temporal dependence structure of daily river flows? *Hydrological Processes*, 29, 1353-1369.
- CHIVERTON, A., HANNAFORD, J., HOLMAN, I. P., CORSTANJE, R., PRUDHOMME, C., HESS, T. M. & BLOOMFIELD, J. P. 2015b. Using variograms to detect and attribute hydrological change. *Hydrol. Earth Syst. Sci.*, 19, 2395-2408.
- CHRISTIERTSON, B. V., VIDAL, J.-P. & WADE, S. D. 2012. Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology*, 424–425, 48-67.
- CLIMENT-SOLER, D., HOLMAN, I. & ARCHER, D. 2009. Application of flow variability analysis to identify impacts of agricultural land use change on the river Axe, southwest England. *Hydrology Research* 40, 380-393.
- DESCROIX, L., MAHÉ, G., LEBEL, T., FAVREAU, G., GALLE, S., GAUTIER, E., OLIVRY, J. C., ALBERGEL, J., AMOGU, O., CAPPELAERE, B., DESSOUASSI, R., DIEDHIOU, A., LE BRETON, E., MAMADOU, I. & SIGHOMNOU, D. 2009. Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis. *Journal of Hydrology*, 375, 90-102.
- DODANGEH, E., SOLTANI, S., SARHADI, A. & SHIAU, J.-T. 2014. Application of L-moments and Bayesian inference for low-flow regionalization in Sefidroud basin, Iran. *Hydrological Processes*, 28, 1663-1676.
- DOOGE, J. C. I. 1986. Looking for hydrologic laws. *Water Resources Research*, 22, 46S-58S.
- ELTAHIR, E. A. B. & YEH, P. A. J. F. 1999. On the asymmetric response of aquifer water level to floods and droughts in Illinois. *Water Resources Research*, 35, 1199-1217.
- ENVIRONMENT AGENCY 2008. Water resources in England and Wales - current state and future pressures. Almondsbury, Bristol, UK.
- FLEIG, A. K., TALLAKSEN, L. M., HISDAL, H. & HANNAH, D. M. 2011. Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. *Hydrological Processes*, 25, 1163-1179.
- GOTTSCHALK, L. 1985. Hydrological Regionalization of Sweden. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*, 30, 65-83.
- HALTAS, I. & KAVVAS, M. L. 2011. Scale Invariance and Self-Similarity in Hydrologic Processes in Space and Time. *Journal of Hydrologic Engineering*, 16, 51-63.
- HANNAFORD, J. 2015. Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography*, 39, 29-48.
- HANNAFORD, J., BUYS, G., STAHL, K. & TALLAKSEN, L. M. 2013. The influence of decadal-scale variability on trends in long European streamflow records. *Hydrol. Earth Syst. Sci.*, 17, 2717-2733.
- HANNAFORD, J. & MARSH, T. 2006. An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. *International Journal of Climatology*, 26, 1237-1253.
- HANNAFORD, J. & MARSH, T. J. 2008. High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology*, 28, 1325-1338.



- HAWKINS, E. & SUTTON, R. 2009. The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society*, 90, 1095-1107.
- HESS, T., KNOX, J., KAY, M. & WEATHERHEAD, K. 2010. Managing the Water Footprint of Irrigated Food Production in England and Wales. 78-92.
- HOLMES, M. G. R., YOUNG, A. R., GOODWIN, T. H. & GREW, R. 2005. A catchment-based water resource decision-support tool for the United Kingdom. *Environmental Modelling & Software*, 20, 197-202.
- HOSKING, J. R. M. & WALLIS, J. R. 1993. Some statistics useful in regional frequency analysis. *Water Resources Research*, 29, 271-281.
- HRACHOWITZ, M., SAVENIJE, H. H. G., BLÖSCHL, G., MCDONNELL, J. J., SIVAPALAN, M., POMEROY, J. W., ARHEIMER, B., BLUME, T., CLARK, M. P., EHRET, U., FENICIA, F., FREER, J. E., GELFAN, A., GUPTA, H. V., HUGHES, D. A., HUT, R. W., MONTANARI, A., PANDE, S., TETZLAFF, D., TROCH, P. A., UHLENBROOK, S., WAGENER, T., WINSEMIUS, H. C., WOODS, R. A., ZEHE, E. & CUDENNEC, C. 2013. A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal*, 58, 1198-1255.
- HRACHOWITZ, M., SOULSBY, C., TETZLAFF, D., DAWSON, J. J. C. & MALCOLM, I. A. 2009. Regionalization of transit time estimates in montane catchments by integrating landscape controls. *Water Resources Research*, 45.
- INSTITUTE OF HYDROLOGY 1999. *Flood estimation handbook*, Wallingford, UK, Institute of Hydrology, (reprinted 2008 by the Centre for Ecology and Hydrology).
- IPCC 2014. *Climate change 2013: The Physical Science Basis. Contribution of Working group I*, New York, Cambridge University Press.
- KENDON, M., MARSH, T. & PARRY, S. 2013. The 2010–2012 drought in England and Wales. *Weather*, 68, 88-95.
- KOUTSOYIANNIS, D. 2013. Hydrology and change. *Hydrological Sciences Journal*, 58, 1177-1197.
- KUMAR, P. 2007. Variability, Feedback, and Cooperative Process Dynamics: Elements of a Unifying Hydrologic Theory. *Geography Compass*, 1, 1338-1360.
- LAAHA, G. & BLÖSCHL, G. 2006. A comparison of low flow regionalisation methods—catchment grouping. *Journal of Hydrology*, 323, 193-214.
- LAIZÉ, C. L. R. & HANNAH, D. M. 2010. Modification of climate–river flow associations by basin properties. *Journal of Hydrology*, 389, 186-204.
- LAVERS, D., PRUDHOMME, C. & HANNAH, D. M. 2010. Large-scale climate, precipitation and British river flows: Identifying hydroclimatological connections and dynamics. *Journal of Hydrology*, 395, 242-255.
- LYON, S. W. & TROCH, P. A. 2010. Development and application of a catchment similarity index for subsurface flow. *Water Resources Research*, 46.
- MACDONALD, N., PHILLIPS, I. D. & MAYLE, G. 2010. Spatial and temporal variability of flood seasonality in Wales. *Hydrological Processes*, 24, 1806-1820.
- MADSEN, H., LAWRENCE, D., LANG, M., MARTINKOVA, M. & KJELDSSEN, T. R. 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology*, 519, Part D, 3634-3650.

- MAHMOOD, R., FOSTER, S. A., KEELING, T., HUBBARD, K. G., CARLSON, C. & LEEPER, R. 2006. Impacts of irrigation on 20th century temperature in the northern Great Plains. *Global and Planetary Change*, 54, 1-18.
- MARSH, T. 2008. A hydrological overview of the summer 2007 floods in England and Wales. *Weather*, 63, 274-279.
- MARSH, T., COLE, G. & WILBY, R. 2007. Major droughts in England and Wales, 1800–2006. *Weather*, 62, 87-93.
- MARTIN, E. H., KELLEHER, C. & WAGENER, T. 2012. Has urbanization changed ecological streamflow characteristics in Maine (USA)? *Hydrological Sciences Journal*, 57, 1337-1354.
- MCDONNELL, J. J. 2013. Are all runoff processes the same? *Hydrological Processes*, 27, 4103-4111.
- MCGLYNN, B. L. & MCDONNELL, J. J. 2003. Quantifying the relative contributions of riparian and hillslope zones to catchment runoff. *Water Resources Research*, 39.
- MCGLYNN, B. L., MCDONNELL, J. J., SEIBERT, J. & KENDALL, C. 2004. Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. *Water Resources Research*, 40.
- MCGUIRE, K. J., MCDONNELL, J. J., WEILER, M., KENDALL, C., MCGLYNN, B. L., WELKER, J. M. & SEIBERT, J. 2005. The role of topography on catchment-scale water residence time. *Water Resources Research*, 41, W05002.
- MCINTYRE, N., WHEATER, H. S. & LEES, M. 2002. Estimation and propagation of parametric uncertainty in environmental models. *Journal of Hydroinformatics*, 4, 177 - 198.
- MCNAMARA, J. P., CHANDLER, D., SEYFRIED, M. & ACHET, S. 2005. Soil moisture states, lateral flow, and streamflow generation in a semi-arid, snowmelt-driven catchment. *Hydrological Processes*, 19, 4023-4038.
- MENDICINO, G. & SENATORE, A. 2013. Evaluation of parametric and statistical approaches for the regionalization of flow duration curves in intermittent regimes. *Journal of Hydrology*, 480, 19-32.
- MERZ, B., VOROGUSHYN, S., UHLEMANN, S., DELGADO, J. & HUNDECHA, Y. 2012. HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". *Hydrol. Earth Syst. Sci.*, 16, 1379-1387.
- MERZ, R. & BLÖSCHL, G. 2009. A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. *Water Resources Research*, 45, W01405.
- MONK, W. A., WOOD, P. J., HANNAH, D. M. & WILSON, D. A. 2007. Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications*, 23, 113-122.
- MORRIS, S. E., COBBY, D. C. & DONOVAN, B. 2012. Developing indicators to detect changes in the seasonality, frequency and duration of medium and high river flows. *Water and Environment Journal*, 26, 38-46.
- MUCHAN, K., LEWIS, M., HANNAFORD, J. & PARRY, S. 2015. The winter storms of 2013/2014 in the UK: hydrological responses and impacts. *Weather*, 70, 55-61.
- MURPHY, J., SEXTON, D., JENKINS, G., BOORMAN, P., BOOTH, B., CLARK, R., COLLINS, M., HARRIS, G. & KENDON, L. 2010. UK Climate Projections science report: Climate change projections. Met Office Hadley Centre, Exeter, UK.

- MURPHY, J. M., SECTON, D. H. M., JENKINS, G. L., BOOTH, B. B. B., BROWN, C. C., CLARK, R. T., COLLINS, M., HARRIS, G. R., KENDON, E. J., BETTS, R. A., BROWN, S. J., HUMPHREY, K. A., MCCARTHY, M. P., MCDONALD, R. E., STEPHENS, A., WALLACE, C., WARREN, R. F., WILBY, R. L. & WOOD, R. A. 2009. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter, UK.
- NERC 1975. *Flood Studies Report (5 volumes)*. Natural Environmental Research Council (Institute of Hydrology)
- NEW, M., TODD, M., HULME, M. & JONES, P. 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology*, 21, 1889-1922.
- O'CONNELL, P. E., EWEN, J., O'DONNELL, G. & QUINN, P. 2007. Is there a link between agricultural land-use management and flooding? *Hydrol. Earth Syst. Sci.*, 11, 96-107.
- OLDEN, J. D. & POFF, N. L. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, 19, 101-121.
- ONS 2008. 2008-Based National Population Projections. Office for National Statistics, Newport, UK.
- OSBORN, T. J. & HULME, M. 2002. Evidence for Trends in Heavy Rainfall Events over the UK. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 360, 1313-1325.
- OSBORN, T. J., HULME, M., JONES, P. D. & BASNETT, T. A. 2000. Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology*, 20, 347-364.
- LOUDIN, L., ANDRÉASSIAN, V., PERRIN, C., MICHEL, C. & LE MOINE, N. 2008. Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments. *Water Resources Research*, 44.
- LOUDIN, L., KAY, A., ANDRÉASSIAN, V. & PERRIN, C. 2010. Are seemingly physically similar catchments truly hydrologically similar? *Water Resources Research*, 46.
- PARTON, W. J., GUTMANN, M. P., WILLIAMS, S. A., EASTER, M. & OJIMA, D. 2005. ECOLOGICAL IMPACT OF HISTORICAL LAND-USE PATTERNS IN THE GREAT PLAINS: A METHODOLOGICAL ASSESSMENT. *Ecological Applications*, 15, 1915-1928.
- PECHLIVANIDIS, I. G., JACKSON, B. M., MCINTYRE, N. R. & WHEATER, H. S. 2011. CATCHMENT SCALE HYDROLOGICAL MODELLING: A REVIEW OF MODEL TYPES, CALIBRATION APPROACHES AND UNCERTAINTY ANALYSIS METHODS IN THE CONTEXT OF RECENT DEVELOPMENTS IN TECHNOLOGY AND APPLICATIONS *Global NEST*, 12, 193 - 214.
- PEEL, M. C. & BLÖSCHL, G. 2011. Hydrological modelling in a changing world. *Progress in Physical Geography*, 35, 249-261.
- PEEL, M. C., MCMAHON, T. A., FINLAYSON, B. L. & WATSON, F. G. R. 2001. Identification and explanation of continental differences in the variability of annual runoff. *Journal of Hydrology*, 250, 224-240.

- PROSDOCIMI, I., KJELDSSEN, T. R. & MILLER, J. D. 2015. Detection and attribution of urbanization effect on flood extremes using nonstationary flood-frequency models. *Water Resources Research*, 51, 4244-4262.
- PRUDHOMME, C., CROOKS, S., KAY, A. & REYNARD, N. 2013a. Climate change and river flooding: part 1 classifying the sensitivity of British catchments. *Climatic Change*, 119, 933-948.
- PRUDHOMME, C., KAY, A., CROOKS, S. & REYNARD, N. 2013b. Climate change and river flooding: Part 2 sensitivity characterisation for British catchments and example vulnerability assessments. *Climatic Change*, 119, 949-964.
- PRUDHOMME, C., YOUNG, A., WATTS, G., HAXTON, T., CROOKS, S., WILLIAMSON, J., DAVIES, H., DADSON, S. & ALLEN, S. 2012. The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. *Hydrological Processes*, 26, 1115-1118.
- RAMACHANDRA RAO, A. & SRINIVAS, V. V. 2006. Regionalization of watersheds by hybrid-cluster analysis. *Journal of Hydrology*, 318, 37-56.
- REYNARD, N. S., CROOKS, S., KAY, A., L. & PRUDHOMME, C. 2009. Regionalised Impacts of Climate Change on Flood Flows - FD2020 DEFRA: <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=13958>.
- ROBSON, A. & REED, D. 1999. *Flood Estimation Handbook Volume 3: statistical procedures for flood frequency estimation*, Wallingford, UK, Institute of Hydrology.
- ROJAS, R., FEYEN, L. & WATKISS, P. 2013. Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change*, 23, 1737-1751.
- SAFT, M., WESTERN, A. W., ZHANG, L., PEEL, M. C. & POTTER, N. J. 2015. The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective. *Water Resources Research*, 51, 2444-2463.
- SALINAS, J. L., LAAHA, G., ROGGER, M., PARAJKA, J., VIGLIONE, A., SIVAPALAN, M. & BLÖSCHL, G. 2013. Comparative assessment of predictions in ungauged basins; Part 2: Flood and low flow studies. *Hydrol. Earth Syst. Sci.*, 17, 2637-2652.
- SAUQUET, E. & CATALOGNE, C. 2011. Comparison of catchment grouping methods for flow duration curve estimation at ungauged sites in France. *Hydrol. Earth Syst. Sci.*, 15, 2421-2435.
- SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrol. Earth Syst. Sci.*, 15, 2895-2911.
- SAWICZ, K. A., KELLEHER, C., WAGENER, T., TROCH, P., SIVAPALAN, M. & CARRILLO, G. 2014. Characterizing hydrologic change through catchment classification. *Hydrol. Earth Syst. Sci.*, 18, 273-285.
- SHAO, Q., CAMPBELL, N., FERDOWSIAN, R. & O'CONNELL, D. 1999. *Analysing Trends in Groundwater Levels*.
- SIVAPALAN, M. 2006. Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale. *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd.

- SKØIEN, J. O., BLÖSCHL, G. & WESTERN, A. W. 2003. Characteristic space scales and time scales in hydrology. *Water Resources Research*, 39.
- SKØIEN, J. O., MERZ, R. & BLÖSCHL, G. 2006. Top-kriging - geostatistics on stream networks. *Hydrol. Earth Syst. Sci.*, 10, 277-287.
- SRINIVAS, V. V., TRIPATHI, S., RAO, A. R. & GOVINDARAJU, R. S. 2008. Regional flood frequency analysis by combining self-organizing feature map and fuzzy clustering. *Journal of Hydrology*, 348, 148-166.
- STAHL, K., HISDAL, H., HANNAFORD, J., TALLAKSEN, L. M., VAN LANEN, H. A. J., SAUQUET, E., DEMUTH, S., FENDEKOVA, M. & JÓDAR, J. 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrol. Earth Syst. Sci. Discuss.*, 7, 5769-5804.
- STANKE, C., KERAC, M., PRUDHOMME, C., MEDLOCK, J. & MURRAY, V. 2013. Health effects of drought: a systematic review of the evidence. *PLoS Curr*, 5.
- SUN, F., RODERICK, M. L. & FARQUHAR, G. D. 2012. Changes in the variability of global land precipitation. *Geophysical Research Letters*, 39.
- TETZLAFF, D., SEIBERT, J., MCGUIRE, K. J., LAUDON, H., BURNS, D. A., DUNN, S. M. & SOULSBY, C. 2009. How does landscape structure influence catchment transit time across different geomorphic provinces? *Hydrological Processes*, 23, 945-953.
- TROMP-VAN MEERVELD, H. J. & MCDONNELL, J. J. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, 42.
- UCHIDA, T., TROMP-VAN MEERVELD, I. & MCDONNELL, J. J. 2005. The role of lateral pipe flow in hillslope runoff response: an intercomparison of non-linear hillslope response. *Journal of Hydrology*, 311, 117-133.
- UNAL, Y., KINDAP, T. & KARACA, M. 2003. Redefining the climate zones of Turkey using cluster analysis. *International Journal of Climatology*, 23, 1045-1055.
- VAN LOON, A. F. & LAAHA, G. 2014. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*.
- VOGEL, H. J., HOFFMANN, H. & ROTH, K. 2005. Studies of crack dynamics in clay soil: I. Experimental methods, results, and morphological quantification. *Geoderma*, 125, 203-211.
- WAGENER, T., SIVAPALAN, M., TROCH, P. & WOODS, R. 2007. Catchment Classification and Hydrologic Similarity. *Geography Compass*, 1, 901-931.
- WAGENER, T., SIVAPALAN, M., TROCH, P. A., MCGLYNN, B. L., HARMAN, C. J., GUPTA, H. V., KUMAR, P., RAO, P. S. C., BASU, N. B. & WILSON, J. S. 2010. The future of hydrology: An evolving science for a changing world. *Water Resources Research*, 46.
- WAGENER, T., WHEATER, H. S. & HOSHIN, V. G. 2004. *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments*, London, UK, Imperial College Press.
- WATTS, G., BATTARBEE, R. W., BLOOMFIELD, J. P., CROSSMAN, J., DACCACHE, A., DURANCE, I., ELLIOTT, J. A., GARNER, G., HANNAFORD, J., HANNAH, D. M., HESS, T., JACKSON, C. R., KAY, A. L., KERNAN, M., KNOX, J., MACKAY, J., MONTEITH, D. T., ORMEROD, S. J., RANCE, J., STUART, M. E., WADE, A. J., WADE, S. D., WEATHERHEAD, K., WHITEHEAD, P. G. & WILBY, R. L. 2015. Climate change and water in the UK - past changes and future prospects. *Progress in Physical Geography*, 39, 6-28.



- WEILER, M. & NAEF, F. 2003. An experimental tracer study of the role of macropores in infiltration in grassland soils. *Hydrological Processes*, 17, 477-493.
- WIGLEY, T. M. L., LOUGH, J. M. & JONES, P. D. 1984. Spatial patterns of precipitation in England and Wales and a revised, homogeneous England and Wales precipitation series. *Journal of Climatology*, 4, 1-25.
- WINTER, T. C. 2001. THE CONCEPT OF HYDROLOGIC LANDSCAPES1. *JAWRA Journal of the American Water Resources Association*, 37, 335-349.
- YOUNG, A. R. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. *Journal of Hydrology*, 320, 155-172.
- ZEHE, E., ELSENBEER, H., LINDENMAIER, F., SCHULZ, K. & BLÖSCHL, G. 2007. Patterns of predictability in hydrological threshold systems. *Water Resources Research*, 43.

## **2 Which catchment characteristics control the temporal dependence structure of daily river flows?**

### **Abstract**

Hydrological classification systems seek to provide information about the dominant processes in the catchment to enable information to be transferred between catchments. Currently there is no widely agreed-upon system for classifying river catchments. This chapter develops a novel approach to classifying catchments based on the temporal dependence structure of daily mean river flow time series, applied to 116 near natural “Benchmark” catchments in the UK. The classification system is validated using 49 independent catchments. Temporal dependence in river flow data is driven by the flow pathways, connectivity and storage within the catchment, and can thus be used to assess the influence catchment characteristics have on moderating the precipitation-to-river flow relationship. Semi-variograms were computed for the 116 Benchmark catchments to provide a robust and efficient way of characterising temporal dependence. Cluster analysis was performed on the semi-variograms, resulting in four distinct clusters. The influence of a wide range of catchment characteristics on the semi-variogram shape was investigated, including: elevation, land cover, physiographic characteristics, soil type and geology. Geology, depth to gleyed layer in soils, slope of the catchment and the percentage of arable land were significantly different between the clusters. These characteristics drive the temporal dependence structure by influencing the rate at which water moves through the catchment and/or the storage in the catchment. Quadratic discriminant analysis was used to show that a model with five catchment characteristics is able to predict the temporal dependence structure for un-gauged catchments. This method could form the basis for future regionalisation strategies, as a way of transferring information on the precipitation-to-flow relationship between gauged and un-gauged catchments.

## 2.1 Introduction

Hydrology has yet to achieve a widely agreed-upon system which classifies catchments based on the movement and storage of water within the catchment (Wagener et al., 2007; Ley et al., 2011). Even though internal complexity will remain within each class as every catchment is unique (Beven, 2000), a broad classification process should be possible. This is based on the general assumption that some level of organisation and therefore predictability in catchment ‘function’ (i.e. the translation of catchment input into river flow) exists (Dooge, 1986; Blöschl et al., 2013). A broad classification process should cluster together similar catchments, thus limiting the variability within classes and maximising the variability between them. The between-catchment similarities may be a result of natural self-organisation or the co-evolution of climate, soils, vegetation and topography (Sivapalan, 2006).

Classification is a means to identify the dominant processes and mechanisms operating in a given catchment type, as well as the most important controls on water fluxes and pathways (McDonnell and Woods, 2004). Identifying the dominant processes which transform precipitation into runoff will enhance understanding about the similarity or dissimilarity between catchments (Gottschalk, 1985). Being able to classify catchments has a range of benefits (Grigg, 1965; 1967):

- 1) *To give names to things* (enable grouping as seen in other disciplines).
- 2) *To permit transfer of information* (from gauged to un-gauged catchments as well as enabling comparison between studies in different catchments).
- 3) *To permit development of generalisations* (improve knowledge about the drivers behind the precipitation-to-river flow relationship).

As the impacts of a non-stationary climate are becoming of greater concern (Wagener et al., 2010), Sawicz et al. (2011) added a fourth:

- 4) *To provide a first order environmental change impact assessment* (identify the impacts from land use/cover and climate change).



Hydrological science has developed descriptive classifications describing catchments in terms of, e.g. land cover (forested, urban, arable, etc); climate (humid, arid, semi-arid, etc); flow pathways (fast, slow); storage (groundwater dominated, surface water catchments); etc (Wagener et al., 2007). These groupings do not provide a comprehensive classification system as they do not enable understanding about the partitioning of water nor the importance of different water stores (McDonnell and Woods, 2004). A further drawback with the aforementioned groupings is that no information is provided about the impact of the interaction between different descriptors. Previous classification studies have either focused on physical catchment characteristics (e.g. Acreman and Sinclair (1986) and Burn and Boorman (1993)) or on indicators derived from specific aspects of the flow record (e.g. floods - Robson and Reed (1999); low flows and flow duration curves - Holmes et al. (2005); seasonally averaged flows - Laizé and Hannah (2010); long-term average annual regimes and long-term annual flow average - Bower et al. (2004)). Bower et al. (2004) differentiated between first and second order controls (precipitation and catchment characteristics respectively) on flow. Ali et al. (2012) and Ley et al. (2011) showed a lack of correlation between flow-derived indicators and catchment characteristics. The difference is likely to be caused by the catchment characteristics not adequately capturing the climatic effects (first-order control of flow).

Temporal dependence represents the similarity between the river flow on a given day and river flow on the preceding days. As temporal dependence is likely to be driven by catchment characteristics (Szolgayova et al., 2013), classification based on the temporal dependence has some key advantages: 1) temporal dependence is calculated using all of the daily river flow data, rather than having to calculate indicators which discard much of the daily flow data (e.g. annual or seasonal averages, minimum or maximum flows). 2) The method can handle missing data. 3) The classification is based on catchment function (i.e. the degree to which catchment characteristics filter rainfall into runoff) and not a specific part of the flow regime. This confers significant benefits for advancing our understanding of the drivers behind the precipitation-to-flow relationship in a much more generalised way (benefit 3, above) rather than for a specific process (e.g. flooding or low flows).

Szolgayova et al. (2013) suggested that catchment properties can influence the temporal dependence of river flow. Such properties are likely to include those governing the predominant second-order controls (i.e. catchment characteristics which modify the precipitation-to-flow relationship, Bower et al. 2004). These will influence: partitioning between vertical and lateral pathways (e.g. interception, overland flow, infiltration and percolation); connectivity of the drainage network and hydraulic gradients (Buttle, 2006) and storage (e.g. soil moisture storage, lakes and storage in the saturated zone (Black, 1997)).

This chapter will develop a new catchment classification system based on the temporal dependence of river flow; an integration of water input, storage and flow pathways within the catchment. A hydrological classification method becomes more powerful if catchments can be classified without the use of river flow data; enabling un-gauged catchments to be classified and hence allowing data transfer between gauged and un-gauged catchments. Therefore, the second part of this chapter will demonstrate how un-gauged catchments could be clustered into the same classification using their catchment characteristics thereby facilitating data transfer (benefit 2).

The methodology used in this chapter is designed to capture differences in the precipitation-to-river flow relationship (benefit 3). This novel approach of assessing the temporal dependence in a catchment based on semi-variograms, created using daily river flow data, will be applied to a range of catchments throughout the UK. The term semi-variogram refers to the semi-variance calculated from the data without fitting a model (also known as the experimental or empirical variogram) (Chandler and Scott, 2011).

## **2.2 Data**

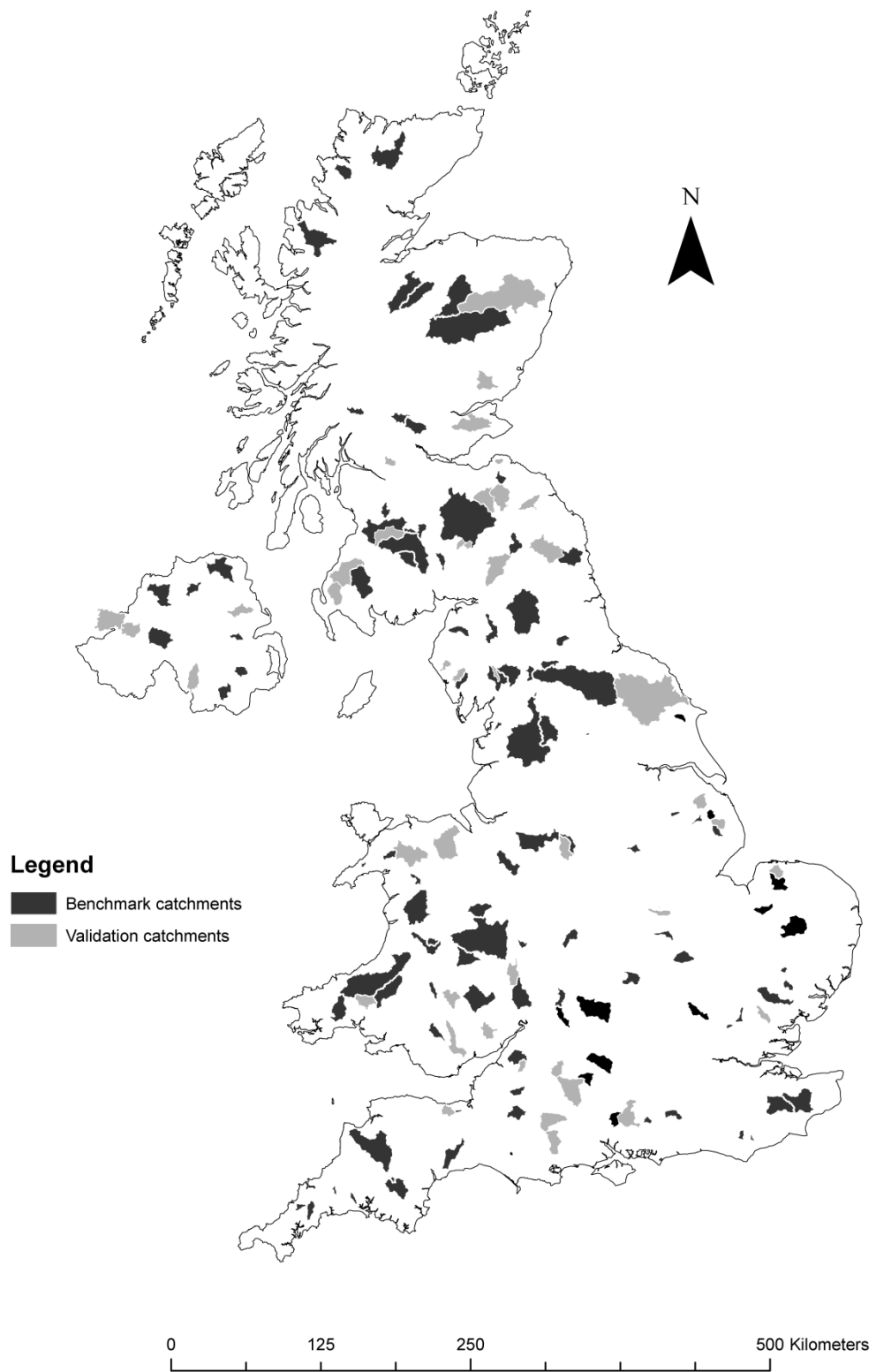
### **2.2.1 Catchment selection**

A sample of catchments was needed to represent the population of UK catchments in terms of spatial location and catchment characteristics. The choice of catchments selected was constrained: 1) to remove the influence of weather, the time series is averaged over a long time period. Therefore, only catchments with a record length of 30-years or more with less than 5% missing data were considered. 2) As controls from climate and land use change through time (Wagener et al., 2007), a common time period (1980 to 2010) was

used to enable comparisons between catchments. 3) Artificial influences on river flows (such as reservoirs or sewage discharges) could affect the dependence structure of the data series, so near-natural UK Benchmark catchments, with only modest net impacts from artificial influences were chosen (Bradford and Marsh, 2003). 4) Nested catchments with similar flow regimes were removed.

Any study using observed hydrometric data faces an inevitable degree of uncertainty due to limitations with the measurement techniques (MacMillan et al., 2012). The amount of uncertainty will depend on the gauging station to a great degree. In this study, the impacts of data error were minimised insofar as possible through judicious selection of catchments. One of the criteria Bradford and Marsh (2003) used to develop the Benchmark network was hydrometric performance, with the gauging stations in the network generally producing good quality data. Furthermore, the data used in this study have undergone validation by the National River Flow Archive (NRFA) as outlined in Dixon et al., (2013) and demonstrated by Muchan and Dixon (2014) to have few data quality issues.

The locations of the 116 catchments displayed in Figure 2.1 provide a good coverage of UK catchment types with varying catchment characteristics (Table 2.1). However, catchments in the South East are smaller, artificial influences are more pervasive in this densely populated region. In addition a further 49 catchments were selected for validation purposes (Figure 2.1). These were selected using the approach outlined above, except the requirement to be a Benchmark catchment was removed; instead they were screened for artificial influences using the metadata records from the NRFA. The hydrometric data were collected by the measuring authorities (Environment Agency in England, Natural Resources Wales in Wales, Scottish Environment Protection Agency in Scotland, and the Rivers Agency in Northern Ireland) and stored on the NRFA (<http://www.ceh.ac.uk/data/nrfa/>). Daily rainfall data for each catchment were also calculated from 1km by 1km gridded rainfall data using the method outlined in Keller et al. (2006).



*Figure 2.1: Location of the 116 Benchmark catchments (black) and the 49 validation catchments (grey) used in this chapter.*

### 2.2.2 Catchment characteristics

In order to investigate the drivers behind the different shapes of semi-variogram, several catchment characteristics were analysed, grouped into categories: elevation<sub>(e)</sub>, land cover<sub>(Lc)</sub>, physiographic and hydrological descriptors from the FEH<sub>(FEH)</sub> (Flood Estimation Handbook, the UK's principal methodology for flood estimation at un-gauged sites; (Robson and Reed, 1999), geology<sub>(g)</sub>, storage<sub>(St)</sub> and soils classification<sub>(s)</sub> (Table 2.1).

Five elevation characteristics were considered to assess how topography varies between the clusters, all derived from the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990), as published in the UK Hydrometric Register (Marsh and Hannaford, 2008). Land cover was derived from the Land Cover Map 2000 (LCM2000) (Fuller et al., 2002), grouped into four categories from the 26 LCM2000 subclasses, to ensure the representation in the 116 catchments and preservation of the four major land covers. Nine characteristics from the FEH were included, incorporating the important characteristics of the catchment and excluding discharge features (e.g. return periods). Four different Hydrology Of Soils Types (HOST) (Boorman et al., 1995) soil types based on the depth to gleyed layer (reduced from 29 HOST classes) and seven different hydrologically important rock types calculated from the 1:625000 scale digital hydrogeological map of the UK were identified. As with land cover these categories were defined to capture the main hydrological differences whilst being represented throughout the 116 catchments. In addition to the HOST soil classes, BFIHOST and Base Flow Index (BFI) are included as indicators of catchment storage. BFI is not a catchment characteristic *per se* as it is calculated from the flow data. However, it is frequently used as an indication of storage and is included here to compliment the BFIHOST values, which are BFI values predicted from HOST classes.

Table 2.1: Summary of the catchment characteristics investigated.

Catchment characteristic	Abbreviation	Units	Description	Min	Max	Mean	Median
<b>Altitude<sub>(e)</sub></b>	N/A	m	Altitude of the gauging station to the nearest datum* (derived using IHDTM**).	3	356	60	35
<b>Elevation 10<sub>(e)</sub></b>	Elv-10	m	Height above datum* below which 10% of the catchment lies (derived using IHDTM**).	9	408	114	92
<b>Elevation 50<sub>(e)</sub></b>	Elv-50	m	As above but for 50%.	20	604	198	164
<b>Elevation 90<sub>(e)</sub></b>	Elv-90	m	As above but for 90%.	52	889	316	279
<b>Elevation max<sub>(e)</sub></b>	Elv-M	m	As above but for the maximum value.	68	1309	484	470
<b>Woodland<sub>(Lc)</sub></b>	Wood	%	Amount of the catchment covered by woodland. Calculated from CEH land cover maps 2000. This is an aggregation of: broad-leaved / mixed woodland and coniferous woodland.	0	49	12	10
<b>Arable<sub>(Lc)</sub></b>	N/A	%	As above but using an aggregation of: arable cereals, arable horticulture and arable non-rotational.	0	86	23	12
<b>Grassland<sub>(Lc)</sub></b>	Grass	%	As above but using an aggregation of: improved grassland, neutral grassland, set-aside grassland, bracken, calcareous grassland, acid grassland and fen, marsh and swamp.	6	96	47	45
<b>Urban<sub>(Lc)</sub></b>	N/A	%	As above but using an aggregation of: suburban, urban and inland bare ground.	0	40	2	1
<b>Area<sub>(FEH)</sub></b>	N/A	km <sup>2</sup>	Area of the catchment calculated using the CEH's Digital Terrain Model (IHDTM**).	3.07	1500	227.6	108.5
<b>Drainage path slope<sub>(FEH)</sub></b>	DPS	m km <sup>-1</sup>	Mean drainage path slope calculated from the mean of all inter-nodal slopes (derived using IHDTM**).	12	309	100	91
<b>PROPWET<sub>(FEH)</sub></b>	P-WET	%	Proportion of the time soils are wet (defined as a soil moisture deficit of less than 6mm).	23	83	48	46
<b>Flood plain extent<sub>(FEH)</sub></b>	FPext	Ratio	Proportion of the floodplain which would be covered by the 1 in 100 year flood event.	0.008	0.226	0.064	0.051
<b>Longest drainage path<sub>(FEH)</sub></b>	LDP	km	Longest drainage path from a catchment node to the defined outlet.	4.01	116.1	33.49	27.76
<b>Drainage path length<sub>(FEH)</sub></b>	DPL	km	Mean drainage path length from the distances between all nodes and the catchment outlet.	2.04	60.39	17.78	14.96
<b>FARL<sub>(FEH)</sub></b>	N/A	ratio	Flood attenuation attributed to reservoirs and lakes.	0.664	1.000	0.979	0.992
<b>BFIHOST<sub>(St)</sub></b>	BFI-H	ratio	Area-weighted base flow index derived using the Hydrology Of Soil Types (HOST) classification.	0.24	0.95	0.5	0.48
<b>BFI<sub>(St)</sub></b>	N/A	ratio	Calculated from mean daily flow data using the method outlined in Gustard et al. (1992)	0.16	0.96	0.5	0.48
<b>HOST no gleying<sub>(s)</sub></b>	S-no	%	Percentage of the catchment made up of classes: 1 to 8, 16 and 17.	0	98	34	29
<b>HOST gleyed between 40 and 100cm<sub>(s)</sub></b>	S-deep	%	Percentage of the catchment made up of classes: 13 and 18 to 23	0	99	19	13

<b>HOST gleyed within 40cm<sub>(s)</sub></b>	S-shal	%	Percentage of the catchment made up of classes: 9,10,14,24 and 25.	0	93	22	15
<b>HOST peat<sub>(s)</sub></b>	Peat	%	Percentage of the catchment made up of classes: 11,12,15 and 26 to 29.	0	90	24	11
<b>Fracture High<sub>(g)</sub></b>	F-High	%	Percentage of the catchment underlain by highly productive fractured rocks.	0	100	13	0
<b>Fracture Medium<sub>(g)</sub></b>	F-Med	%	Percentage of the catchment underlain by moderately productive fractured rocks.	0	100	23	0
<b>Fracture Low<sub>(g)</sub></b>	F-Low	%	Percentage of the catchment underlain by low productivity fractured rocks.	0	100	45	31
<b>Intergranular High<sub>(g)</sub></b>	I-High	%	Percentage of the catchment underlain by highly productive intergranular rocks.	0	42	2	0
<b>Intergranular Medium<sub>(g)</sub></b>	I-Med	%	Percentage of the catchment underlain by as moderately productive intergranular rocks.	0	71	5	0
<b>Intergranular Low<sub>(g)</sub></b>	I_Low	%	Percentage of the catchment underlain by low productivity intergranular rocks.	0	11	0	0
<b>No Groundwater<sub>(g)</sub></b>	No-G	%	Percentage of the catchment underlain by rocks classed as having essentially no groundwater.	0	100	11	0

\* Datum refers to Ordnance Datum or, in Northern Ireland, Malin Head Datum.

\*\* IHDTM refers to the Integrated Hydrological Digital Terrain Model (Morris and Flavin, 1990).

## 2.3 Method

An overview of the methods used in this chapter is provided here, before more detail is provided in the following sections. Firstly, the daily flow data are transformed to make them suitable for (semi-)variogram analysis. Secondly, a semi-variogram is created for each catchment. Thirdly, the semi-variograms for all sites are categorised into groups using cluster analysis. Finally, the influence catchment characteristics have on the temporal dependence of each of these clusters is analysed in two ways: through box plots, to investigate the distribution of catchment characteristics for each cluster; and by using Quadratic Discriminate Analysis (QDA) to independently predict membership of the

clusters using catchment characteristics rather than the semi-variogram, which is calculated from the river flow data.

### **2.3.1 River flow data transformation**

To calculate a semi-variogram the data should first be transformed into a normally distributed, deseasonalised time series (Skøien et al., 2003). Therefore a number of transformation steps were implemented, each one using the data from the previous, starting with raw daily river flow data:

1) As some hydrological time series had periods of no data and all sites had a good analogue station the time series were in-filled to improve the fit of the periodic function used for deseasonalisation (step 3). Analogue stations were chosen based on the correlation with the catchment being in-filled during the period for which they both had data (minimum of ten years). The infilling was carried out using the equipercntile linking method (Hughes and Smakhtin, 1996) where the flows from one gauging station are linked to another through percentile ranks. Harvey et al. (2012) showed that the equipercntile method outperforms other methods such as scaling factors for infilling mean daily river flow data.

2) Logarithms were taken to create a near normal distribution. Zero values were replaced by  $0.001 \text{ m}^3\text{s}^{-1}$ .

3) Seasonality was removed (to avoid exaggerating the temporal dependence) using Fourier representation; a periodic function was fitted to the data using a sum of sine and cosine waves, at frequencies which are integer multiples of the annual cycle. Each catchment has a different function fitted to it with the number of covariates set to six to enable a good fit to the data (more covariates increases the flexibility of the function, enabling a better fit to the data). While it is acknowledged that using six covariates might over fit the model, this is deemed appropriate to model the seasonal effects (and not to extrapolate). Akaike Information Criterion (AIC), a relative goodness of fit measure, was used to select the best parameters for the periodic function. The effect of seasonality was removed by deducting the magnitude and dividing by standard deviation caused by seasonality (both calculated from the periodic function) for each day in a year. Although



infilling the data enhanced the ability to fit a periodic function to the data and improved the removal of seasonality, the in-filled data were considered less accurate than measured data, so were removed after the seasonality had been taken out.

4) The flow data for each catchment were standardised by deducting the mean and dividing by the standard deviation of the time series; standardising enables comparison of catchments with different magnitudes of flow. In general, larger catchments will have a bigger absolute difference between the high and low flows resulting in a larger Sill.

### 2.3.2 Semi-variograms

The temporal dependence structure can be represented by a one-dimensional temporally averaged (semi-)variogram (see Chandler and Scott (2011) or Webster and Oliver (2007) for detailed background about the (semi-)variogram). A semi-variogram has several components (displayed in Figure 2.2) throughout this chapter the “Sill” is defined as the semi-variance where the gradient of the (semi-)variogram is zero. A zero gradient indicates the limit of temporal dependence

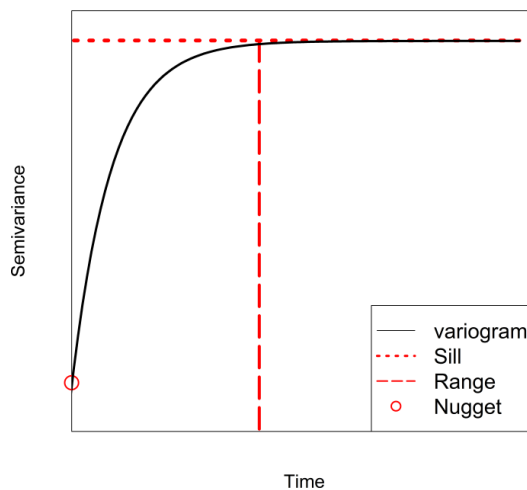


Figure 2.2: The variogram parameters for a theoretical semi-variogram.

and is an indicator for the total amount of variance in the time series. The “Range” is the time it takes to reach the zero gradient. If the lag time between water landing in the catchment and reaching the gauging station is small and the catchment has little storage then the resulting semi-variogram would be expected to have a short Range.

For second-order stationary processes the (semi-)variogram and autocorrelation graph are symmetrical. However, (semi-)variograms are defined for a wider class of processes and therefore enable temporal dependence to be analysed even if there is missing data or a trend. The Nugget, which is the y intercept on the modelled semi-variogram, represents a combination of measurement error and sub-daily variability. The partial-Sill is the Sill minus the Nugget and shows the temporally dependent component. A semi-variogram

was calculated for each catchment using the average squared difference between all pairs of values which are separated by the corresponding time lag (Equation 2.1):

$$\hat{v}(h) = \frac{1}{2(\mathbf{N} - \mathbf{h})} \sum_{i=1}^{\mathbf{N}-\mathbf{h}} [(Y(t_{i+h}) - Y(t_i))^2] \quad (\text{Equation 2.1})$$

Where  $\mathbf{h}$  is the lag time,  $Y(t_i)$  is the value of the transformed data at time  $t_i$  and  $(\mathbf{N}-\mathbf{h})$  is the number of pairs with time lag  $\mathbf{h}$ . A maximum lag distance over which to calculate the semi-variogram was defined to enable the clustering to capture differences in the temporal dependence structure.

In order to quantify the differences between the mean values in each cluster, variogram models were fitted to the average semi-variogram for each cluster (see below for details of clustering). These were fitted using the variofit function from the geoR package in the R statistical software. Ten different model shapes (Matern, exponential, gaussian, spherical, circular, cubic, wave, powered exponential, Cauchy and gneiting) were fitted to the semi-variogram using the Cressie method (Cressie, 1985). The Matern shape produced the best fit and was used to model the semi-variogram for the cluster average.

### 2.3.3 Clustering

Catchments were clustered using a Euclidean squared distance matrix, calculated using the whole of the semi-variogram to maximise the information going into the clustering algorithm (Wagener et al., 2007). There are many clustering methods available, with none universally outperforming the others (Hannah et al., 2005). Hierarchical clustering was undertaken using seven methods (Ward, single, complete, average, McQuitty, median and centroid), resulting in dendrograms, agglomeration schedules and maps. These were used to assess the spread of catchments across the clusters (i.e. how many catchments there are within each cluster) and physical explanation of clusters. Ward's method gave the best results for clustering based on the semi-variogram shape, with relatively well defined evenly sized clusters. Ward's method has been found to be robust for clustering catchments in terms of hydrological response in a wide range of other studies (e.g. Laizé and Hannah (2010); Köplin et al. (2012) and Bower et al. (2004)). Agglomerative clustering based on Ward's minimum variance method was applied to the distance matrix.

The algorithm starts with  $n$  clusters (i.e. the number of catchments), at each step the joining of every cluster pair is considered and the two clusters which results in the minimum increase in the sum of squared differences are combined. The final number of clusters is subjective, based on assessing the structure of the dendrogram and changes in gradient of the agglomeration.

#### 2.3.4 Quadratic discriminant analysis (QDA)

Discriminant analysis was used to determine which catchment characteristics can be used to attribute a catchment to a cluster. The analysis identifies whether the mean of the catchment characteristic differs between clusters. Once the variables (characteristics) have been selected, discriminant analysis creates an equation with the aim of minimising the possibility of misclassifying catchments. The equation will be in the form:

$$D = v_1X_1 + v_2X_2 + v_3X_3 + \dots + v_nX_n + C \quad (\text{Equation 2.2})$$

Where  $D$  is the discriminant function;  $v$  is the coefficient for the variable;  $X$  is the transformed value for the variable;  $C$  is a constant and  $n$  is the number of variables. The  $v$ 's are selected to maximise the difference between clusters. There is one less discriminant equation than the number of clusters. Each equation explains as much of the between-cluster variability as possible with the first equation explaining the most. Quadratic discriminant analysis was used (as opposed to linear discriminant analysis) because it allows a different covariance matrix for each cluster, increasing the model's flexibility. This is deemed acceptable due to the number of catchments being investigated.

To meet the assumptions associated with discriminant analysis, the catchment characteristics were transformed to be normally distributed. The Shapiro-Wilks value was used to select the best transformation. In addition, to avoid making prior assumptions about the characteristics which best discriminated between the different clusters, a backwards stepwise variable selection was used. A matrix containing total variance and covariance and matrix containing pooled within-group variance and covariance were compared using a multivariate F test. This indicates the extent to which a variable makes

a unique contribution to the prediction of cluster membership. The F value was used to select the variables to be removed at each step. Further to this, to avoid redundant variables, characteristics which were highly correlated ( $>0.8$  or  $<-0.8$  Spearman's rank) were removed.

Finally, the 49 independent catchments were used in a separate 'validation' analysis to evaluate the discriminant expressions fitted to the 116 original catchments. In order to determine whether the validation catchments were successfully clustered from their catchment characteristics, the validation catchments were fitted into the clusters derived from the 116 Benchmark catchments. The validation catchments were placed into the cluster for which the semi-variogram was closest to the mean semi-variogram of the cluster.

## **2.4 Results**

### **2.4.1 Clustering**

Four clusters were selected because analysis of the agglomeration showed that the benefit of increasing the number of clusters to more than four was small. Analysis of the semi-variograms showed that 87 % (101 catchments) had a Range of ~ 90 days or less, and the maximum lag was set to 90 days to maximise the difference of the catchments with semi-variogram Ranges of less than 90 days. It is acknowledged that differences between the remaining 13 % (15 catchments) which have a range much greater than 90 days are unlikely to be identified during the clustering process.

### **2.4.2 Distinction between the clusters**

The clustering analysis (Figure 2.3 and Figure 2.4), gave 32 catchments in Cluster 1, 34 catchments in Cluster 2, 35 catchments in Cluster 3 and 15 catchments in Cluster 4. There is a spatial difference between the clusters with catchments in Clusters 1 and 2 being predominantly in the North and West and catchments in Clusters 3 and 4 which are predominantly in the Midlands and South East.

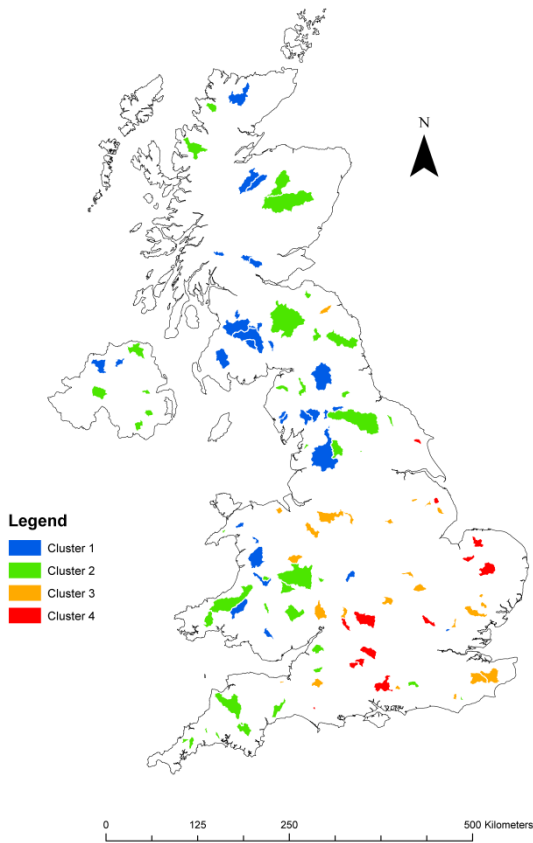


Figure 2.4: Location of the catchments coloured by cluster.

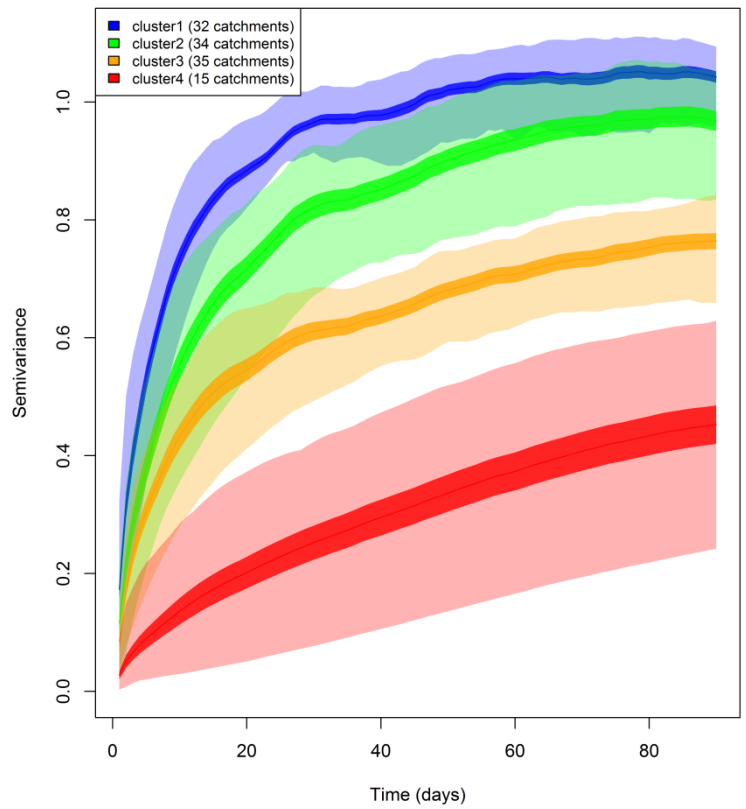


Figure 2.3: Semi-variograms from daily river flow for the four identified clusters with the 95% confidence intervals (dark shaded area) and the upper and lower bounds of each cluster (light shaded area).

The difference in the shape of the temporal dependence structure between the clusters is illustrated in Figure 2.3 and Table 2.2, with increases in Range, and decreases in the Sill and Nugget from Clusters 1 to 4. An increasing Range indicates less short-term (less than 90 days) variability in the daily mean river flow, while a decreasing Sill is caused by less temporally autocorrelated variability throughout the 30-year record. Figure 2.3 also shows that the clusters are reasonably well defined; there is overlap between all four clusters for the short time lags due to similarity in the temporal dependence of the first few days. At longer lags (after ~ 30 days) there is only overlap between Clusters 1 and 2 due to the different shapes of the semi-variograms and no overlap at the 95 % confidence interval.

Table 2.2: Characteristics of the variogram models fitted to the mean semi-variogram of each cluster.

Cluster number	Nugget	Partial sill	Range (days)
1	0.0186	0.67	29
2	0.0099	0.54	40
3	0.0088	0.48	45
4	0.0075	0.32	172

In order to investigate the influence of rainfall on the temporal dependence of river flow, the same method of temporal dependence analysis was applied to catchment averaged daily precipitation from 1980 to 2008 for all catchments. Results showed no significant difference (at the 95 % confidence interval) in the temporal dependence of rainfall between catchments in different clusters (Figure 2.5). Compared with discharge, the temporal dependence is much shorter in rainfall, only lasting around 10 days.

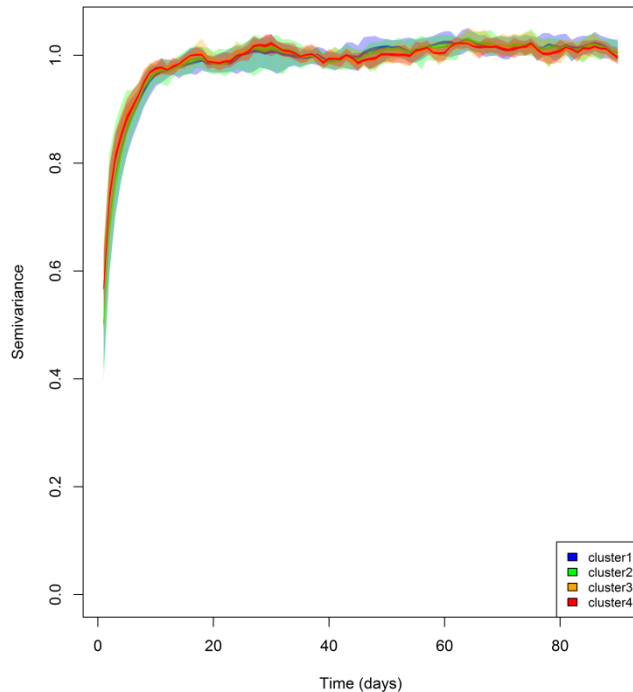


Figure 2.5: Semi-variograms from daily precipitation data for the four identified clusters with the mean of each cluster (line) and the 95% confidence intervals (shaded area).

### 2.4.3 Identify the catchment characteristics which differ between the clusters

Initially, box plots were used to investigate the possible catchment characteristics driving the differences between the four identified clusters. All the characteristics in Table 2.1 are shown except for the percentage of urban land cover, FARL and elevation 90 which were removed because the majority of the catchments had little or no urban area or FARL, and elevation 90 was almost identical to elevation max. The characteristics that differ

most between all four clusters are shown in Figure 2.6. Figure 2.7 identifies characteristics which distinguish between two or more clusters. Whilst Figure 2.8 shows characteristics for which the median does not change between clusters. BFIHOST represents the distribution of BFI between clusters (Figure 2.6) agreeing with Marechal and Holman (2005) who showed that BFIHOST is a robust way to calculate BFI, low flow statistics and the percentage of runoff. As BFI is not a catchment characteristic (being calculated from flow data) it is removed from subsequent analysis.

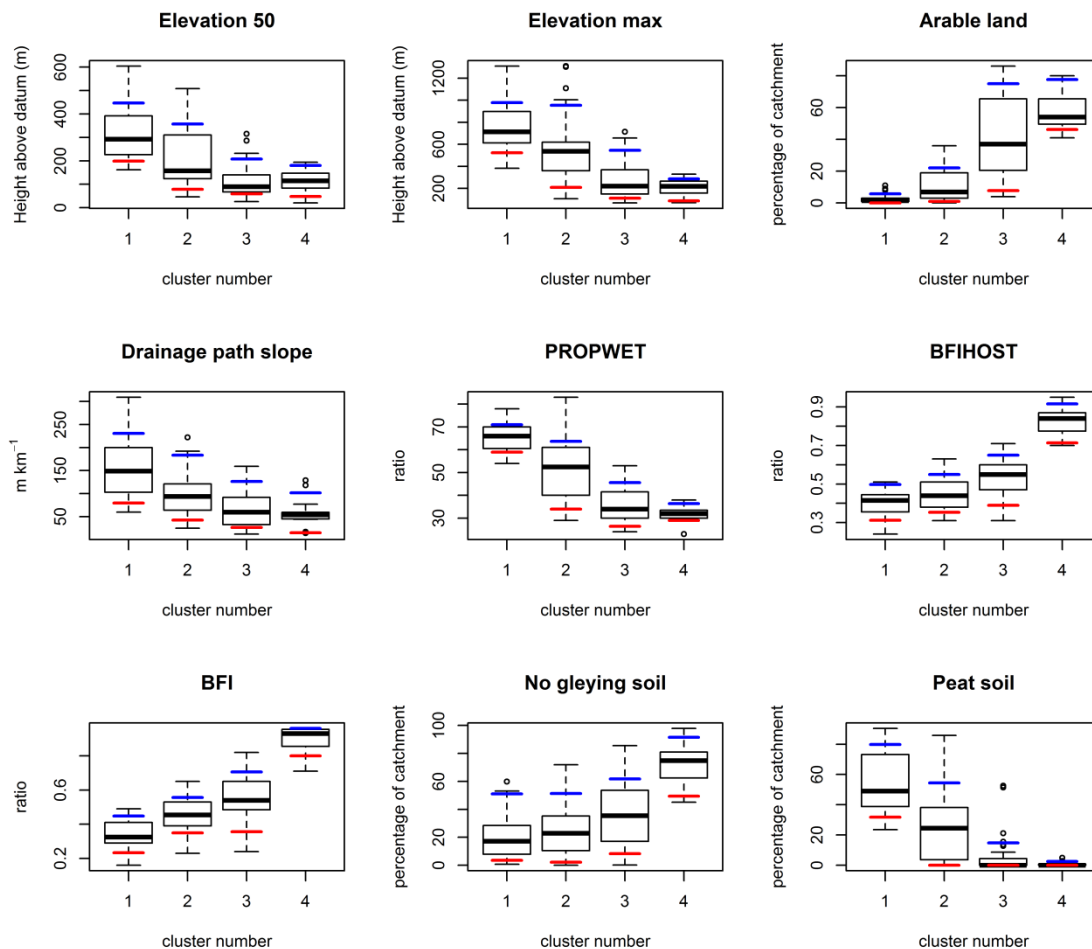


Figure 2.6: Box plots of characteristics which differ between all four clusters. Thick black line is the median value. Box shows the inter-quartile range. Black whiskers represent 1.5 times the inter-quartile range. Blue and red lines show the upper and lower 90% confidence intervals respectively and the circles show outliers.

Figure 2.9 shows the correlation between all the characteristics which differentiate between clusters (Figure 2.7 and Figure 2.8). The physical catchment characteristics in Table 2.1 are not independent from each other, as shown in Figure 2.9 by scatter plots and (Spearman's rank) correlation. The correlation between different catchment

characteristics highlights the influence elevation (elevation max and elevation 90) has on the value of PROPWET, DPSBAR, percentage of peat soils and percentage of arable land, all of which have correlations greater than  $|0.7|$ . Characteristics describing the pathway and storage are also highly ( $> 0.7$ ) correlated (e.g. BFIHOST and the percentage of highly productive fractured rock).

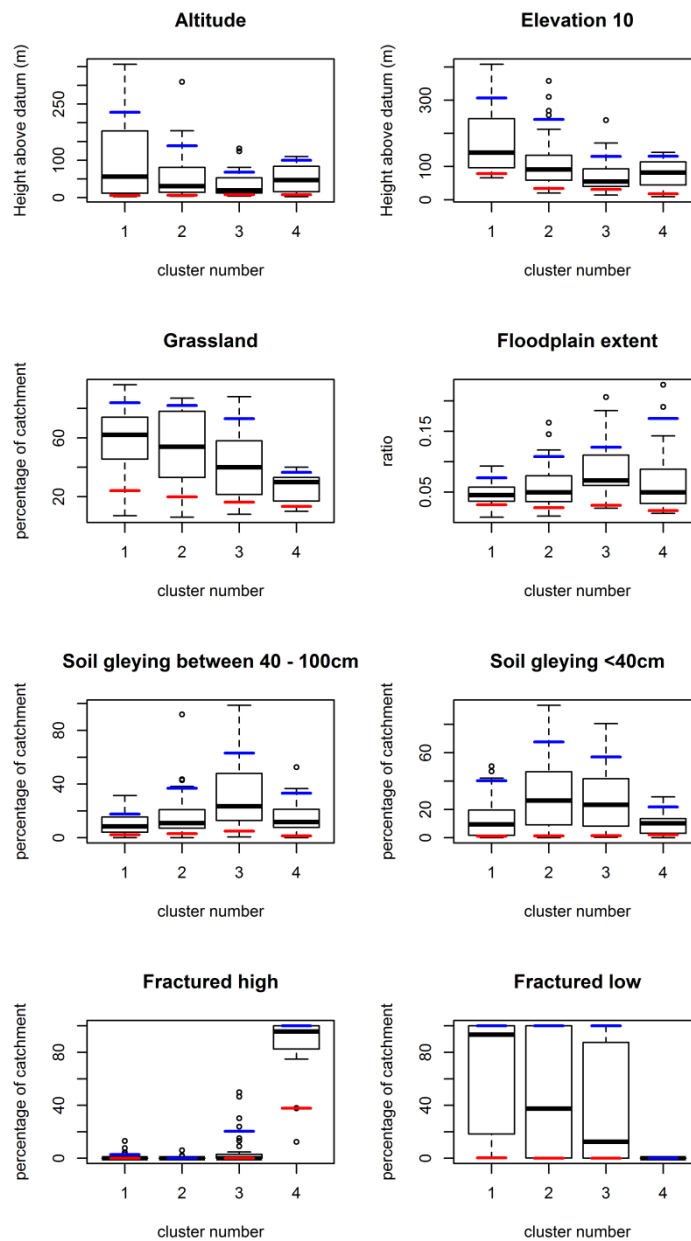


Figure 2.7: Box plots of characteristics which differ between two or three clusters, as in Figure 2.6.



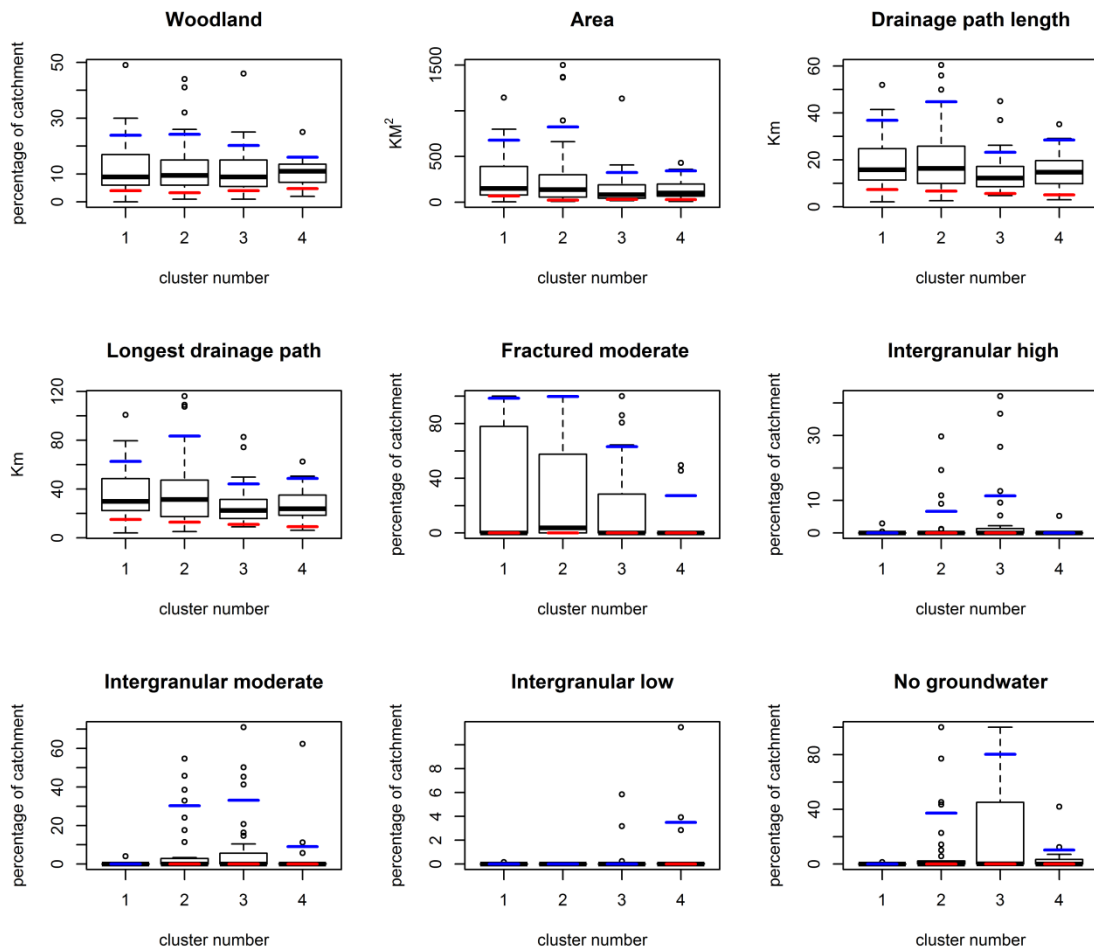


Figure 2.8: Box plots of characteristics which do not differ between clusters, as in Figure 2.6.

#### 2.4.4 Quadratic discriminant analysis

Due to the statistical distribution of: peat soils, PROPWET, and all the rock descriptors (Figure 2.9), a transformation to a normal distribution was not possible and these were excluded from the discriminant analysis. In addition, elevation characteristics were highly correlated ( $>0.8$  or  $<-0.8$  Spearman's rank; Spearman 1904) with one another and drainage path slope. Highly correlated variables invalidate the assumption of independence. Therefore, elevation 10, elevation 50, elevation 90 and elevation max (elevation characteristics with the lowest F values) were also removed from the discriminant analysis. Further to this, BFIHOST and no gleying soils were also highly correlated; the percentage of no gleying soils correctly clustered slightly more

catchments, therefore BFIHOST was also omitted. The transformations applied to the characteristics included in the QDA are shown in Table 2.3.

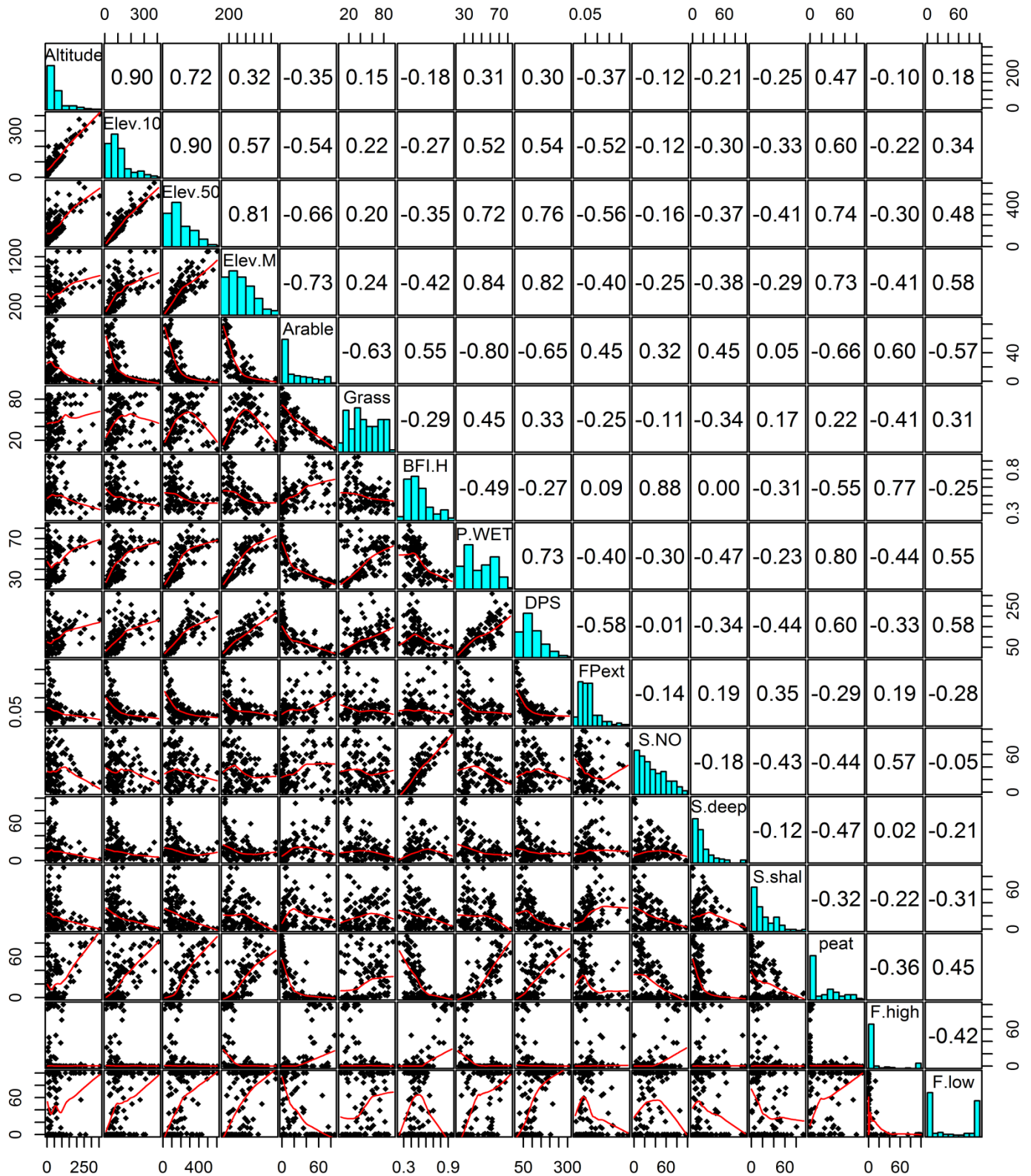


Figure 2.9: Relationship between the catchment characteristics shown as scatter plots with locally weighted smoothed red line and histograms. Correlation values are calculated using Spearman's rank.

For each variable combination a set of three equations (in the format of Equation 2.2) which maximise the difference between clusters were created. For every combination of variables, equations 2.2<sub>i</sub> and 2.2<sub>ii</sub> explained between 85 and 88% and 7 to 10% of the between-cluster variability respectively with information added by each equation significant at the 99.9% confidence interval. The third equation (2.2<sub>iii</sub>) explained the remaining (2 to 5%), with a significance of between 94 and 99%. The resulting values from equations 2.2<sub>i</sub> to 2.2<sub>iii</sub> were used to cluster the catchments based on the probability of the catchment being in each of the four clusters (Table 2.4).

Table 2.3: Transformations applied to each catchment characteristic in order to create a normal distribution.

Characteristic	Transformation
<b>Elev 10</b>	$\sqrt[5]{x}$
<b>Woodland</b>	$\sqrt[3]{x}$
<b>Arable</b>	$\sqrt[3]{x}$
<b>Grassland</b>	$\sqrt[3]{x}$
<b>Area</b>	$\ln(x)$
<b>DPS</b>	$\sqrt[3]{x}$
<b>FPext</b>	$\ln(x)$
<b>LDP</b>	$\ln(x)$
<b>DPL</b>	$\sqrt[5]{x}$
<b>No Gleying soils</b>	$\sqrt[2]{x}$
<b>Gleying 40-100cm</b>	$\sqrt[3]{x}$
<b>Gleying &lt;40cm</b>	$\sqrt[3]{x}$

Table 2.4 Different discriminant models and the percentage of catchments which were correctly classified by using the catchment characteristics. Shaded cells show the catchment characteristics included in the model.

Model number (number of variables)	% classified correctly (Benchmark)	% validated correctly	Wood	DPL	Area	Grass	Elev-10	LDP	FPext	DPS	Gleyed less than 40cm	Gleyed between 40 and 100cm	No gleyed soil	Arable
12	89.7	32.7												
11	89.7	30.6												
10	87.9	57.1												
9	86.2	63.3												
8	81.9	53.1												
7	80.1	57.1												
6	75.9	63.2												
5	72.4	71.4												
4	70.7	71.4												
3	68.1	73.4												
2	67.2	75.5												
1	54.3	55.1												

The more catchment characteristics there are in the model, the higher the percentage of correctly classified Benchmark catchments (89.7% with 12 characteristics and 54.3% with 1 characteristic). In addition, Table 2.4 identifies that the percentage of arable land discriminates best between the clusters. A relatively accurate model can be made using only a few variables (arable land, depth to gleying in soils and altitude).

### 2.4.5 Validation

The 49 validation catchments were clustered based on the distance of their semi-variogram to the centre of the already generated clusters (Figure 2.3). This resulted in 14 from Cluster 1, 12 from Cluster 2, 14 from Cluster 3 and 9 from Cluster 4. To test the quadratic discriminant models these were then clustered using their catchment characteristics and the same equations generated for the 116 catchments, the percentage clustered correctly is shown in Table 2.4.

The validation of the discriminant analysis on the 49 independent catchments (Table 2.4) shows that models with fewer explanatory variables are more robust. Although a model using 12 catchment characteristics correctly classified 104 out of 116 Benchmark catchments, the percentage of correctly clustered validation catchments (Table 2.4) highlighted that models with a lot of parameters were over-fitted to the data. Based on the percentage of catchments correctly classified in both the Benchmark and validation catchments (in models with less than 6 variables), Model 5 (Table 2.5) is deemed to have the best performance as both the Benchmark and validation catchments are clustered well.

*Table 2.5: Variables and associated coefficients used in Model 5 to classify the catchments based on their catchment characteristics.*

	Arable	No gleying	Gleyed 40 - 100cm	Gleyed <40	DPS
<b>Model 5 (eq1)</b>	1.12	0.25	-0.44	-0.37	-0.60
<b>Model 5 (eq2)</b>	0.09	-0.19	0.83	0.51	0.05
<b>Model 5 (eq3)</b>	-0.91	0.51	0.46	1.02	-0.29

The values are calculated for each catchment by multiplying the adjusted values for the catchment characteristics (i.e. the values obtained after transforming the data as outlined

in Table 2.3 which correspond to the X's in Equation 2.2) by the coefficient (i.e. the v's in Equation 2.2) e.g. for model 5 (eq1):

$$D = ((\text{arable}(X_1) * 1.12(V_1)) + (\text{no gley}(X_2) * 0.25(V_2)) + (\text{gleyed 40-100}(X_3) * -0.44(V_3)) + (\text{gleyed}<40 (x_4)*-0.37 (V_4) + (\text{DPS} (X_5) * -0.60(V_5))$$

Although Model 5 does not classify all the catchments correctly, all but one of the misclassified catchments is predicted to be in an adjacent cluster (Table 2.6). If a catchment is predicted to be in a higher numbered cluster than the actual cluster, the catchment characteristics indicate larger storage and/or faster response than is indicated by the discharge. Catchments predicted to be less than their actual class demonstrate the opposite.

Table 2.6: Confusion matrix showing Benchmark and validation (in brackets) catchments in each cluster after clustering using the catchment characteristics in model 5.

		Actual class			
		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Predicted class	Cluster 1	27 (11)	10 (2)	0 (0)	0 (0)
	Cluster 2	6 (3)	23 (6)	4 (3)	0 (0)
	Cluster 3	1 (0)	8 (6)	19 (10)	0 (0)
	Cluster 4	0 (0)	0 (0)	1 (1)	15 (9)
% correctly clustered		<b>79 (79)</b>	<b>55 (50)</b>	<b>76 (71 )</b>	<b>100 (100)</b>

The results (Table 2.4) highlighted that arable is the catchment characteristics which best discriminates between the temporal dependence-based clusters for the 116 Benchmark catchments. However, unlike the rest of the characteristics, land cover is dynamic and will change through time, thereby potentially leading to a change in the cluster allocation. In order to investigate this issue the discriminant analysis was re-done without land cover characteristics (Table 2.7), which showed a deterioration of less than 2% for the model with 5 variables.

Table 2.7: Discriminant models and the percentage of catchments which were correctly classified, shaded cells show the catchment characteristics which were included in the model.

Model number (number of variables)	% classified correctly (Benchmark)	% validated correctly	Area	DPL	Elev-10	LDP	FPext	Gleyed less than 40cm	Gleyed between 4 and 100cm	No gleyed soil	DPS
9	79.3	20.6	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
8	80.1	20.6	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
7	78.4	55.1	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
6	76.7	55.1	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
5	70.7	69.4	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
4	69.8	69.4	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
3	66.4	63.2	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
2	66.4	67.3	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
1	38.7	40.8	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded

## 2.5 Discussion

This chapter identified four distinct clusters of catchments based on the temporal dependence structure of 116 catchments throughout the UK. The mapping of these clusters (Figure 2.4) highlighted a spatial pattern between Clusters 1 and 2 against Clusters 3 and 4. This spatial pattern is indicative of a broad north-west to south-east gradient in several inter-related variables in the UK (e.g. precipitation, temperature, elevation, soil type, land use and to a certain extent rock type) as found in previous clustering (Bower et al., 2004). The temporal dependence of rainfall (Figure 2.5) showed no difference between the clusters, indicating that precipitation is not influencing the river flow dependence structure. The homogeneity of the rainfall dependence structure is caused by the high temporal variability (Chang et al., 1984) and lack of precipitation attenuation features (i.e. characteristics which influence lag time).

The characteristics which differentiated best between the clusters (benefit 3) were those that drive (or are highly correlated with characteristics which drive) the precipitation-to-flow relationship; by influencing either the pathway from precipitation to discharge and/or the amount of storage in a catchment (Ali et al., 2012). Values describing the

highest parts of the catchment (i.e. elevation 50 and above) have bigger variations between the clusters than lowland elevation values (Figure 2.7). Topography controls the strength of the forces acting on surface and groundwater flows as well as influencing the evolution of soils and vegetation (Bloschl et al., 2013) which in turn alter the macropores in the soil, hence the travel time of water through the catchment. This is seen with the higher elevations being correlated with drainage path slope, PROPWET and the percentage of peat soils (Figure 2.9) which all influence infiltration and hence lag time. PROPWET and peat soils provide information about how waterlogged the soil is and hence drive the partitioning of water between surface and subsurface flow paths as well as the depth to which water can percolate before horizontal flow occurs. High elevation and low infiltration will result in water travelling via a fast pathway where less attenuation of the precipitation will occur, hence, the variability in the river flow will be greater (higher maximum semi-variance) and the Range shorter (e.g. Cluster 1 in Figure 2.3 and Table 2.2). This is consistent with Ley et al. (2011) who highlighted a relationship between flow characteristics and the steepness and infiltration capacity of the catchment. Laizé and Hannah (2010) also identified that upland catchments were more impermeable, and thus had a stronger relationship with the regional climate drivers, than lowland permeable catchments.

BFIHOST and the percentage of no gleying soils are highly correlated ( $>0.80$ , Figure 2.9) and are an indication of infiltration and storage. No gleying soils do not become waterlogged and hence water can percolate through the soil, and BFIHOST is an indication of storage and is correlated ( $>0.7$ ) with highly productive fractured rock. Sawicz et al. (2011) also showed that the precipitation-to-discharge relationship is influenced by soil characteristics. High infiltration and storage (exhibited in Cluster 4) results in semi-variograms with a long Range due to the attenuation resulting from the slow transformation from precipitation to discharge.

Figure 2.6 shows that BFIHOST differentiates Cluster 4 from the other clusters. However, there is considerable overlap between Clusters 1 to 3. It appears that BFIHOST does not adequately capture the differences between catchments with fast precipitation-to-flow relationships (Dunn and Lilly, 2001) as other characteristics (e.g. topography) have a large influence.



Cluster 4 has a median BFIHOST of around 0.84. With a median proportion of soils without gleying of 75%, Cluster 4 is dominated by HOST class 1 (median proportion of 46% and an Inter Quartile Range (IQR) of between 34% and 67%) and HOST class 18 (median of 7% and IQR of 1% - 18%). HOST class 1 are free draining soils which overlay chalk aquifers (Figure 2.6) whilst HOST class 18 is characterised by soils with a high soil water storage capacity but which are developed in low permeability superficial deposits.

In contrast, Cluster 1 has a median BFIHOST of 0.42 and is characterised by a high proportion of peat soils (median percentage of 50%) and only 16% of soils without gleying. The soils are dominated by HOST classes 15 (median of 14% with an IQR of 6% - 30%) and 29 (median of 18%, IQR of 10% - 25%) with large proportions of 17 (median of 6%, and IQR of 1% - 18%), 24 (median of 7%, IQR of 1% - 16%) and 26 (median of 6%, IQR of 1% - 12%). HOST classes 15, 26 and 29 are peat soils. HOST classes 17 and 24 have a range of permeability but overlay superficial or solid geological deposits with no significant groundwater.

Clusters 2 and 3, with their intermediate BFIHOST, differentiate on the seasonal duration of soil waterlogging, with Cluster 2 having a lower proportion of soils in HOST classes with no gleying or gleying 40-100cm; and higher proportion of peat soils (HOST classes 15, 26, 29) and soils with gleying at <40 cm. The seasonally waterlogged soils of HOST class 24 are the most common class in both Clusters 2 and 3 with median proportion of 22 % and 8 % and IQRs of 6 - 34 % and 2 – 28 % respectively.

The final characteristic in Figure 2.6 is the percentage of arable land. Although Ragab and Cooper (1993) show that arable land has a significantly lower hydraulic conductivity value than grassland; the difference is unlikely to be seen at catchment scale. It is likely that the differences in the percentage of arable between the clusters is caused by the negative correlation (<-0.7) with high elevations, PROPWET and to a lesser extent peat soils which have a large effect on infiltration (Masicek et al., 2012). This agrees with Yadav et al. (2007) who identified that land cover (woodland and grassland) characterises some of the river flow response. Grassland does not differentiate between the clusters as well as arable. This is likely to be because of the lower correlation with characteristics which drive changes in temporal dependence.



The distribution of high and low productivity fractured rocks between the clusters (Figure 2.7) show that the majority of catchments in Cluster 4 have a larger percentage of highly productive fractured rock (predominantly Chalk). River flow in catchments in Cluster 4 thus has a greater contribution from groundwater than in the other three clusters, this will have the effect of moderating higher frequency variability in precipitation and is consistent with the relatively large Range and small semi-variance exhibited in catchments in Cluster 4 (Figure 2.3 and Table 2.2). The converse is seen in the box plot for catchments underlain by low productivity fractured rock where Cluster 1 has a larger median value. For catchments in this cluster there will be negligible groundwater-to-river flow, and river flows will be characterised by much shorter temporal dependence (Figure 2.3 and Table 2.2). These observations are consistent with the findings of Bloomfield and Marchant (2013) who showed that differences in temporal dependence in groundwater are correlated with hydraulic diffusivity (the product of transmissivity and storage). The similarity between the box plots for BFIHOST (Figure 2.9) and that for the highly productive fractured aquifer type is also consistent with the above conceptualisation of controls on surface water flows and the results of Bloomfield et al. (2009) who demonstrated the correlation between aquifer type and BFI for 44 sub-catchments in the Thames, UK. The percentage of grassland in each catchment also differentiates between the clusters.

The intergranular aquifer types do not show the same variations between clusters as the fractured rocks (Figure 2.8). This could be caused by: 1) the catchments are mainly situated on fractured rock, hence do not adequately represent the impact of intergranular aquifer types. 2) The seven classes of rock used are too simplistic and do not capture the difference in sub-surface processes occurring in different catchments. 3) The velocity of water through the consolidated intergranular aquifers is relatively low (Gehlin and Hellström, 2003) and not captured in the time scales being investigated for gauged flow in this chapter. Area, longest drainage path and drainage path length showed no significant difference between the clusters due to the flow data being standardised. Woodland also does not distinguish between the clusters and is not correlated with any of the driving characteristics (Figure 2.6). Therefore these characteristics are not expected to influence the shape of a semi-variogram (Figure 2.3).

The inter-quartile ranges of all the catchment characteristics in Figure 2.6 overlap; suggesting that no single catchment characteristic fully describes the temporal dependence structure, which underlines the importance of a multivariate approach. As such, quadratic discriminant analysis was used to investigate how accurately the catchment characteristics could be used to cluster the catchments into the clusters derived from the semi-variograms. Assessing new (validation) catchments, based on the catchment characteristics, provided an indication of how accurately these models could be applied to un-gauged catchments (benefit 2). Model 5 was deemed to be the best model and successfully clustered most of Benchmark and validation catchments. All but one of the misclassified catchments were predicted to be in an adjacent cluster (Table 2.6), this could be caused by overlap between the clusters (Figure 2.3).

As previously discussed arable land is not likely to be the driver behind the different dependence structures exhibited by the catchments. Arable is highly correlated with high elevation (-0.73) and peat soils (-0.66) which drive PROPWET (-0.8 correlation with arable) and is correlated with F-high (0.6) which indicates a large amount of storage in rocks which also have pathways which enable relatively quick flow. Therefore, arable land (in the UK) is characterising low, well drained land (particularly separating clusters 1 and 2 from 3 and 4). The percentage of no gleying soil is the second best characteristic at differentiating between the clusters and is highly correlated (0.88) with BFIHOST indicating that it is representing the storage in the catchment, particularly separating Cluster 4 from the rest. Other key catchment characteristics included soil type and slope which describe the residuals left after the percentage of arable land and the percentage of no gleying soils have been used to discriminate between the clusters and mainly help to discriminate between Clusters 1 to 3.

Models which excluded land use characteristics were developed (as arable is not temporally stable). Except for models 4 and 5 there was a large decrease between the percentage of correctly clustered catchments for both the validation and Benchmark data sets (Table 2.4 and Table 2.7). In the models, arable land was replaced with drainage path slope (the variable used in the discriminant analysis which is most correlated with arable). However, drainage path slope is less correlated with BFIHOST than arable, indicating that storage is not as well characterised.

## 2.6 Conclusion

This study developed a novel technique to classify catchments into clusters based on the temporal dependence structure of daily flow data using semi-variograms. The clusters were investigated in the context of identifying the catchment characteristics which moderate the precipitation flow relationship implicit in the semi-variogram structure. Semi-variograms have the advantage over other techniques for indexing dependence of being able to handle missing data and being able to use all the daily river flow data, rather than having to calculate indicators from the discharge data (e.g. annual or seasonal averages, minimum/maximum flows). Therefore, this technique could be applied to any set of catchments for which daily flow data are available, including sites with incomplete data coverage. The results show that clustering the catchments based on the semi-variogram is an effective way to obtain separate groups of catchments based on their catchment function and not a specific aspect of the flow regime; this method could provide a useful basis for future catchment typologies.

Four clusters best represented the range of temporal dependence structures found in the UK. Catchments with characteristics indicative of fast flow paths and low storage (i.e. upland catchments) resulted in semi-variograms with a large gradient, levelling off after a few weeks. In contrast, catchments with characteristics which enable water to infiltrate deep into the soil/rock have a small gradient and do not level off within 90 days (benefit 3, improving knowledge about drivers). The key catchment characteristics able to discriminate between catchments with different controls on the precipitation-to-river flow relationship (pathways and storage) were found to be: percentage of arable land, depth to gleyed layer in soils, slope, PROPWET, BFI, percentage of highly productive fractured rock and elevation. It is likely that arable land is not a driver behind the different clusters *per se*, but a surrogate for a combination of other characteristics (elevation, PROPWET and peat soils) which drive infiltration and hence the precipitation-to-river flow relationship.

This chapter also demonstrated that using a combination of catchment characteristics enables un-gauged catchments to be classified into clusters; consequently the shape of the (semi-)variogram can be estimated. The preferred model (Model 5) with 5 variables

(arable land, depth to gleyed layer (x3) and drainage path slope) correctly clustered 70.7-72.4 % and 69.4-71.4 % of the Benchmark and validation catchments, respectively, depending on whether land cover parameters were excluded. This study found the amount of arable land in a catchment to be a useful characteristic for distinguishing between the clusters. However, as arable land is not temporally stable, values from different time periods could provide different results.

This method is valuable for transferring information about the precipitation-to-river flow relationship from gauged to un-gauged catchments (benefit 2). This could be expanded upon in future work to enable predictions of regime characteristics at un-gauged sites to be made. In addition, ongoing work by the authors will use this temporal dependence approach to assess the impact catchment characteristics have on moderating the non-stationary of hydrological regimes (benefit 4); catchment properties will likely have major influence on the response of river flow regimes to climate variability (e.g. Laizé and Hannah (2010)) and future anthropogenic climate change (Prudhomme et al., 2013).

## 2.7 References

- ACREMAN, M. C., SINCLAIR, C. D. 1986. Classification of Drainage Basins According to Their Physical Characteristics - an Application for Flood Frequency-Analysis in Scotland. *J Hydrol*, 84: 365-380. DOI: 10.1016/0022-1694(86)90134-4.
- ALI, G. TETZLAFF, D., SOULSBY, C., MCDONNELL, J. J., CAPELL, R., 2012. A comparison of similarity indices for catchment classification using a cross-regional dataset. *Adv Water Resour*, 40: 11-22. DOI: 10.1016/j.advwatres.2012.01.008.
- BEVEN, K. J. 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrol Earth Syst Sc*, 4: 203-213.
- BLACK, P. E. 1997. Watershed functions. *J Am Water Resour As*, 33: 1-11. DOI: 10.1111/j.1752-1688.1997.tb04077.x.
- BLOOMFIELD, J. P., ALLEN, D. J., GRIFFITHS, K. J. 2009. Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK. *J Hydrol*, 373: 164-176. DOI: <http://dx.doi.org/10.1016/j.jhydrol.2009.04.025>.
- BLOOMFIELD, J. P., MARCHANT, B. P. 2013. Analysis of groundwater drought using a variant of the Standardised Precipitation Index. *Hydr Earth Syst Sci Discussions*, 10: 7537-7574. DOI: 10.5194/hessd-10-7537-2013.
- BLOSCHL, G., SIVAPALAN, M., WAGENER, T., VIGLIONE, A., SAVENIJE, H. 2013. *Runoff Prediction in Ungauged Basins, Synthesis across Processes, Places and Scales*. Cambridge University press.

- BOORMAN, D., HOLLIS, J. M., LILLY, A. 1995. *Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Report No 126*. Institute of Hydrology, UK.
- BOWER, D., HANNAH, D. M., MCGREGOR, G. R. 2004. Techniques for assessing the climatic sensitivity of river flow regimes. *Hydrol Process*, 18: 2515-2543. DOI: Doi 10.1002/Hyp.1479.
- BRADFORD, R., MARSH, T. 2003. Defining a network of Benchmark catchments for the UK. *Water and Maritime Engineering*, 156: 109-116.
- BURN, H. D., BOORMAN, D. B. 1993. Estimation of hydrological parameters at ungauged catchments. *J Hydrol*, 143: 429-454.
- BUTTLE, J. 2006. Mapping first-order controls on streamflow from drainage basins: the T-3 template. *Hydrol Process*, 20: 3415-3422. DOI: 10.1002/Hyp.6519.
- CHANDLER, R., SCOTT, M. 2011. *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences*. John Wiley and Sons, Ltd, UK.
- CHANG, T. J., KAVVAS, M. L., DELLEUR, J. W. 1984. Daily precipitation modelling by discrete autoregressive moving average processes. *Wat Resour Res*, 20: 565-580.
- CRESSIE, N. 1985. Fitting Variogram Models by Weighted Least Squares. *Mathematical Geol*, 17: 563-570.
- DIXON, H., HANNAFORD, J., FRY, M. 2013. The effective management of national hydrometric data: experiences from the United Kingdom. *Hyd Sci J*. 58: 1383-1399.
- DOOGE, J. C. I. 1986. Looking for Hydrologic Laws. *Wat Resour Res*, 22: S46-S58. DOI: 10.1029/Wr022i09sp0046s.
- DUNN, S. M., Lilly, A. 2001. Investigating the relationship between a soils classification and the spatial parameters of a conceptual catchment scale hydrological model. *J Hydrol*. 252: 157 – 173. DOI: 10.1002/hyp.1127.
- FULLER, R.M., SMITH, G. M., SANDERSON, J.M., Hill, R. A., THOMPSON, G. 2002. *The UK Land Cover Map 2000: Construction of a parcel-based vector map from satellite images*. *Cartogr J*, 39: 15-25.
- GEHLIN, S. E. A., HELLSTROM, G. 2003. Influence on thermal response test by groundwater flow in vertical fractures in hard rock. *Renewable Energy*, 28: 2221-2238. DOI: [http://dx.doi.org/10.1016/S0960-1481\(03\)00128-9](http://dx.doi.org/10.1016/S0960-1481(03)00128-9).
- GOTTSCHALK, L. 1985. Hydrological Regionalization of Sweden. *Hydrolog Sci J*, 30: 65-83. DOI: 10.1080/02626668509490972.
- GRIGG, D. B. 1965. The logic of regional systems. *Ann Assoc of American Geog*, 55: 465.
- GRIGG, D. B. 1967. *Regions, Models and Classes. Models in Geography*, Methuen, London: 467-509.
- GUSTARD, A., BULLOCK, A., DIXON, J. M. 1992. *Low flow estimation in the United Kingdom, Report No. 108*. Institute of Hydrology, UK.
- HANNAH, D. M., KANSAKAR, S. R., GERRARD, A. J., REES, G. 2005. Flow regimes of Himalayan rivers of Nepal: nature and spatial patterns. *J Hydrol*, 308: 18-32. DOI: <http://dx.doi.org/10.1016/j.jhydrol.2004.10.018>.
- HARVEY, C. L., DIXON, H., HANNAFORD, J. 2012. An appraisal of the performance of data-infilling methods for application to daily mean river flow records in the UK. *Hydrol Res*, 43: 618-636. DOI: 10.2166/Nh.2012.110.

- HOLMES, M. G. R., YOUNG, A. R., GOODWIN, T. H., GREW, R. 2005. *A catchment-based water resource decision-support tool for the United Kingdom*. Environ Modell Softw, 20: 197-202. DOI: /dx.doi.org/10.1016/j.envsoft.2003.04.001.
- HUGHES, D. A., SMAKHTIN, V. 1996. Daily flow time series patching of extension: a spatial interpolation approach based on flow duration curves. *Hydr Sci*, 41: 851-871.
- KELLER, V., YOUNG, A. R., MORRIS, D., DAVIES, H. 2006. Continuous Estimation of River Flows (CERF) Technical Report: Estimation of Precipitation Inputs.
- KOPLIN, N., SCHADLER, B., VIVIROLI, D., WEINGARTNER, R. 2012. Relating climate change signals and physiographic catchment properties to clustered hydrological response types. *Hydrol Earth Syst Sc*, 16: 2267-2283. DOI: 10.5194/hess-16-2267-2012.
- LAIZE, C. L. R., HANNAH, D. M. 2010. Modification of climate–river flow associations by basin properties. *J Hydrol*, 389: 186-204. DOI: 10.1016/j.jhydrol.2010.05.048.
- LEY, R., CASPER, M. C., HELLEBRAND, H., MERZ, R. 2011. Catchment classification by runoff behaviour with self-organizing maps (SOM). *Hydrol Earth Syst Sc*, 15: 2947-2962. DOI: 10.5194/hess-15-2947-2011.
- MARECHAL, D., HOLMAN, I. 2005. Development and application of a soil classification-based conceptual catchment-scale hydrological model. *J Hydrol*. 312: 277-293.
- MARSH, T., HANNAFORD, J. 2008. *UK Hydrometric Register*. Hydrological data UK series. Centre for Ecology & Hydrology. 210pp
- MASICEK, T., TOMAN, F., VICANOVA, M. 2012. Comparison of infiltration capacity of permanent grassland and arable land during the 2011 growing season. *ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS*, 60: 257- 266.
- MCDONELL, J. J., WOODS, R. 2004. On the need for catchment classification. *J Hydrol*, 299: 2-3. DOI: 10.1016/j.jhydrol.2004.09.003.
- MCMILLAN, H., KRUEGER, T., FREER, J. 2012. Benchmarking observational uncertainties for hydrology: rainfall river discharge and water quality. *Hydrol Process*. 26: 4078-4111 DOI: 10.1002/hyp.9384.
- MORRIS, D. G., FLAVIN, R. W. 1990. A Digital Terrain Model for Hydrology. *Proc 4th International Symposium on Spatial Data Handling*. 1: 250-262.
- MUCHAN, K., DIXON, H. 2014. Ensuring hydrometric data are fit-for-purpose through a national Service Level Agreement. *Proceedings of FRIEND-Water 2014*, In Press.
- PRUDHOMME, C., KAY, A. L., CROOKS, S., REYNARD, N. 2013. Climate change and river flooding: Part 2 sensitivity characterisation for British catchments and example vulnerability assessments. *Climatic Change*. 119 (3-4). 949-964. DOI: 10.1007/s10584-013-0726-3.
- RAGAB, R., COOPER, J. D. 1993. Variability of unsaturated zone water transport parameters: implications for hydrological modelling. 1. In situ measurements. *J Hydrol*, 148: 109-131. DOI: http://dx.doi.org/10.1016/0022-1694(93)90255-8.
- ROBSON, A., REED, D. 1999. *Flood Estimation Handbook Volume 3: statistical procedures for flood frequency estimation*. Institute of Hydrology, UK.
- SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A., CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on



- catchment function in the eastern USA. *Hydrol Earth Syst Sc*, 15: 2895-2911. DOI: 10.5194/hess-15-2895-2011.
- SIVAPALAN, M. 2006. Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale. DOI: 10.1002/0470848944.hsa012.
- SKOIEN, J. O., BLOSCHL, G., WESTERN, A. W. 2003. Characteristic space scales and time scales in hydrology. *Water Resour Res*, 39: 11 - 19. DOI: 10.1029/2002wr001736.
- SPEARMAN, C. 1904. General intelligence, objectively determined and measured. *Am J Physiol*. 15: 201-293.
- SZOLGAYOVA, E., LAAHA, G., BLOSCHL, G., BUCHER, C. 2013. Factors influencing long range dependence in streamflow of European rivers. *Hydrol Process*, 15: 2895-2911 DOI: 10.1002/hyp.9694.
- WAGERER, T., SIVAPALAN, M., TROCH, P., WOODS, R. 2007. Catchment Classification and Hydrologic Similarity. *Geography Compass*, 1: 30. DOI: 10.1111/j.1749-8198.2007.00039.x.
- WAGENER, T., SIVAPALAN, M., TROCH, P. A., MCGLYNN, B. L., HARMAN, C. J., GUPTA, H. V., KUMAR, P., RAO, P. S. C, BASU, N. B., WILSON, J. S. 2010. The future of hydrology: An evolving science for a changing world. *Water Resour Res*, 46. DOI: 10.1029/2009wr008906.
- WEBSTER, R., OLIVER, M. 2007. *Geostatistics for Environmental Scientists*. John Wiley and Sons Ltd, UK.
- YADAV, M., WAGENER, T., GUPTA, H. 2007. Regionalization of constraints on expected watershed response behavior for improved predictions in ungauged basins. *Adv Water Resour*, 30: 1756-1774. DOI: 10.1016/j.advwatres.2007.01.005.

### **3 Using variograms to detect and attribute hydrological change**

#### **Abstract**

There have been many published studies aiming to identify temporal changes in river flow time series, most of which use monotonic trend tests such as the Mann-Kendall test. Although robust to both the distribution of the data and incomplete records, these tests have important limitations and provide no information as to whether a change in variability mirrors a change in magnitude. This study develops a new method for detecting periods of change in a river flow time series using Temporally Shifting Variograms, TSV, based on applying variograms to moving windows in a time series and comparing these to the long-term average variogram, which characterises the temporal dependence structure in the river flow time series. Variogram properties in each moving window can also be related to potential meteorological drivers. The method is applied to 91 UK catchments which were chosen to have minimal anthropogenic influences and good quality data between 1980 and 2012 inclusive. Each of the four variogram parameters (Range, Sill and two measures of semi-variance) characterise different aspects of change in the river flow regime, and have a different relationship with the precipitation characteristics. Three variogram parameters (the Sill and the two measures of semi-variance) are related to variability (either day-to-day or over the time series) and have the largest correlations with indicators describing the magnitude and variability of precipitation. The fourth (the Range) is dependent on the relationship between the river flow on successive days and is most correlated with the length of wet and dry periods. Two prominent periods of change were identified: 1995 to 2001 and 2004 to 2012. The first period of change is attributed to an increase in the magnitude of rainfall whilst the second period is attributed to an increase in variability in the rainfall. The study demonstrates that variograms have considerable potential for application in the detection and attribution of temporal variability and change in hydrological systems.



### 3.1 Introduction

Increasing scientific agreement on climate change (IPCC, 2014) has been paralleled by a rise in the number of studies investigating the potential impacts on various aspects of the earth system, economies and society. One projected impact from climate change is a change in river flow dynamics, in particular changes in the magnitude, seasonality and variability of river flows which could have major impacts on the management of water resources and flood risk (e.g. Hirabayashi et al. (2013) and Gosling and Arnell (2013)) on a global scale. For the UK, the potential impact of climate change on water resources and flooding has recently been reviewed by Watts et al. (in press). Examining future changes in river flow is a focus for many modelling studies. However, the uncertainties inherent in scenario-based future projections (Prudhomme et al., 2003) highlight the need for observational evidence of change (Huntington, 2006).

Being able to detect and attribute changes in observed data is challenging, particularly in systems which are the result of complex, often non-linear, interactions between several processes (e.g. precipitation, evapotranspiration, storage and transport within a catchment). Further levels of complexity are added due to temporal changes in catchment characteristics (e.g. land cover and land management), anthropogenic modification of rivers (e.g. abstraction, impoundments and channel modifications) and changes in the location and hydrometric performance of gauging stations.

Previous studies have shown trends of increases and decreases in observed river flow for individual catchments, but at the regional to national scale the picture is more complex and regional patterns are often not spatially coherent (as noted for Europe, e.g. Kjeldsen et al. (2014)) and results are dependent on the methods and the study periods used. In the UK, significant heterogeneity in river flow trends has been reported, with trends of different sign occurring in catchments in close proximity (Hannaford and Buys, 2012). These spatial and temporal differences in published results of change detection studies are an obstacle to efforts to develop appropriate adaptation responses, particularly when there is a lack of congruency with scenario-based projections for the future. This has led to calls for fresh approaches to change detection, as highlighted by several recent synthesis reviews (e.g. Burn et al. (2012); Merz et al. (2012); Hall et al. (2013)) and the

IAHS decade ‘Panta Rhei’ (‘everything flows’) which aims to reach an improved understanding of the changing dynamics in the water cycle (Montanari et al., 2013). This chapter describes one such new avenue for change detection, namely Temporally Shifting Variograms.

### **3.1.1 Review of previous approaches to change detection**

Detection of environmental change is a huge area of research which cannot easily be reflected in an introduction. More extensive reviews of change detection methods in hydrology are available (e.g. Yue et al. (2002a)) and there are textbooks on trend testing in the environmental sciences in general (e.g. Chandler & Scott, 2011). The overview below will give the reader a flavour of the range of methods which are available, with a brief critique, to set the new method described in 1.2 in context. The choice of change detection method clearly depends on the users’ aims and available data.

The majority of hydrological change detection studies use monotonic trend tests such as Mann-Kendall (details of which can be found in Yue et al. (2002b)) which are influenced by the amount of autocorrelation in the data as well as by the start and end points of periods to which the trend tests are applied (Hannaford et al. (2013) and Chen and Grasby (2009)). This is particularly problematic when the gauging stations have relatively short records starting in a dry or wet period. For example, the UK gauging station network was largely built in the 1960s when the North Atlantic Oscillation Index (NAOI) was in a strong negative phase resulting in conditions for the UK which were drier than much of the following record. Furthermore, monotonic trend tests only provide information as to whether change has occurred over the time-period being investigated and no information is gained as to the type (e.g. abrupt or gradual) or the timing of change. This is a major limitation as it makes it difficult to link a simple monotonic trend in river flow to trends in potential drivers of change (i.e. changes in meteorological conditions or catchment properties). A further weakness of current change detection methods is that they often use indicators of flow selected *a priori* to characterise a particular aspect of the flow regime (e.g. the Q<sub>95</sub>; 7-day minimum flow; frequency of Peaks-Over-Threshold, etc), which potentially introduces bias by selecting a pre-determined aspect of the flow regime.

Another approach to change detection is change-point analysis, which can be used to identify the temporal location where change occurs (e.g. Beaulieu et al. (2012) applied change-point analysis to climate variables and Jandhyala et al. (2013) reviews change-point analysis including a plethora of studies which investigated change-points in the Nile river flow time series). Change-point analysis identifies the temporal location at which one or more properties of the river flow time series change abruptly (e.g. a change in the magnitude, variability or autocorrelation, etc), but are associated with several limitations. Firstly, there is increased uncertainty about change-points detected close to the start or end of the time series (due to a higher risk of false detection). Secondly, the method only detects one aspect of the time series (e.g. changes in linear trend, magnitude, variability or autocorrelation). Finally, although change-point analysis is designed to detect abrupt changes there is, in practice, great difficulty in discriminating between trends and abrupt changes (as demonstrated by Rougé et al. (2013). Jarušková (1997) provides a cautionary review of change-point detection methods for river flow data.

An alternative approach to change detection is through analysis of periodicities. There is a wide range of methods available for decomposition of time series into various components (e.g. Fourier methods, Empirical Mode Decomposition, Wavelets; see for example Labat (2005) and Sang (2013)). These approaches can detect complex non-linear patterns of variability and do not require the selection of indicators as they are normally based on the whole time series. However, such approaches normally characterise periodicities over a range of scales, rather than changes over time. It is hard to relate the change in spectral shape to the hydrological regime (Smith et al., 1998). This is indicated by recent studies in the UK which applied these methods and did not go beyond looking at the high-level drivers, particularly the NAOI (e.g. Sen (2009) and Holman et al. (2011)). Similarly, Kumar and Duffy (2009) use single spectral analysis to look at the precipitation – temperature – river flow relationship. This analysis enabled the authors to link the identified temporal changes to the southern oscillation as well as large anthropogenic influences (dam building and pumping), but did not investigate how changes in different aspects of the precipitation regime (e.g. seasonality and magnitude) influence the river flow time series.

### 3.1.2 The proposed new method

Here a novel and fundamentally different methodology for detection of hydrological change is introduced using variograms that are applied to moving windows in a river flow time series (hereafter, Temporally Shifting Variograms, TSV<sub>s</sub>). The TSV method gives insights into how river flow dynamics evolve through time, without relying on fixed study periods or pre-determined flow indicators. This enables river flow changes to be linked explicitly with external drivers (e.g. meteorological forcing). Variograms are able to capture the temporal dependence structure of the river flow (i.e. on average, how dependent river flow on a particular day is on river flow on the preceding days). The temporal dependence structure is closely related to the amount of variability at different temporal scales in the time series and, as it is influenced by catchment characteristics (Chiverton et al., 2015) it enables inferences to be made about the precipitation-to-flow relationship in a catchment.

As previously noted in the introduction there are several methods of identifying temporal changes in river flow and a large range of indicators which could also be investigated using a moving window. The TSV has additional key advantages over existing methods. Firstly, the variogram can be thought of as a composite indicator which provides information about a range of aspects in the river flow time series, hence enabling a range of possible temporal changes in river flow dynamics (e.g. standard deviation and seasonality) to be captured. Variograms can also detect changes in daily river flow which other indicators may not be able to (e.g. changes in variability at a range of time scales). Furthermore the variogram is calculated using daily flow data and does not rely on the user extracting pre-conceived aspects of the river flow regime via the calculation of indicators (e.g. annual or seasonal averages, minimum or maximum flow). This enables the whole flow regime to be investigated, rather than much of the daily flow information being discarded, as is the case when calculating some indicators (e.g. annual 7 day minimum flow).

It is worth noting that there are a range of stochastic techniques which can characterise the basic autocorrelation structure of data (e.g. AR, ARIMA, etc). These classical time series analysis approaches have been widely used to investigate hydrological behaviour

(e.g. Salas et al. (1982), Montanari et al. (1997), Chun et al. (2013)). Such approaches characterise temporal dependence and can also in principle be applied to moving windows (e.g. AR1 applied in 20-year moving windows by Pagano and Garen (2005)). A limitation with the classical models is that the user has to select the appropriate AR and MA parameters, a potentially subjective process, which will vary between catchments. In practice, they have not been widely used to examine changes in temporal dependence through time.

The method we propose uses variograms to characterise the autocorrelation so that the AR parameter does not need to be specified. Furthermore, variograms are designed to handle missing data which is common in river flow time series. The variogram has several defined parameters (e.g. Nugget, Sill and Range) which characterise different aspects of the autocorrelation structure that can be used in moving window analysis. This enables changes in several aspects of the river flow regime to be analysed.

Conventionally most trend analysis studies focus on change detection and attribution is often based on qualitative reasoning and relies on published work to support the hypothesis (Merz et al., 2012). The TSV method enables changes in river flow (associated with changes in variogram parameters) to be quantitatively related to meteorological characteristics. This work is an attempt to provide a formal ‘proof of consistency’ (Merz et al. 2012) that river flow changes can be associated to changes in meteorological drivers. This is an important new development as few published studies of river flow change have sought to explain observed patterns through links to precipitation. We acknowledge that this does not amount to full attribution without ‘proof of inconsistency’ with other drivers (e.g. land use change), but it does provide a solid foundation for such attribution studies. In principle, the method could be used with a wider range of drivers, both natural and anthropogenic, if temporal data on, e.g. land use change, were also available.

This study has the following objectives: develop a novel change detection method (TSV) to detect both linear and non-linear changes throughout the river flow regime; test the performance of the method by imposing artificial changes to a river flow time series; identify patterns of temporal change in rivers for a set of 94 catchments in the UK; and explain the contribution of precipitation to the detected variability in variogram parameters. This chapter is structured as follows: section 3.2 describes the data employed;

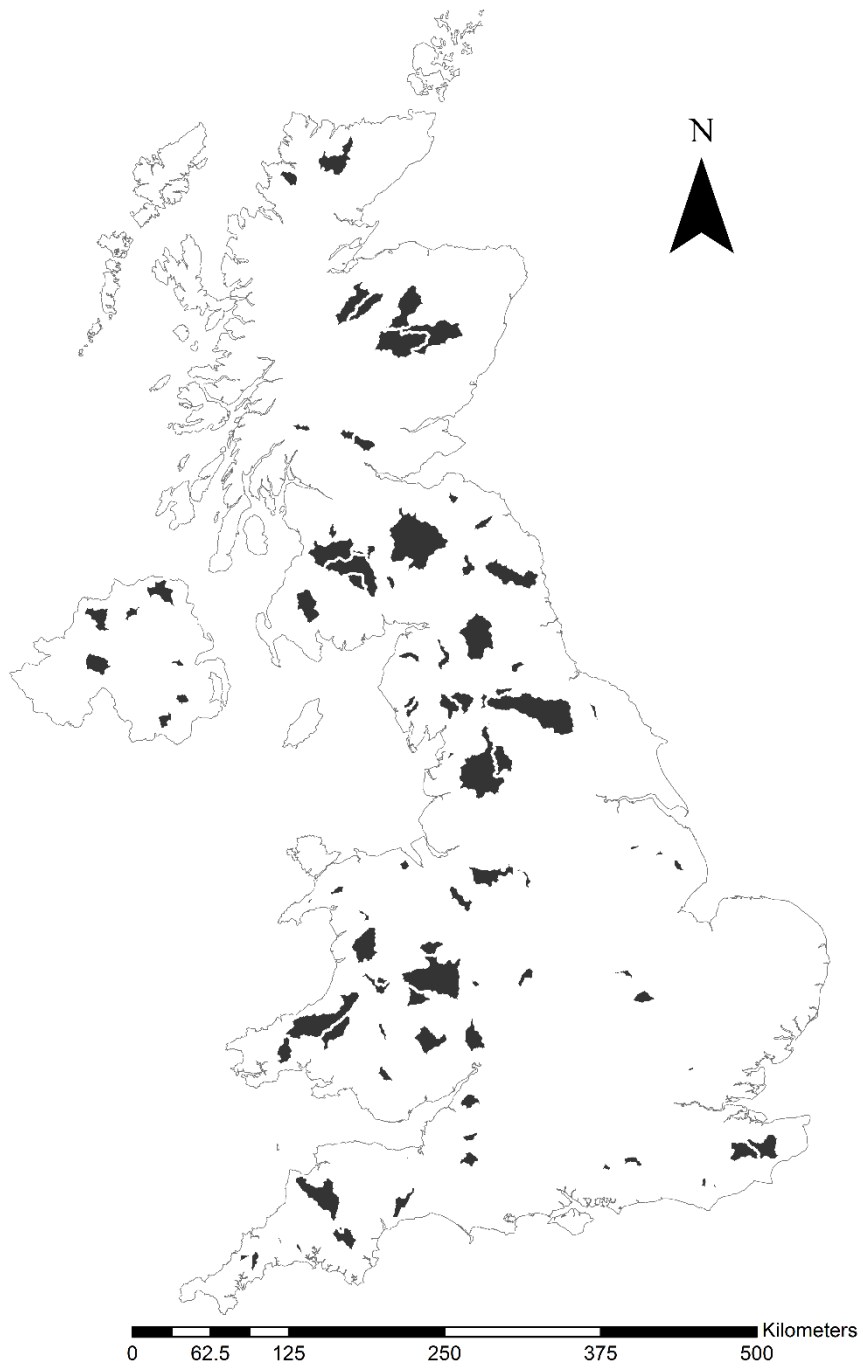
section 3.3 details the TSV method; section 3.4 tests the TSV method using an artificially perturbed river flow time series; section 3.5 identifies the periods of change across the 94 UK catchments and investigates the meteorological drivers.

## **3.2 Data**

### **3.2.1 Catchment selection**

Near-natural UK Benchmark network catchments, with only modest net impacts from artificial influences (Bradford and Marsh, 2003), were chosen. These catchments are deemed to have good data quality and therefore artificial influences will be limited. Furthermore, only catchments with a record length of 33 years or more (1980 – 2012) of daily river flow data and with less than 5% missing data were considered. Nested catchments with similar flow regimes were excluded.

This data set was used in a previous study that classified UK catchments into four classes according to their average temporal dependence structure (Chiverton et al. 2015). One of these classes was excluded from the present study; this comprises catchments which have high infiltration and storage, hence with distinctly different precipitation-to-flow relationships than the rest of the catchments. In particular, Chiverton et al. (2015) demonstrated that these catchments have a very long range of temporal autocorrelation of over a year, instead of weeks to a few months like the other catchments. This is largely due to the influence of groundwater storage. To avoid this very different catchment response time overly influencing results, catchments which overlay highly productive aquifers were removed (mainly in the SE of England). This resulted in 94 catchments, shown in Figure 3.1.



*Figure 3.1: Locations of the catchments used in this chapter.*

### 3.2.2 Precipitation characteristics

Daily catchment-averaged precipitation values were calculated from CEH-GEAR, a 1km<sup>2</sup> gridded precipitation dataset (Tanguy et al., 2014) derived using the method outlined in Keller et al. (2015). From this data, characteristics which represent different aspects of the precipitation regime were calculated (Table 3.1).

*Table 3.1: Daily precipitation characteristics.*

Precipitation characteristic	Units	Description
<b>Mean</b>	mm	Average daily precipitation values.
<b>Standard deviation</b>	mm	Standard deviation of the daily precipitation values.
<b>25<sup>th</sup> percentile</b>	mm	Daily precipitation amount which is not exceeded 25% of the time.
<b>Median</b>	mm	Daily precipitation amount which is not exceeded 50% of the time.
<b>75<sup>th</sup> percentile</b>	mm	Daily precipitation amount which is not exceeded 75% of the time.
<b>90<sup>th</sup> percentile</b>	mm	Daily precipitation amount which is not exceeded 90% of the time.
<b>95<sup>th</sup> percentile</b>	mm	Daily precipitation amount which not is exceeded 95% of the time.
<b>Max length of precipitation above or below 1mm day<sup>-1</sup></b>	days	The maximum number of successive days for which the precipitation is above/below the threshold.
<b>Average length of precipitation above or below 1mm day<sup>-1</sup></b>	days	The average number of successive days for which the precipitation is above/below the threshold. Only periods of time greater than 2 days were analysed.
<b>Winter / summer precipitation ratio</b>	unitless	The mean rainfall in December, January and February divided by the mean rainfall for June, July and August.
<b>Autumn / spring precipitation ratio</b>	unitless	The mean rainfall in September, October and November divided by the mean rainfall for March, April and May.

### 3.3 The Temporally Shifting Variograms methodology

Before going into the details of the method it is important to point out that this chapter is not aiming to ascribe the behaviour in the global variogram as the definitive expression of the temporal dependence structure. This chapter develops a method which identifies differences between variogram parameters at different time scales that represent significant changes in the temporal dependence structure that are due to meteorological drivers (or, theoretically, anthropogenic influences e.g. land management change, although this is not considered here; see also section 3.6).

The methodology consists of four steps, as follows: transformation of river flow data for analysis using variograms (section 3.3.1); creation of variograms for each catchment



(section 3.3.2); detection of periods of change in river flow using TSV (section 3.3.3); and analysis of the influence of meteorological drivers using Pearson correlation and multiple linear regression methods (section 3.3.4).

### 3.3.1 Data transformation

An overview of how the river flow time series has been de-seasonalised and standardised (steps 1 to 5) is provided here, but in-depth discussion can be found in Chiverton et al. (2015).

- 1) The river flow data were in-filled, using the equipercntile linking method (Hughes and Smakhtin, 1996), to remove periods of missing data. This was required to improve the de-seasonalisation (step 3).
- 2) A log-transform of the time series was undertaken to stabilise the variance and create a near-normal distribution. To enable the data to be logged, values of zero were replaced by  $0.001 \text{ m}^3\text{s}^{-1}$  prior to transformation. It should be noted that a variogram could be created for a river flow time series which has not been logged, however, the user would need to take care in the fitting to ensure: a) the variogram fits the data well and b) the shape of the variogram is not overly influenced by extreme values.
- 3) Seasonality was removed using Fourier representation. This was done to avoid exaggerating the temporal dependence. The de-seasonalising was carried out using the ‘deseasonalize’ package in R, see Hipel and McLeod (2005) and Chandler and Scott (2011) for further details and illustrative examples.
- 4) The in-filled data from step 1 were removed. The in-filled data were solely used for the de-seasonalisation (step above). Since the in-filled data are associated with a greater uncertainty than the measured data, they are removed from the subsequent analysis as variograms are well suited to handling missing data.
- 5) Flow data were standardised for each catchment by subtracting the mean and dividing by the standard deviation of the time series. Standardising enables comparison of catchments with different magnitudes of flow.

### 3.3.2 Creating variograms

The temporal dependence structure can be represented by a one-dimensional temporally averaged variogram (see Chandler and Scott (2011) or Webster and Oliver (2007) for detailed background about variograms). Based on the transformed, de-seasonalised standardised flow data, an empirical semi-variogram was calculated for each catchment using the average squared difference between all pairs of values which are separated by the corresponding time lag (Equation 3.1 which calculates the semi-variance):

$$\hat{\nu}(h) = \frac{1}{2(\mathbf{N} - \mathbf{h})} \sum_{i=1}^{\mathbf{N}-\mathbf{h}} [(Y(t_{i+h}) - Y(t_i))^2] \quad (\text{Equation 3.1})$$

Where  $\mathbf{h}$  is the lag time,  $Y(t_i)$  is the value of the transformed data at time  $t_i$  and  $(\mathbf{N}-\mathbf{h})$  is the number of pairs with time lag  $\mathbf{h}$ .

A variogram model was then fitted (using the variofit function from the geoR package in R and the Cressie method (Cressie, 1985)) to the empirical semi-variogram to enable the following parameters to be calculated (Figure 3.2): the Nugget, which is the y intercept, represents a combination of measurement error and sub-daily variability; the Sill is defined as the semi-variance where the gradient of the variogram is zero. A zero gradient indicates the limit of temporal dependence and is an indicator of the total amount of temporally

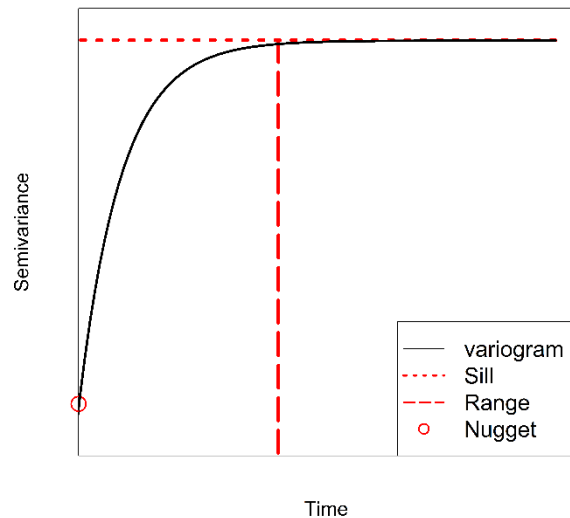


Figure 3.2: Theoretical variogram.

auto-correlated variance in the time series. The Partial-Sill is the Sill minus the Nugget and shows the temporally dependent component, used herein as the Sill. The Range is the lag time at which the variogram reaches the Sill value. Autocorrelation (gradient of the variogram) is essentially zero beyond the Range. The Practical-Range is the smallest distance beyond which covariance is no more than 5% of the maximal covariance (time it takes to reach 95% of the Sill) (Journel and Huijbregts, 1978). As the variogram is only

asymptotic to the horizontal line which represents the Sill, the Practical-Range is used herein as the Range.

### **3.3.3 Detection of change in river flow using TSV**

The fundamental premise of the TSV approach is that variograms are applied in moving windows through a time series, to determine the extent to which variogram properties (which characterise the autocorrelation structure) change through time. To examine how unusual these changes are in the context of the observed river flow record, the method determines whether variogram properties in each moving window are outside thresholds which encompass the 5 – 95% range of expected values based on the original 30-year average variogram. Periods of change (compared to the 30-year average variogram) were thus detected for the 94 catchments using the following method, applied to each catchment:

- 1) Compute bootstrap parameter estimates from multiple realisations of the 30-year average variogram, which are created by simulating 1,000 standardised river flow time series assuming a Gaussian random field model (see Havard and Held (2005) for more detail). The data were simulated using the model parameters from the original 30-year variogram, so the output has the same lags as the original data (i.e. daily). A variogram was then created for each of the time series.
- 2) Calculate upper and lower thresholds (the 5<sup>th</sup> and 95<sup>th</sup> percentiles of the 1,000 variograms). Several thresholds were tested and the 5<sup>th</sup> and 95<sup>th</sup> percentiles were chosen as these were found to detect an appropriate number of threshold exceedances throughout the time series.
- 3) Calculate parameters (see below for details) for variograms applied to 5-year overlapping moving windows (shifting by 1-year) from the original (de-seasonalised and standardised) river flow data. The values for the 5-year moving windows were compared to the range of expected values (between the 5<sup>th</sup> and the 95<sup>th</sup> percentiles) for the 30-year average variogram to see if they were above, below or inside the thresholds. Different sized windows between 1 and 10 years were analysed; 5-year overlapping windows were found to be long enough to

obtain a good fitting variogram whilst being short enough not to characterise the average behaviour of the system.

Four variogram parameters were calculated. The Sill and Range were calculated, however, as the data used are relatively high frequency (daily) and good quality, the value for the Nugget is low (although not zero as there is measurement error and sub-daily variability) and the 5<sup>th</sup> percentile is zero. Therefore, the Nugget cannot be handled in the same way as the other variogram parameters (i.e. decreases below the lower bound cannot be investigated). Instead, a new parameter, the 3 Day Average Semi-Variance (3DASV) (average of the first three points of the semi-variogram) was defined and used to investigate changes in very short-term temporal dependence. A further parameter was defined, the Half Range Average Semi-Variance (HRASV) (average of the points up to half the Practical-Range) to provide information on the intermediate temporal variability (between the 3 DASV and the Partial-Sill, which is the total amount of auto-correlated variability).

It is acknowledged that there is uncertainty surrounding the variogram calculated from the river flow data. Part of the uncertainty comes from river flow measurement and part from the fitting of the variogram model. Due to the number of catchments and moving windows it is beyond the scope of this chapter to do a full uncertainty analysis as discussed in Marchant and Lark (2004). Therefore a stability test was carried out in order to verify if the changes detected in the TSV method are caused by a change in the autocorrelation structure or by a few extreme points influencing how the variogram model fits the data. This is usually undertaken by doing a split test. However, due to the requirement of having a large data set to calculate the variogram, splitting the 5-year moving window in two was not deemed appropriate. Instead each data point in the 5-year moving window was randomly assigned to one of ten equally sized groups. The variogram was then fitted to the data 10 times, each time removing the data from one of the groups meaning that the variogram was fitted to 90% of the data. This resulted in 10 values for each variogram parameter which were calculated using 90% of the data. These points are then plotted against the variogram parameters which were calculated using 100% of the data to provide an indication as to the stability of the variogram parameter estimates.

### 3.3.4 Relating change to the meteorological drivers

Having established patterns of temporal variability using the TSV approach, the potential meteorological drivers behind the detected changes in the variogram parameters are identified before being used to calculate how much of the change they explain.

Firstly, Pearson's product-moment correlation is calculated between the time series of each of the four variogram parameters and the time series of precipitation characteristics, calculated over the same time window. These results are used to determine the likely drivers behind each variogram parameter.

Secondly, Multiple Linear Regression (MLR) is undertaken in order to determine how much variance in the variogram parameters could be explained by a combination of different precipitation characteristics. As precipitation characteristics are correlated with each other, a procedure which penalises extra model parameters is required. Stepwise regression which tests whether parameters are significantly different from zero has limitations – in particular, it can lead to bias in the parameters, over-fitting and incorrect significance tests (see Whittingham et al. (2005) for an in-depth discussion). In addition, the number and order of the potential parameters can influence the final model (Burnham and Anderson, 2002). Instead, Information Theory (IT) based on Akaike's Information Criterion (AIC) is used to analyse how much information is added by each characteristic. For each catchment the model with the lowest AIC score is used to obtain the  $R^2$  value which provides an indication into the amount of change in the variogram parameters which can be explained by precipitation.

The relative importance of each precipitation characteristic is also investigated, providing information on which precipitation characteristics are important in explaining the changes in each variogram parameter. The relative importance is obtained by calculating the  $R^2$  contribution averaged over orderings amongst regressors for each precipitation characteristic using the LMG method proposed by Linderman et al. (1980), as recommended by Gromping (2006).

Positive autocorrelation would influence the efficiency of the explanatory variables causing an overestimation of the significance. However, analysing the residuals from the

MLR between precipitation and river flow (using the Durbin–Watson test for autocorrelation disturbance) showed no significant autocorrelation. Therefore, regressing against several precipitation variables with similar autocorrelation to the variogram parameters (both averaged over 5-year moving windows) is deemed to adequately remove the autocorrelation.

### 3.4 Testing the TSV method using artificially perturbed time series

To demonstrate the suitability of the TSV approach, it was first applied to river flow time series with known artificially perturbed periods. To identify which variogram parameters respond to changes in the river flow time series, a series of artificial changes were imposed onto a 7-year (1987 to 1994) section of the observed 33 year (1980 – 2012) de-seasonalised river flow time series (Figure 3.3): 5-year moving windows starting between 1982 and 1994 (inclusive) will exhibit changes. The changes were imposed on three rivers, the South Tyne in the North East of England, the Yscir in Wales and the Tove in eastern England. The three catchments range from a relatively upland catchment with a low amount of storage (South Tyne) to a more lowland catchment with higher storage (Tove), although still a catchment with limited groundwater contribution; Base-Flow Index (BFI) values are 0.45, 0.34 and 0.54 with drainage path slope (DPS) values of 138, 107 and 37 m km<sup>-1</sup> for the Yscir, South Tyne and Tove, respectively (Marsh and Hannaford, 2008).

The perturbations applied represent plausible scenarios of the likely types of change to be seen in river flow time series due to climate variability, other extrinsic drivers (e.g. land management) or a change in the gauging station.

- **Increase in the standard deviation:** a random, normally distributed set of numbers with a mean of zero and a standard deviation of 0.5 were added to the standardised river flow time series.
- **Increase in variability:** the smallest 20 % of values were decreased by 20% whilst the largest 20% of values were increased by 20%.
- **Increased dependence:** a cosine wave with a wavelength of 365 days and amplitude of 0.5 was added to the standardised river flow time series. This increases the relationship between river flow on successive days.

- **Increase in the mean:** 1.0 was added to all the standardised river flow time series increasing the mean from 0 to 1.
- **Periods of persistence:** a 30 day period each December was forced to equal the mean.

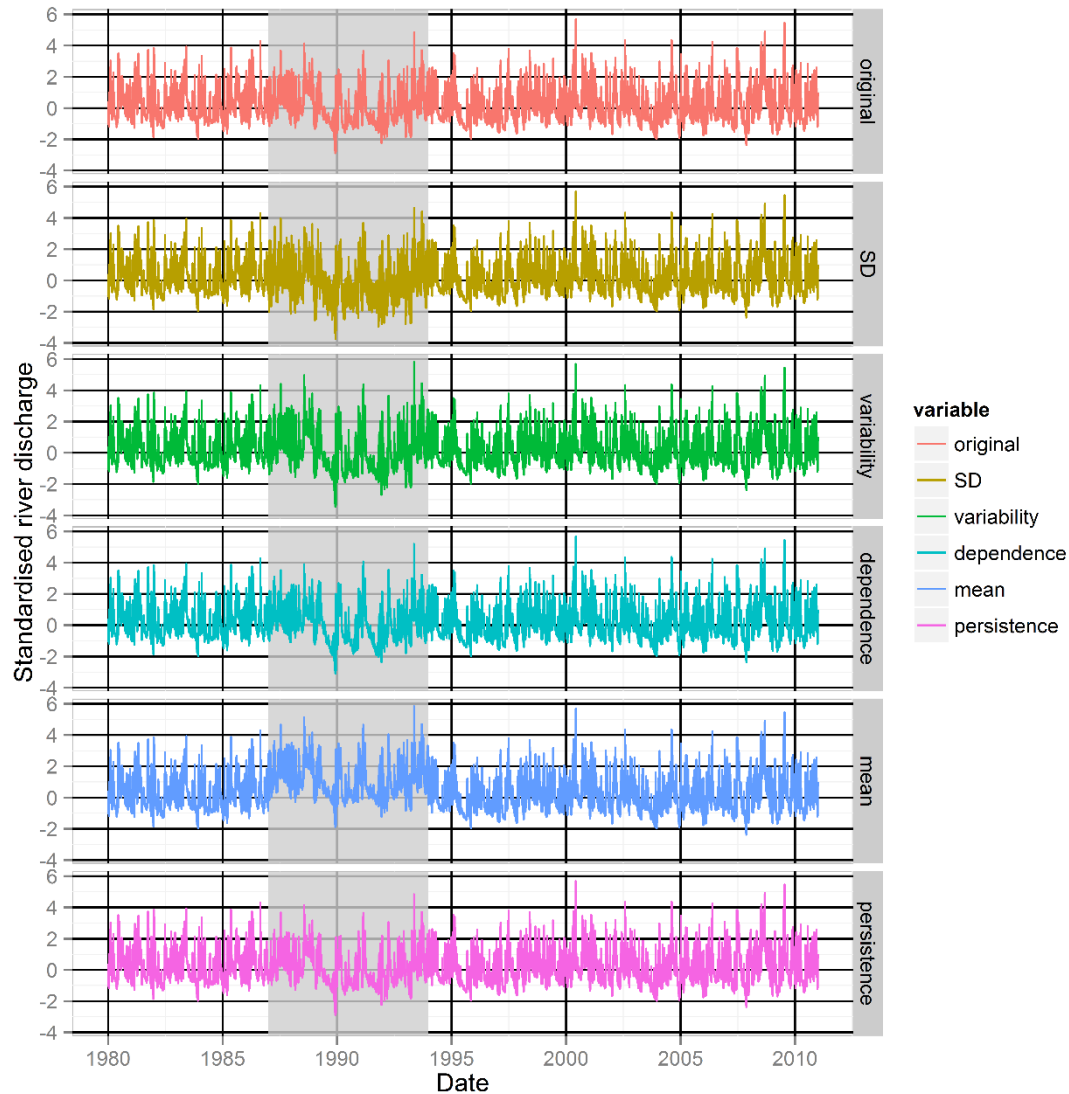


Figure 3.3: The time series resulting from the addition of artificial changes between 1987 and 1994 (shaded area) to normalised river flows for the South Tyne river.

Imposing artificial changes onto raw time series was selected as a more challenging test for the variogram change detection method, compared to applying the changes to a randomly generated artificial statistically-stationary time series, as it requires the method to be able to detect changes amongst the naturally occurring variability in the time series. For all three catchments, a variogram was calculated for each 5-year overlapping moving

window (i.e. 1980 – 1984, 1981 – 1985 ... 2008 – 2012) for the original and each of the artificial time series (Figure 3.3). The variation in time of the variogram parameters provides information on whether the enforced changes in the input time series would be detected, and which variogram parameters are affected by different types of change.

Figure 3.4 shows the outputs of the TSV analysis for the artificially modified time series. The outputs from the three catchments were similar and therefore only the output from the South Tyne is shown, as an example.

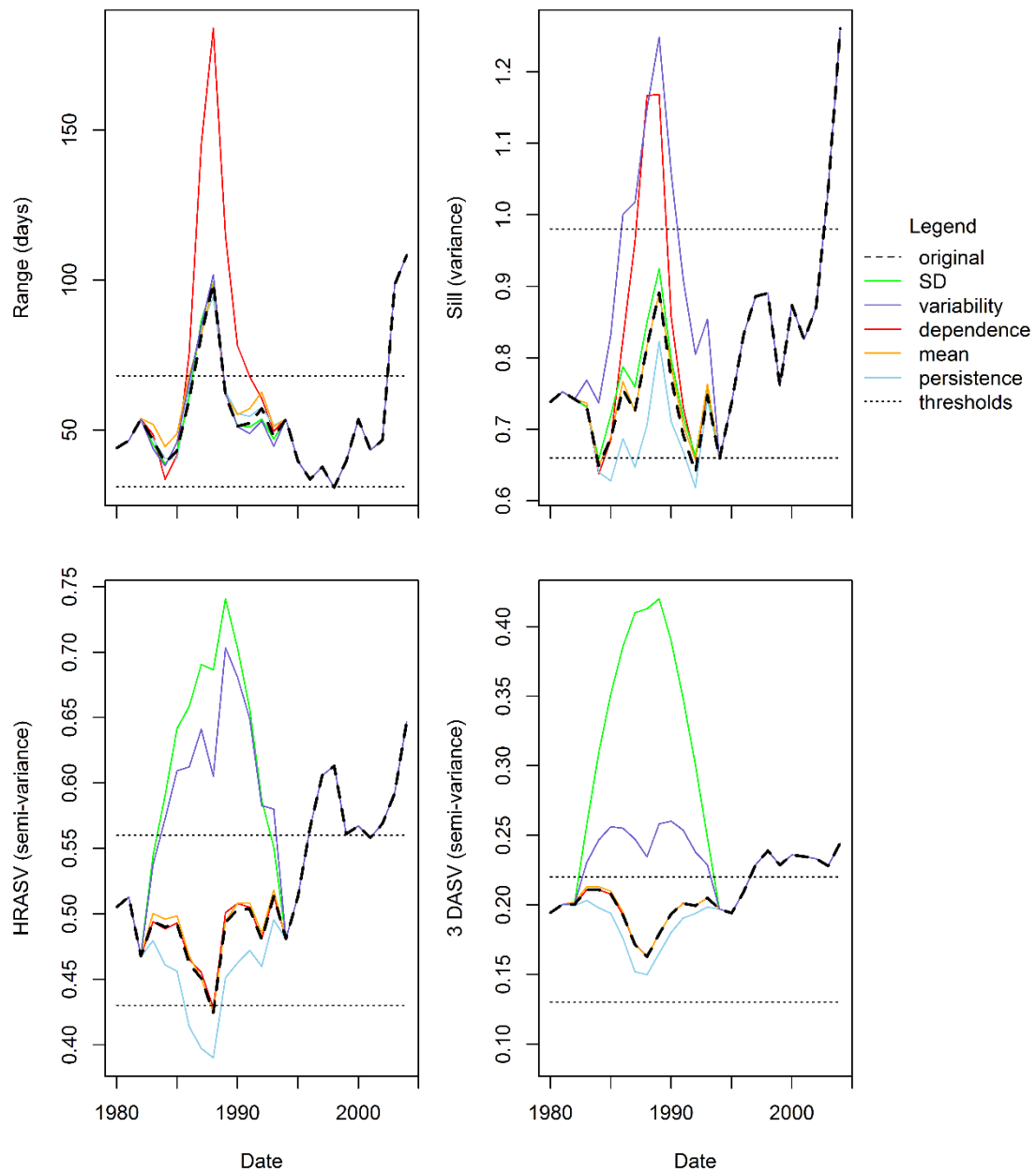


Figure 3.4: Changes in the variogram parameters resulting from the artificial changes to the time series for the South Tyne.



The magnitude of change varies depending on the type of perturbation to the flow regime (Figure 3.4). Variogram parameters are sensitive to realistic changes to aspects of the flow regime which can cause the parameters to exceed the 5<sup>th</sup> or 95<sup>th</sup> percentile threshold. In addition, the individual variogram parameters respond differently to each of the changes:

**Range:** the only artificial perturbation which has a large influence on the Range is the dependence. The increase in Range is caused by creating dependency between flow on given days which lasts for a longer time.

**Sill:** influenced mainly by the dependence and variability. Adding a wave also increases the difference between the largest and smallest values, hence the total amount of variability (the Sill) increases.

**HRASV:** mainly influenced by the standard deviation and the variability, both of which influence the variability (short-term and long-term respectively). In addition, the persistence also has a small negative impact as this would reduce the short-term variability.

**3 DASV:** influenced by the same artificial perturbation as the HRASV, however, the variability has less of an influence.

## 3.5 Application of the TSV method to Benchmark catchments

### 3.5.1 Stability analysis

Before the temporal changes were identified, the stability of the variogram parameters were analysed to investigate if certain data points were having a large influence on the shape of the variogram and hence the variogram parameters. Figure 3.5 shows the relationship between the variogram parameters which are calculated using 100 % of the available river flow data and the same parameters calculated using 90 % of the available data. The figure highlights that there is a strong relationship between the points calculated using 90 % and 100 % of the data. However, there are points which deviate much from the  $x=y$  gradient. The red dashed lines in Figure 3.5 represent small deviations from the  $y=x$  plot which are deemed to be an acceptable amount of variation due to the removal of

10% of the data. Any catchment which has a point or more outside these lines, for any variogram parameter was removed. This resulted in three catchments being removed from subsequent analysis. As well as the points outside of the red dashed lines, the Range has two groups of values that exceed the length of the red dashed lines (catchments with a Range of over 170 days). These two groups have large variability in the 10 values containing 90 % of the data. The large variability is probably due to the extrapolation by the model from the calculated semi-variance. Due to the fact that all the values are above the 95<sup>th</sup> threshold (and therefore it is likely that they capture a true change in the Range) these values were retained.

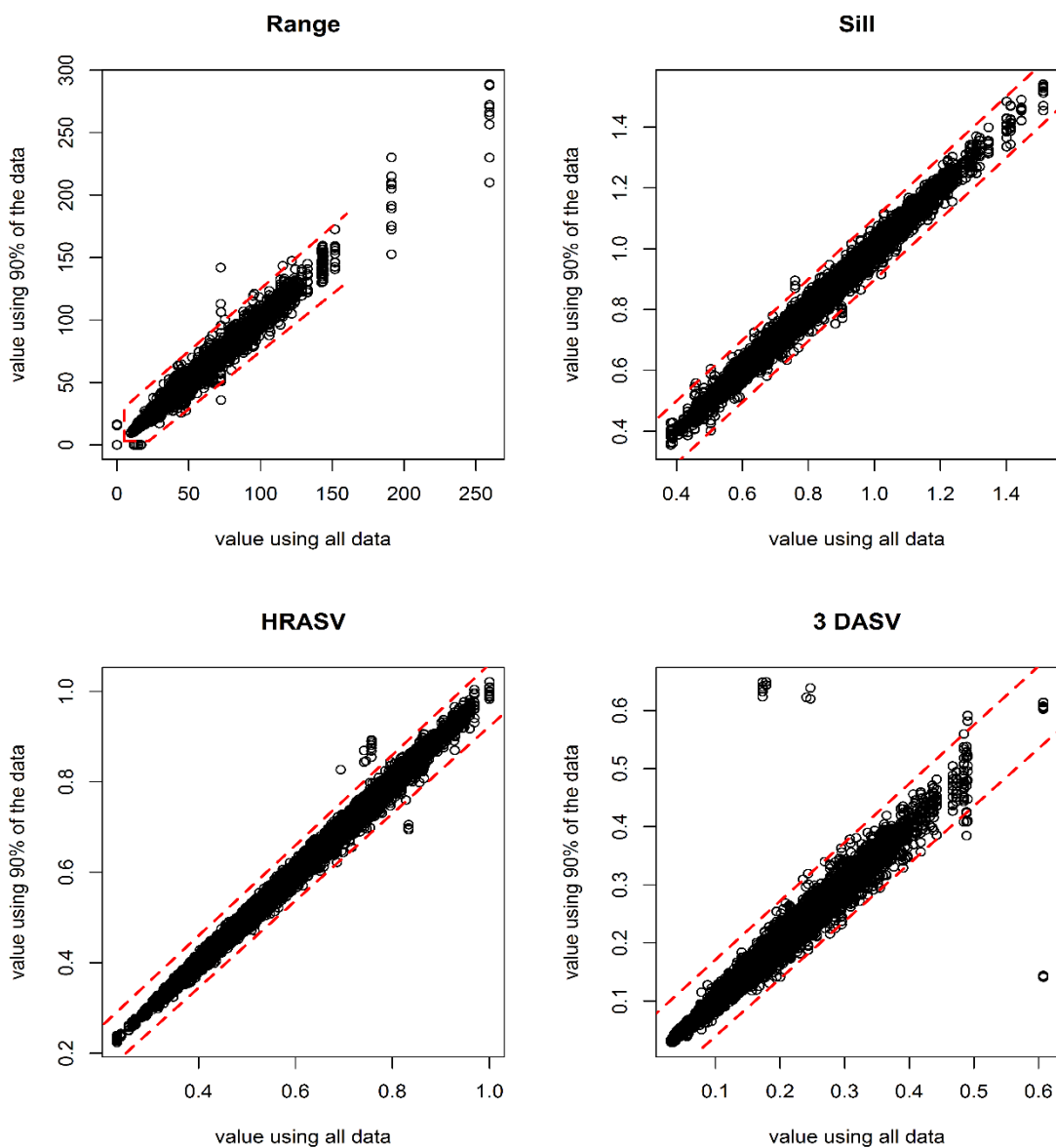


Figure 3.5: Relationship between the variogram parameters when calculated using all the available data and the parameters using 90 % of the data. The red lines show the range of acceptable values. Any catchments with points outside the red lines were removed.

### 3.5.2 Identifying periods of change

Figure 3.6 identifies the periods when the TSV characteristics go above or below the 95<sup>th</sup> or 5<sup>th</sup> percentiles from the average variogram, respectively, for the 91 catchments. Different variogram parameters exhibit different changes through time. The 3 DASV shows relatively little change, until after 2004 when there is a peak in the number of catchments above the upper threshold. The Sill has peaks in the number of catchments going above the upper threshold around 1980, 1990 and after 2004. The Range and the HRASV show several periods where the number of catchments above the upper threshold is much greater than the number of catchments below the lower threshold and vice versa. The Range and the HRASV see dramatic increases in the number of catchments which go beyond the lower and upper thresholds respectively, during approximately 1995 to 2001. Throughout this period the total amount of variability (the Sill) remains the same, as does the 3 DASV. The medium-term variability (HRASV) shows an increase and the length of time the temporal dependence lasts (the Range) decreases. In addition to the 1995 to the 2001 period, every variogram parameter exhibits an increase in catchments exceeding the thresholds after around 2004. This indicates increases in the total (Sill) and short to medium-term (3 DASV and HRASV) variability in the river flow time series.

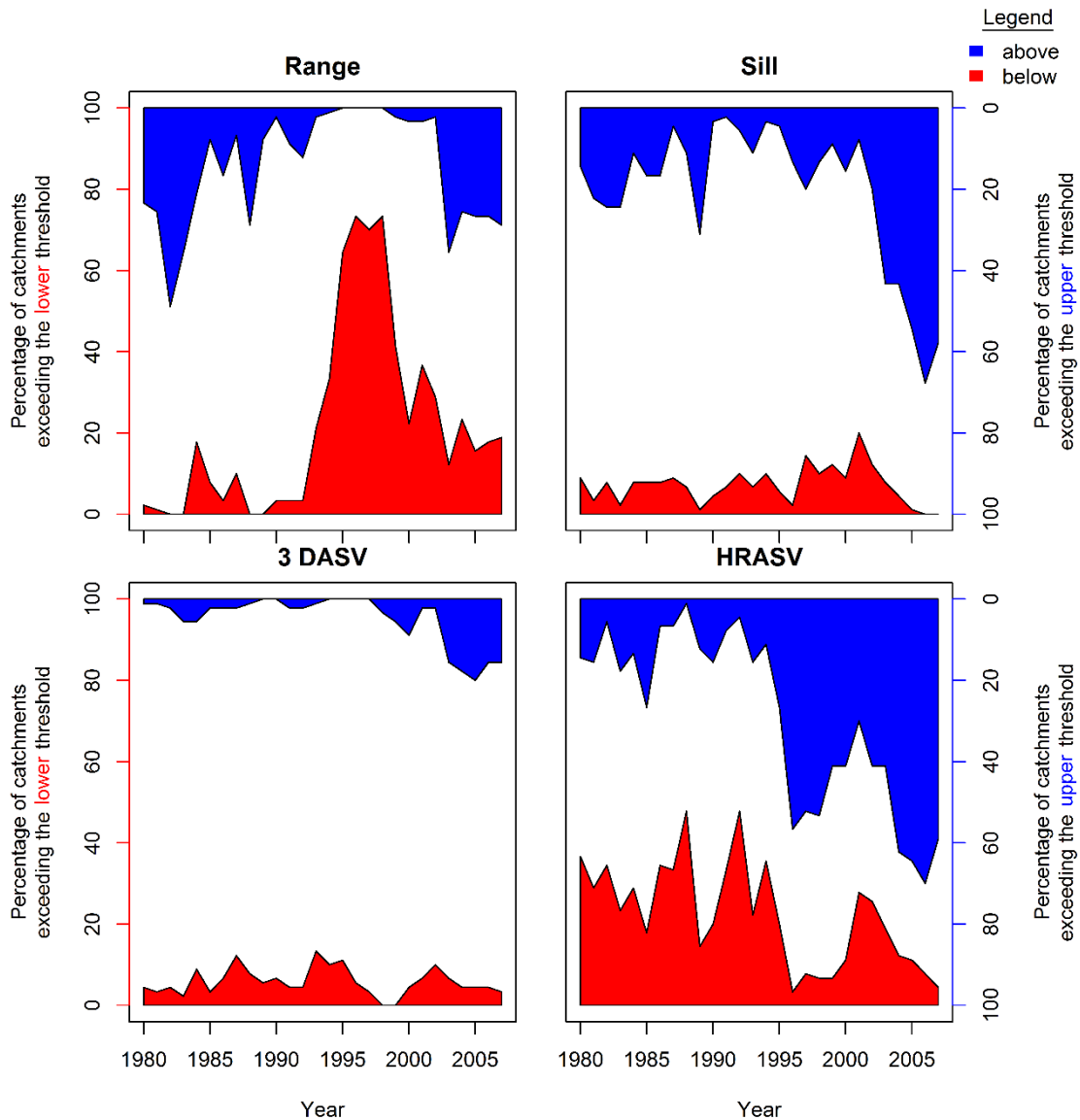


Figure 3.6: Percentage of catchments which exceed thresholds through time.

### 3.5.3 Drivers behind the change

Initial analysis investigated the difference in precipitation between the periods which show the greatest changes, in terms of the number of catchments which go below / above the thresholds (approximately 1995 - 2001 and 2004 - 2012), with the preceding time series (1980 - 1994). The periods where the most exceedances occur (1995 - 2001 and 2004 - 2012) are significantly more variable than the preceding time series (Table 3.2).

Table 3.2: Change in the median value of the potential driving characteristics for 1995 – 2001 and 2004 - 2012, compared to 1980 – 1994. The median value (taken from all the 91 catchments) is presented along with the significance level (if significantly different from 1980 – 1994 at or above the 95% CI).

Characteristic	1980 - 1994	1995 – 2001	2004 - 2012
Mean (standardised)	-0.013	-0.006 (99.9%)	0.006 (99.9%)
Standard deviation (standardised)	0.975	0.993 (99%)	1.01 (99.9%)
Median (standardised)	-0.461	-0.458 (95%)	-0.451(99.9%)
25 <sup>th</sup> percentile (standardised)	-0.55	-0.55	-0.55
75 <sup>th</sup> percentile (standardised)	0.10	0.12 (99%)	0.14 (99.9%)
90 <sup>th</sup> percentile (standardised)	1.12	1.16 (99.9%)	1.17 (99.9%)
Winter / Summer	1.36	1.60 (99.9%)	1.03 (99.9%)
Autumn / Spring	1.32	1.48 (99.9%)	1.47 (99.9%)
Max consecutive number of days below 1 mm (days)	29	27 (99%)	25 (99.9%)
Max consecutive number of days above 1 mm (days)	16	17	16
Average consecutive number of days below 1 mm (days)	17	17	17
Average consecutive number of days above 1 mm (days)	16	16	16

To explore the links with drivers more quantitatively, the relationships between precipitation characteristics and variogram parameters in the 5-year moving windows were calculated, with the results summarised for all catchments in Table 3.3.

Table 3.3: Percentage of catchments with significant (at the 95% CL) correlation between the 5-year precipitation and variogram characteristics. The average correlation (for catchments with significant correlations) is in brackets. The darker the colour, the larger the absolute average correlation.

Characteristic	Sill	Range	3 DASV	HRASV
Mean	37 (0.33)	29 (-0.42)	32 (0.46)	54 (0.61)
Standard deviation	48 (0.48)	35 (-0.29)	40 (0.53)	64 (0.61)
Average length of wet period (above 1mm)	54 (-0.08)	55 (-0.47)	48 (-0.20)	63 (0.12)
Average length of dry period (below 1mm)	47 (-0.10)	51 (0.49)	38 (-0.10)	59 (-0.10)
Max length of wet period (above 1mm)	30 (-0.03)	34 (-0.22)	30 (-0.05)	28 (0.06)
Max length of dry period (below 1mm)	32 (0.24)	36 (0.50)	29 (-0.03)	34 (-0.21)
25 <sup>th</sup> percentile	32 (0.13)	32 (-0.50)	27 (0.34)	43 (0.53)
Median	31 (0.06)	40 (-0.43)	26 (0.37)	52 (0.48)
75 <sup>th</sup> percentile	30 (0.12)	36 (-0.21)	27 (0.38)	55 (0.51)
90 <sup>th</sup> percentile	38 (0.35)	30 (-0.12)	34 (0.42)	52 (0.51)
Winter / Summer	65 (-0.51)	23 (-0.36)	55 (-0.44)	61 (-0.50)
Autumn / Spring	22 (0.01)	17 (-0.16)	19 (-0.02)	26 (0.16)

The Sill has the largest relationship with the winter to summer ratio (negative) followed by the standard deviation (positive). Although these appear contradictory, closer inspection found that the winter value seldom changed whereas the summer value

increased (decreasing the winter to summer ratio), increasing the Sill. The Range is most correlated with the lower percentiles (negative) and the length of wet and dry periods (negative and positive respectively). Similar to the Sill, the 3 DASV has the largest correlations with the standard deviation (positive), winter to summer ratio (negative), mean (positive) and 90th percentile (positive). The largest correlations are with the HRASV which is highly correlated with the percentiles (positive), SD (positive) and the mean (positive).

Each variogram characteristic has a different relationship with the precipitation characteristics (Table 3.3). As expected from the artificial analysis (Figure 3.4); the Sill, HRASV and 3 DASV are more influenced by precipitation characteristics which affect the short-term or total amount of variability in the time series (e.g. standard deviation and the different percentiles). The Range is most influenced by aspects of the precipitation which enhance correlation between the river flow on successive days (e.g. length of wet and dry periods). The relationship between the precipitation characteristics and the Range is usually in the opposite direction to the other variogram parameters.

The average relative importance of each indicator in predicting each variogram parameter was calculated using the LMG method. The three most important characteristics for the Sill (accounting for over 30% of the explained variance between them) are the winter to summer ratio, standard deviation and 90th percentile. The three most influential characteristics for the 3 DASV were the same as for the Sill. The average length of time below and above 1 mm accounts for over 30% of the explained variance for the Range. For the HRASV; standard deviation, winter to summer ratio and the mean precipitation account for over 30% of the explained variance. Although these key drivers have been identified, the total amount of

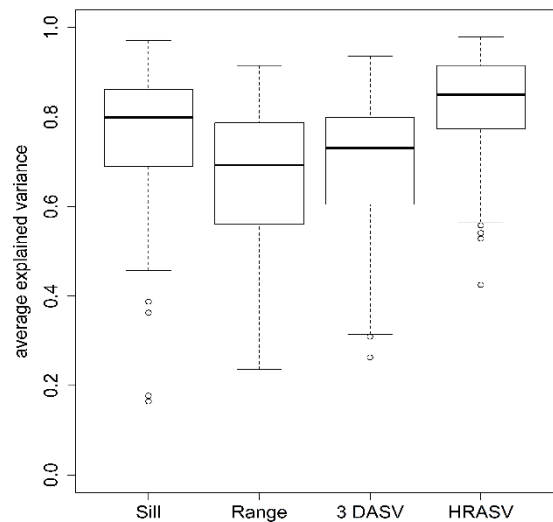


Figure 3.7: The average variance in 5-year variogram characteristics explained (adjusted R<sup>2</sup>) by meteorological characteristics, calculated using the variables in the model with the lowest AIC value (calculated using IT) for each catchment.

variability in the variogram parameters which is explained by precipitation characteristics is mixed and depends on both the variogram parameter and the catchment, as shown by the range of values of explained variance for individual catchments (Figure 3.7).

### 3.6 Discussion

The TSV method provides information about temporal changes in the whole autocorrelation structure of the daily river flow data and shows the relationship between river flow on successive days. Persistent changes in precipitation can cause the river flow regime to change in a way which will alter the autocorrelation structure and be detectable using the TSV method. This is demonstrated by the analysis of the artificially perturbed time series which showed that it is possible to identify plausible and realistic (i.e. likely to be seen in a river flow time series) changes in a river flow time series using the Temporal Shifting Variogram (TSV) approach. The TSV technique goes beyond monotonic change detection methods (such as the widely used Mann-Kendall test) as it does not require the whole time series (which is driven by multiple non-linear interactions) to alter in a near-linear way for change to be detected. Change in any form (e.g. gradual linear and non-linear) can be characterised by plotting the variogram parameters over time. This is an advantage over change point analysis which is designed to detect abrupt changes. Another benefit of the TSV method is that it provides more information about the autocorrelation structure than an AR / ARMA model. Changes throughout different aspects of the river flow regime will be detected as the individual variogram parameters (Sill, Range, HRASV and 3 DASV) are sensitive to different types of change. Finally, the identified change is in relation to expected flow dynamics which represent the whole time period, enabling anomalous periods at the start and end of the records to be identified.

Applied to 91 UK catchments, the TSV method was able to identify clear changes from the normal river flow behaviour. Changes in each variogram parameter (Range, Sill, HRASV and 3 DASV) characterise different aspects of the river flow regime. The Range is dependent on the relationship between the flow on successive days; the value of the Sill depends on the overall variability; the 3 DASV is related to the day-to-day variability and the HRASV is a combination of short-term and long-term variability. As this is a new

method, the changes in the variogram parameters are discussed below in the context of previous studies on observed changes in river flow and precipitation. This is done in order to corroborate the river flow variations that the variogram parameters are detecting, as well as their meteorological drivers.

The variogram parameters exhibit different changes throughout the record. For the Range there is a clear increase in the number of catchments going below the lower threshold (5% threshold, from the 1,000 river flow time series simulations) approximately between 1995 and 2001. Analysis of the perturbed time series shows a decrease in the Range is likely to be caused by a reduction in the dependence between flow on successive days. This period was exceptionally wet (CEH, 2002) with less seasonality (Table 3.2) meaning that catchments would have often been wetter, decreasing the available storage and the lag time between precipitation and river flow and increasing the variability in river flow. This also indicates why the number of catchments which exceed the HRASV upper threshold (95% threshold) increases approximately between 1995 and 2001. The HRASV is influenced by standard deviation and variability in the river flow (Figure 3.4), both of which will be influenced by wetter conditions in the catchment.

Post-2004 there is a large increase in the number of catchments which exceed the upper threshold for the Sill. This increase is likely caused by the increase in variability of river flow after 2004 (Figure 3.4). This time period experienced some of the most unusual hydrological conditions in the UK since records began: among the highest annual precipitation totals on record were recorded in 2008 (CEH, 2009), whereas January to June 2010 was the second driest since 1910. The 2010 - 2012 drought, one of the most severe droughts for a century (Kendon et al., 2013) terminated abruptly, leading to widespread flooding due to the wettest April to July in England and Wales for almost 250 years (Parry et al., 2013). In addition, the standard deviation in the river flow was significantly larger than for both the 1980 – 1995 and the 1995 – 2001 periods. The high correlation between standard deviation and the 3 DASV explains the post-2004 increase in the number of catchments which exceed the upper threshold for the 3 DASV.

Different meteorological characteristics influence each variogram parameter. The Sill, HRASV and 3 DASV are largely controlled by precipitation characteristics which influence the total amount and variability of precipitation (mean, standard deviation, 95<sup>th</sup>



percentile). The Range is more dependent on the length of wet and dry periods. The precipitation characteristics, on average, explain a large amount of the variability in the variogram parameters (Figure 3.7) (75%, 67%, 83% and 69% for the Sill, Range, HRASV and 3 DASV respectively). The medium-term (half of the Range) variability has the strongest correlation with the precipitation characteristics (Table 3.3). This suggests that the catchment characteristics may be having more of an influence on the relationship than the Sill and 3DASV have with precipitation.

Although, on average precipitation explains a large proportion of the river flow variability, there are large differences in the amount of explained variability across catchments (Figure 3.7). The unexplained proportion could be caused by: (1) land management change or other human disturbances which would alter the precipitation-to-river flow relationship; (2) other meteorological characteristics not included in this chapter; (3) catchment characteristics moderating how a river responds to temporal changes in precipitation; (4) unquantified error, (e.g. statistical error), including assumptions made when using information theory. With regards to the first of these factors, the analysis was carried out on Benchmark catchments with limited abstractions / discharges; however, it is likely that other factors will have a greater role in catchments with less natural regimes. Benchmark catchments generally have relatively stable land cover but land use changes over time cannot be ruled out. Other meteorological characteristics (potential factor number 2) could be influential, for example, temperature which will influence the amount of snow and evapotranspiration. Snow will increase the lag time between precipitation and river flow. Furthermore if the snow melt is gradual this will act as a store of water, and the gradual release could influence the variogram, mimicking the effect of a groundwater aquifer. Snow can be important in runoff generation in upland areas of the UK, and in more low-lying settings in some winters. However, it is unlikely to make a large difference that would be discerned in the variogram of the majority of UK Benchmark catchments. A change in the evapotranspiration losses over time could alter the magnitude of river flow, as well as seasonality. Assessing the role of additional meteorological characteristics is an important avenue of future work for developing the TSV methodology.

It is well documented that catchment characteristics moderate the precipitation-to-river flow relationship (e.g. Sawicz et al. (2011) and Ley et al. (2011)) and, more specifically, have been shown to exert a strong control over variogram properties (Chiverton et al. 2015). It therefore stands to reason that the catchment characteristics could be enhancing or dampening a river's response to changes in precipitation; influencing the non-linear precipitation-to-river flow relationship. This would influence the amount of variability explained by multiple linear regression, and possibly explaining the wide range of degrees of explained variance between catchments in Figure 3.7. The influence of catchment characteristics could explain why several studies (e.g. Hannaford and Buys (2012) and Pilon and Yue (2002)) find regional inconsistencies in observed river flow trends in catchments with broadly similar meteorological characteristics. Therefore, the influence that catchment characteristics have on moderating how a river responds to temporal changes in precipitation needs to be established. Finally, using other methods to obtain the optimum combination of precipitation parameters (other than IT and AIC) could produce different results.

Overall, the TSV approach has been shown to be a useful tool for characterising temporal variability in river flow series, going beyond standard monotonic trend tests and relating the changes to precipitation characteristics. As the method is able to detect non-linear changes, and there are four variogram parameters which respond in different ways, a more detailed analysis of links with drivers of change can be provided. In this study, this has been done using a suite of meteorological indicators. However, the approach could also be used with other explanatory variables (e.g. land use changes, changes in artificial influences, etc). In this way, the method could find wider application as a tool for attribution of change using, for example, the Multiple Working Hypothesis approach (e.g. Harrigan et al. (2014)).

### **3.7 Conclusion**

This chapter developed a new method of Temporally Shifting Variograms (TSV), for detecting temporal changes in daily river flow. The TSV approach can detect periods of change (increases and/or decreases) which result from linear or non-linear changes. Each

variogram parameter is related to a different aspect of the river flow, thus providing detailed information as to how river flow dynamics have changed through time.

There are distinct time periods when there is a large increase in the number of UK Benchmark catchments exceeding a threshold (around 1995 – 2001 for the Range and HRASV and post-2004 for all of the variogram parameters). The changes between 1995 and 2001 are attributed to an increase in precipitation; increasing the wetness of the catchment. Increased wetness reduced the amount of short-term (< half the Range) variability which is removed by the catchment characteristics. The period after 2004 incorporated some of the most variable precipitation on record, influencing all of the variogram parameters. Meteorological factors explained a large proportion of the variability in the variogram parameters (75%, 67%, 83% and 69% for the Sill, Range HRASV and 3 DASV respectively). The amount of unexplained variability is potentially caused by catchment characteristics moderating how a river responds to temporal changes in atmospheric conditions.

This chapter has demonstrated that TSV analysis enables changes in river flow dynamics to be characterised. The method will detect a wide range of changes (trends, variations in variability or standard deviation and step changes); the larger the magnitude of the change, the less time is needed before the variogram parameters will exceed the thresholds. The principal advantages to the variograms are: the method is not influenced by the start and end points; changes near the start or the end of the record can be identified; non-linear changes can be detected and the four variogram parameters capture different aspects of the river flow dynamics. Variograms could also be used to identify the impact that catchment characteristics have on moderating how a river responds to temporal changes in precipitation, which could be valuable information for enabling detailed catchment management plans to be drawn up at a local level in a non-stationary environment.

### **3.8 References**

- BEAULIEU, C., CHEN, J. & SARMIENTO, J. L. 2012. *Change-point analysis as a tool to detect abrupt climate variations.*
- BRADFORD, R. & MARSH, T. 2003. Defining a network of Benchmark catchments for the UK. *Water and Maritime Engineering*, 156, 109-116.

- BURN, D. H., HANNAFORD, J., HODGKINS, G. A., WHITFIELD, P. H., THORNE, R. & MARSH, T. 2012. Reference hydrologic networks II. Using reference hydrologic networks to assess climate-driven changes in streamflow. *Hydrological Sciences Journal*, 57, 1580-1593.
- BURNHAM, K., P. & ANDERSON, D., R. 2002. *Model selection and multimodel inference: a practice ractical informatic-theoretic approach*, New York, Springer Verlag.
- CEH 2002. *Hydrological Review of 2001*, Oxfordshire, UK, Centre for Ecology and Hydrology.
- CEH 2009. *UK Hydrological Review 2008*, Oxfordshire, UK, Centre for Ecology & Hydrology.
- CHANDLER, R. & SCOTT, M. 2011. *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences*, Chichester, West Sussex, John Wiley and Sons, Ltd.
- CHEN, Z. & GRASBY, S. E. 2009. Impact of decadal and century-scale oscillations on hydroclimate trend analyses. *Journal of Hydrology*, 365, 122-133.
- CHIVERTON, A., HANNAFORD, J., HOLMAN, I., CORSTANJE, R., PRUDHOMME, C., BLOOMFIELD, J. & HESS, T. M. 2015. Which catchment characteristics control the temporal dependence structure of daily river flows? *Hydrological Processes*, 29, 1353-1369.
- CHUN, K. P., WHEATER, H. & ONOF, C. 2013. Prediction of the impact of climate change on drought: an evaluation of six UK catchments using two stochastic approaches. *Hydrological Processes*, 27, 1600-1614.
- CRESSIE, N., A. C. 1985. When Are Relative Variograms Useful in Geostatistics? *Mathematical Geology*, 17, 563-586.
- GOSLING, S. N. & ARNELL, N. W. 2013. A global assessment of the impact of climate change on water scarcity. *Climatic Change*, 1-15.
- GROMPING, U. 2006. Relative importance for linear regression in R: The package relaimpo. *Journal of Statistical Software*, 17.
- HALL, J., ARHEIMER, B., BORGA, M., BRÁZDIL, R., CLAPS, P., KISS, A., KJELDEN, T. R., KRIAUCIŪNIENĖ, J., KUNDZEWICZ, Z. W., LANG, M., LLASAT, M. C., MACDONALD, N., MCINTYRE, N., MEDIERO, L., MERZ, B., MERZ, R., MOLNAR, P., MONTANARI, A., NEUHOLD, C., PARAJKA, J., PERDIGÃO, R. A. P., PLAVCOVÁ, L., ROGGER, M., SALINAS, J. L., SAUQUET, E., SCHÄR, C., SZOLGAY, J., VIGLIONE, A. & BLÖSCHL, G. 2013. Understanding flood regime changes in Europe: a state of the art assessment. *Hydrol. Earth Syst. Sci. Discuss.*, 10, 15525-15624.
- HANNAFORD, J. & BUYS, G. 2012. Trends in seasonal river flow regimes in the UK. *Journal of Hydrology*, 475, 158-174.
- HANNAFORD, J., BUYS, G., STAHL, K. & TALLAKSEN, L. M. 2013. The influence of decadal-scale variability on trends in long European streamflow records. *Hydrol. Earth Syst. Sci.*, 17, 2717-2733.
- HARRIGAN, S., MURPHY, C., HALL, J., WILBY, R. L. & SWEENEY, J. 2014. Attribution of detected changes in streamflow using multiple working hypotheses. *Hydrol. Earth Syst. Sci.*, 18, 1935-1952.
- HAVARD, R. & HELD, L. 2005. *Gaussian Markov Random Fields: Theory and Applications*, London, UK, Chapman & Hall/CRC.

- HIPEL, K. W. & MCLEOD, A. I. 2005. *Time Series Modelling of Water Resources and Environmental Systems*, Electronic reprint of the book originally published in 1994.
- HIRABAYASHI, Y., MAHENDRAN, R., KOIRALA, S., KONOSHIMA, L., YAMAZAKI, D., WATANABE, S., KIM, H. & KANAE, S. 2013. Global flood risk under climate change. *Nature Clim. Change*, 3, 816-821.
- HOLMAN, I., RIVAS-CASADO, M., BLOOMFIELD, J. & GURDAK, J. 2011. Identifying non-stationary groundwater level response to North Atlantic ocean-atmosphere teleconnection patterns using wavelet coherence. *Hydrogeology Journal*, 19, 1269-1278.
- HUGHES, D., A. & SMAKHTIN, V. 1996. Daily flow time series patching of extension: a spatial interpolation approach based on flow duration curves *Hydrological Sciences Journal*, 41, 851 - 871.
- HUNTINGTON, T. G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology*, 319, 83-95.
- IPCC 2014. *Climate change 2013: The Physical Science Basis. Contribution of Working group I*, New York, Cambridge University Press.
- JANDHYALA, V., FOTOPOULOS, S., MACNEILL, I. & LIU, P. Y. 2013. Inference for single and multiple change-points in time series. *Journal of Time Series Analysis*, 34, 423-446.
- JARUŠKOVÁ, D. 1997. Some Problems with Application of Change-Point Detection Methods to Environmental Data. *Environmetrics*, 8, 469-483.
- JOURNAL, A., G. & HUIJBREGTS, C., J. 1978. *Mining Geostatistics*, New York, Academic Press.
- KELLER, V. D. J., TANGUY, M., PROSDOCIMI, I., TERRY, J. A., HITT, O., COLE, S. J., FRY, M., MORRIS, D. G. & DIXON, H. 2015. CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological use. *Earth Syst. Sci. Data Discuss.*, 8, 83-112.
- KENDON, M., MARSH, T. & PARRY, S. 2013. The 2010–2012 drought in England and Wales. *Weather*, 68, 88-95.
- KJELDSSEN, T. R., MACDONALD, N., LANG, M., MEDIERO, L., ALBUQUERQUE, T., BOGDANOWICZ, E., BRÁZDIL, R., CASTELLARIN, A., DAVID, V., FLEIG, A., GÜL, G. O., KRIAUCIUNIENE, J., KOHNOVÁ, S., MERZ, B., NICHOLSON, O., ROALD, L. A., SALINAS, J. L., SARAUSKIENE, D., ŠRAJ, M., STRUPCZEWSKI, W., SZOLGAY, J., TOUMAZIS, A., VANNEUVILLE, W., VEIJALAINEN, N. & WILSON, D. 2014. Documentary evidence of past floods in Europe and their utility in flood frequency estimation. *Journal of Hydrology*, 517, 963-973.
- KUMAR, M. & DUFFY, C. J. 2009. Detecting hydroclimatic change using spatio-temporal analysis of time series in Colorado River Basin. *Journal of Hydrology*, 374, 1-15.
- LABAT, D. 2005. Recent advances in wavelet analyses: Part 1. A review of concepts. *Journal of Hydrology*, 314, 275-288.
- LEY, R., CASPER, M. C., HELLEBRAND, H. & MERZ, R. 2011. Catchment classification by runoff behaviour with self-organizing maps (SOM). *Hydrol. Earth Syst. Sci.*, 15, 2947-2962.
- LINDERMAN, R., H., MERENDA, P., F. & GOLD, R., Z. 1980. *Introduction to Bivariate and Multivariate Analysis*, Harlow, UK, Longman.

- MARCHANT, B. P. & LARK, R. M. 2004. Estimating Variogram Uncertainty. *Mathematical Geology*, 36, 867-898.
- MARSH, T. & HANNAFORD, J. 2008. *K Hydrometric Register.*, Wallingford, UK, Centre for Ecology & Hydrology.
- MERZ, B., VOROGUSHYN, S., UHLEMANN, S., DELGADO, J. & HUNDECHA, Y. 2012. HESS Opinions "More efforts and scientific rigour are needed to attribute trends in flood time series". *Hydrol. Earth Syst. Sci.*, 16, 1379-1387.
- MONTANARI, A., ROSSO, R. & TAQUU, M. S. 1997. Fractionally differenced ARIMA models applied to hydrologic time series: Identification, estimation, and simulation. *Water Resources Research*, 33, 1035-1044.
- MONTANARI, A., YOUNG, G., SAVENIJE, H. H. G., HUGHES, D., WAGENER, T., REN, L. L., KOUTSOYIANNIS, D., CUDENNEC, C., TOTH, E., GRIMALDI, S., BLÖSCHL, G., SIVAPALAN, M., BEVEN, K., GUPTA, H., HIPSEY, M., SCHAEFLI, B., ARHEIMER, B., BOEGH, E., SCHYMANSKI, S. J., DI BALDASSARRE, G., YU, B., HUBERT, P., HUANG, Y., SCHUMANN, A., POST, D. A., SRINIVASAN, V., HARMAN, C., THOMPSON, S., ROGGER, M., VIGLIONE, A., MCMILLAN, H., CHARACKLIS, G., PANG, Z. & BELYAEV, V. 2013. "Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal*, 58, 1256-1275.
- PAGANO, T. & GAREN, D. 2005. A Recent Increase in Western U.S. Streamflow Variability and Persistence. *Journal of Hydrometeorology*, 6, 173-179.
- PARRY, S., MARSH, T. & KENDON, M. 2013. 2012: from drought to floods in England and Wales. *Weather*, 68, 268-274.
- PILON, P. J. & YUE, S. 2002. Detecting climate-related trends in streamflow data. *Water Sci Technol*, 45, 89-104.
- PRUDHOMME, C., JAKOB, D. & SVENSSON, C. 2003. Uncertainty and climate change impact on the flood regime of small UK catchments. *Journal of Hydrology*, 277, 1-23.
- ROUGÉ, C., GE, Y. & CAI, X. 2013. Detecting gradual and abrupt changes in hydrological records. *Advances in Water Resources*, 53, 33-44.
- SALAS, J. D., BOES, D. C. & SMITH, R. A. 1982. Estimation of ARMA Models with seasonal parameters. *Water Resources Research*, 18, 1006-1010.
- SANG, Y.-F. 2013. A review on the applications of wavelet transform in hydrology time series analysis. *Atmospheric Research*, 122, 8-15.
- SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrol. Earth Syst. Sci.*, 15, 2895-2911.
- SEN, A. K. 2009. Spectral-temporal characterization of riverflow variability in England and Wales for the period 1865–2002. *Hydrological Processes*, 23, 1147-1157.
- SMITH, L. C., TURCOTTE, D. L. & ISACKS, B. L. 1998. Stream flow characterization and feature detection using a discrete wavelet transform. *Hydrological Processes*, 12, 233-249.
- TANGUY, M., DIXON, H., PROSDOCIMI, I., MORRIS, D. G. & KELLER, V. D. J. 2014. Gridded estimates of daily and monthly areal rainfall for the United



- Kingdom (1890-2012) [CEH-GEAR]. NERC Environmental Information Data Centre.
- WATTS, G., BATTARBEE, R., BLOOMFIELD, J., P., CROSSMAN, J., DACCACHE, A., DURANCE, I., ELLIOT, J., GARNER, G., HANNAFORD, J., HANNAH, D., M., HESS, T., JACKSON, S., R., KAY, A., L., KERNAN, M., KNOX, J., MACKAY, J., MONTEITH, D., T., ORMEROD, S., RANCE, J., STUART, M., E., WADE, A., J., WADE, S., D., WEATHERHEAD, K., WHITEHEAD, P., G. & WILBY, R., L. in press. Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography*.
- WEBSTER, R. & OLIVER, M. 2007. *Geostatistics for Environmental Scientists*, Chichester, West Sussex, John Wiley and Sons, Ltd.
- WHITTINGHAM, M. J., SWETNAM, R. D., WILSON, J. D., CHAMBERLAIN, D. E. & FRECKLETON, R. P. 2005. Habitat selection by yellowhammers *Emberiza citrinella* on lowland farmland at two spatial scales: implications for conservation management. *Journal of Applied Ecology*, 42, 270-280.
- YUE, S., PILON, P. & CAVADIAS, G. 2002a. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, 259, 254-271.
- YUE, S., PILON, P., PHINNEY, B. & CAVADIAS, G. 2002b. The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrological Processes*, 16, 1807-1829

## **4 How do catchment characteristics influence a river's response to temporal changes in precipitation?**

### **Abstract**

Precipitation regimes vary through time and drive the variability in the river flow regimes. However, the response of a river is modulated by the processes which occur within the catchment and therefore is not always proportional to the precipitation change. A river's response to a precipitation event is controlled by the complex interactions between the meteorological conditions and the catchment characteristics. Variogram parameters have previously been shown to capture how the catchment characteristics transform precipitation into river flow. Therefore, the Coefficient of Variation (CV) of the variogram parameters which are calculated over 5-year moving windows can be used as an indication as to the consistency of the rate at which precipitation signals propagate through the catchment. This study assesses the drivers behind the CV in the variogram parameters. The results indicate that the CV varies between catchment types, from catchments which overlay highly productive fractured rock having the largest CV to upland catchments with relatively impermeable soils having the smallest CV. Furthermore, it was found that the amount of variability in the variogram parameters explained by precipitation was also related to the catchment characteristics (upland, impermeable catchments were best explained through to the lowland permeable catchments which were least well explained). Therefore, the processes which occur in lowland catchments which are permeable and have a large amount of groundwater storage result in a more non-linear relationship between precipitation and river flow than upland catchments which are relatively impermeable. This means that the way precipitation propagates through these catchments is more stable in the upland, relatively impermeable catchments. These findings suggest that a river's response to future changes in precipitation for the lowland permeable catchments will be more influenced by the catchment characteristics.



## 4.1 Introduction

Investigating how catchment characteristics influence a river's response to precipitation events is a key question yet to be answered. This chapter investigates how catchment characteristics influence the resilience (stability of the precipitation-to-river flow relationship) of a catchment. Understanding a catchment's resilience provides information as to how the catchment is likely to modulate river flow responses to future changes in precipitation. A resilient catchment will have a relatively consistent precipitation-to-river flow relationship and return to average conditions relatively quickly whereas the response of a catchment which is less resilient will have a more non-linear precipitation-to-river flow relationship (subject to more threshold behaviour and will take longer to recover following a given precipitation perturbation).

Due to global warming it is expected that river flow regimes will be modified in many parts of the world. There is already evidence of change in the hydrological cycle, in global data sets (e.g. temperature, snow days, and evaporation (Stocker et al., 2013)). In the future it is virtually certain that temperature will rise (Stocker et al., 2013, Merz and Blöschl, 2009). Furthermore, it is very likely that heat waves and heavy precipitation events will increase and likely that there will be an intensification of drought.

The same evidence of change is not found in global river flow data sets, for example, Milliman et al. (2008) and Dai et al. (2009). This is not surprising as changes in river flow patterns are complicated by anthropogenic influences (e.g. reservoirs, abstractions, discharges and land management changes). Furthermore, even natural rivers are expected to respond differently to temporal changes in precipitation due to catchment characteristics moderating the river's response. Recent studies e.g. Stahl et al. (2010) and Stahl et al. (2012), investigated trends in 400 near-natural rivers across Europe, and Monk et al. (2011) who investigated 255 reference gauging stations in Canada, demonstrate regional patterns of river flow trends. The regional patterns found are linked to differences in climate conditions, particularly the influence of large-scale atmospheric drivers e.g. North Atlantic Oscillation and Pacific Decadal Oscillation. The influence of catchment characteristics was demonstrated by Gaál et al. (2012) using historical data. Furthermore, as demonstrated by Birsan et al. (2005) for a group of 48 catchments throughout

Switzerland, catchment characteristics can influence a river's response to changes in atmospheric conditions.

Numerous studies have assessed temporal changes in the river flow regime at a range of spatial scales. In the UK there have been extensive investigations of changes in different aspects of the river flow regime (see Hannaford (2015) for a review). These studies highlighted differences in the temporal changes in the river flow between different catchments. The differences go beyond the broad regional scale patterns previously mentioned and include differences in the amount and direction of change between catchments which are within close proximity to each other. The differences could be due to the catchment characteristics, indicating that the behaviour of the river is not purely caused by the climatic conditions and that the catchment characteristics will influence how a river responds to changes in atmospheric conditions (discussed in Chapter 1).

The precipitation-to-flow relationship can be thought of as the catchment's function (Black 1997). The catchment function is a result of the reciprocal evolutionary change between interacting processes (co-evolution), in particular with soils, vegetation and topography, mediated by material and energy fluxes in response to fast climate dynamics and slow geological processes (Sivapalan, 2006). Jefferson et al. (2010) demonstrates that dominant flow pathways are different between catchments for which co-evolution has resulted in different combinations of catchment characteristics. However, for any given catchment, the typical pathway water takes will change through time depending on antecedent conditions. There are thus spatial differences in dominant pathways between catchments, but also temporal differences which are likely to yield very complex patterns of river flow response. The connection between the spatial and temporal patterns is often poorly understood (Bloschl et al., 2013).

Each catchment has evolved to be unique (Beven, 2000); however, it is widely assumed that there is some level of organisation in the catchment function (Bloschl et al., 2013). The IAHS decade on Prediction in Ungauged Basins (2003 to 2012) had the aim of identifying similarity in the catchment function and hence enabling the river flow at ungauged catchments to be estimated (Sivapalan et al., 2003). However, there is still debate as to the relative contribution of the catchment characteristics and the climate on the river flow regime (Hrachowitz et al., 2013). Some studies (e.g. Young (2006)) demonstrated

that multivariate regression using catchment characteristics was more successful in predicting daily river flow data in un-gauged catchments than using the nearest neighbour approach. This contrasts with other papers (e.g. Merz and Blöschl (2009)) which found that using catchment characteristics in the regression model (based on spatial location) adds no predictive power.

The differences in the conclusions of the aforementioned studies could be for a number of reasons: 1) location and spatial proximity: using the nearest neighbour approach will work best when there is a dense network of catchments and little spatial variability in the geomorphology of the catchment. The connectivity of the catchments will have a large influence (i.e. whether catchments are sub-catchments of others). Sub-catchments will often provide the best indication as to river flow in the larger catchment. Furthermore, the variability in the climate and catchment characteristics will also depend on the location as some areas (e.g. continental shield regions with homogeneous landscapes) will have low variability in catchment characteristics but potentially high variability in climate, while the reverse is also possible. The UK has high variability in both climate and catchment characteristics. 2) the aspects of the river flow regime investigated: it is likely that different aspects of the river flow regime (e.g. high and low flows) are more or less dependent on the catchment characteristics than others (e.g. low flows are more influenced by catchment storage and release). 3) the catchment characteristics included: each catchment characteristic will influence a different aspect of the precipitation-to-river flow relationship (and the combination of catchment characteristic will interact in complex ways to determine the pathway water takes through the catchment). The difference in the findings demonstrates that further work is needed to identify the drivers (e.g. the relative role of individual catchment and precipitation characteristics) behind why catchments behave similarly.

Hydrological similarity can be split into three broad categories: climate similarity, catchment similarity and runoff similarity. Catchments with similar climate and catchment characteristics are expected to exhibit a similar river flow regime (Merz and Blöschl, 2009). One way to group areas based on climate data is by identifying areas of similar temperature, precipitation and seasonality (Thornthwaite, 1931). Another way to classify climate similarity is by looking at the long-term average relationship between

water and energy availability ((Budyko (1974) and Lvovich (1979))), for example the aridity index (ratio of average annual potential evaporation and annual precipitation). Catchment similarity is the similarity in the catchment characteristics which control the runoff process (McDonnell and Woods, 2004) by influencing the partitioning, transmission, storage and release of water. Runoff similarity is the similarity in runoff signatures (e.g. annual runoff, seasonal runoff, flow duration curves, low flows and runoff hydrographs). Runoff signatures are dependent both on the climate and catchment signatures. If the catchment characteristics are similar then the way the rivers respond to a precipitation event will be similar. This is the basis for regionalisation and prediction of river flow in un-gauged catchments (e.g. Laaha and Blöschl (2007) who estimate low flows at un-gauged sites throughout Austria).

Viglione et al. (2013) showed that some runoff signatures can be predicted more accurately than others, highlighting that different processes control each runoff signature. Furthermore, Laizé and Hannah (2010) identified that a river's response to local climate conditions was influenced by the catchment characteristics, and that in the UK, catchment characteristics have a different influence depending on the season. These findings suggest that catchment characteristics will modulate a river's response to change in atmospheric conditions, a conclusion also found in the USA by Sawicz et al. (2011). The lack of cohesion in the results from the studies which investigated the effect catchment characteristics have on the precipitation-to-river flow relationship, highlights the need to assess how the catchment characteristics influence a river's response to temporal changes in precipitation.

This chapter builds on the work in the previous two chapters. These demonstrated that the shape of the variogram can be used as a proxy for the catchment function and that temporal changes in the variogram parameters can be assessed using a moving window approach.

This chapter assesses the role catchment characteristics have on the resilience (stability of the precipitation-to-river flow relationship) of the variogram properties by addressing three questions (Figure 4.1): 1) how much of the temporal variability in the variogram parameters (calculated in Chapter 3) can be attributed to temporal changes in precipitation characteristics? 2) which catchments have the most temporally stable variogram

parameters? 3) what are the drivers behind the temporal stability in the variogram parameters (e.g. climate characteristics, catchment characteristics and spatial location)?

As well as increasing the understanding of how catchments may respond to future changes in precipitation, the amount of variability in the river flow regime will influence the detectability of changes. Wilby (2006) showed that the amount of time it takes for monotonic trends to be detectable depends on the ratio between the change in the mean and the variability in the river flow. This will be true for any signal being investigated and the noise surrounding it. The stability of the precipitation-to-river flow relationship (resilience) in a catchment will influence how a river responds to changes in precipitation. Catchments which have a low resilience are more likely to exhibit variability in the precipitation-to-river flow relationship and therefore display non-linear responses, e.g. threshold behaviour (Carey et al., 2010). Furthermore, it will be harder to detect a trend in precipitation in catchments with a low resilience as the precipitation signal will be modulated by the processes which occur within the catchment characteristics more than in a resilient catchment.

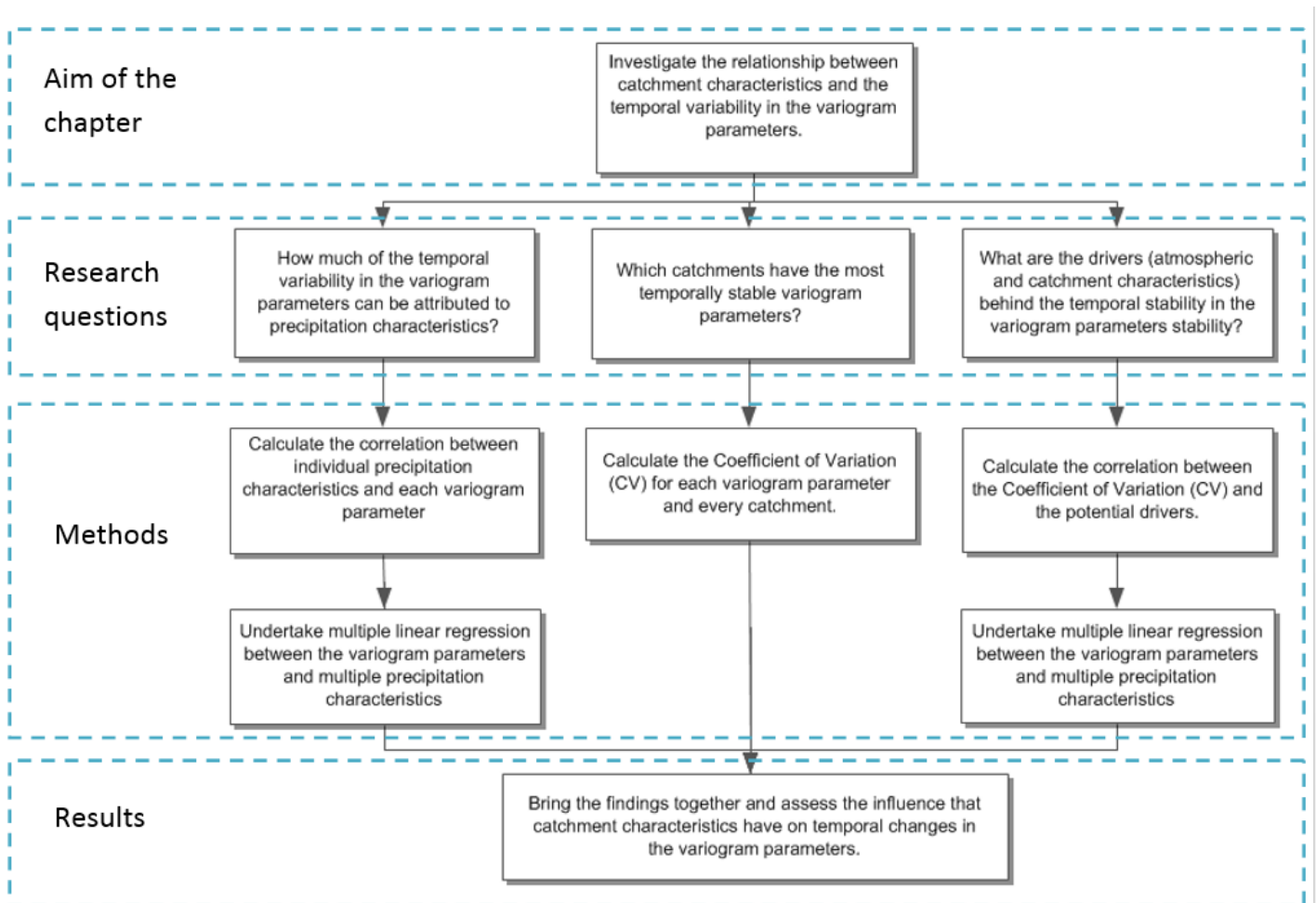


Figure 4.1: Flow diagram of the layout of this chapter.

## 4.2 The variogram parameters

Two variogram parameters are investigated in this chapter, the partial-Sill (Sill minus the Nugget) and the Range. Out of the four variogram parameters investigated in Chapter 3, these are the most distinct from each other, detecting different aspects of the river flow regime (Figure 3.4 and Table 3.3). The Sill is best thought of as capturing the total amount of variability (i.e. difference between largest and smallest values) on a scale of weeks to months. The Range is best thought of as the ‘smoothness’ (i.e. whether the river flow time series is dominated by high or low frequency components) of the river flow time series (Figure 1.4).

### **4.3 Data**

This chapter uses the same catchments and catchment characteristics as in Chapter 2. These are Benchmark catchments and therefore have limited human interference (Bradford and Marsh, 2003). For each catchment, daily river flow and precipitation data between 1980 and 2012 (inclusive) is used. The precipitation characteristics are the same as in Chapter 3. In addition, daily evapotranspiration data was used, as discussed by Robinson et al. (2015). The evapotranspiration data was calculated from 1km<sup>2</sup> grids using the method outlined in Robinson et al. (in prep) which uses the Penman-Monteith equation with a correction to account for interception, as in MORECS (Thompson et al., 1981).

### **4.4 Methods**

Changes in the variogram parameters were calculated using the moving window approach outlined in Chapter 3. The method creates a variogram using standardised daily river flow data over 5-year overlapping time windows. The time periods overlap by four years creating a new value for the variogram in each window (e.g. the first value is calculated from data between 1980 and 1984, the second value uses 1981 to 1985 and this continues up to 2008 to 2012). This results in a time series of 29 variograms (and associated variogram parameters) for each of the 116 catchments.

Section 4.4.1 explains the methods used to investigate how much of the temporal variability can be explained by precipitation and whether the amount which can be explained varies between catchments in the four clusters identified in Chapter 2. Section 4.4.2 explains the methods used to assess the relationship between the Coefficient of Variation (CV) and a range of potential drivers (precipitation, catchment characteristics and location).

#### **4.4.1 Investigating the effect of precipitation changes on the variogram parameters**

The results from Chapter 2 highlighted that each catchment has a different precipitation-to-river flow relationship, driven by the catchment characteristics. Chapter 2 also showed

that the catchments could be grouped into four relatively distinct clusters based on the way that precipitation is transformed into river flow. In addition, Figure 3.6 showed that there is a large spread in the amount of variability in the variogram parameters explained by the precipitation characteristics. Therefore this chapter begins by investigating the relationship between temporal variability in the variogram parameters and the different precipitation characteristics for catchments in each cluster (section 4.4.1.1 and section 4.4.1.2), to determine if the different clusters reveal differences in the amount of river flow variability which can be explained by precipitation. Given the contrasts in catchment characteristics between clusters, this would indicate that catchment characteristics are modulating a river's response to a change in precipitation.

#### **4.4.1.1 The effect of individual precipitation characteristics**

Both the type of change in precipitation and the catchment characteristics are important in determining a river's response. For example, a large amount of groundwater storage in the catchment may provide a buffering against periods of low rainfall. However, the response of the river to a large rainfall event may be more dependent on the infiltration capacity of soils. Therefore, the relationship between the variogram parameters and each precipitation characteristic is investigated. The results (correlation values) are shown as box plots, grouped into the clusters derived in Chapter 2 to give an indication of the influence that the catchment characteristics have on the relationship.

#### **4.4.1.2 The effect of the overall precipitation regime**

Section 4.4.1.2 builds on section 4.4.1.1 and investigates the amount of variability in the variogram parameters explained by multiple precipitation characteristics. This provides an indication to the amount of variability which can be attributed to precipitation and the unexplained proportion. The unexplained proportion could be caused by: other meteorological characteristics not included, modulation of the precipitation by the catchment characteristics or temporal changes in the catchment properties e.g. land cover change.

Only precipitation characteristics which were not highly correlated ( $\leq |0.8|$ ; (Spearman, 1904)) with the other precipitation characteristics were included in the multiple linear



regression model. When two or more of the precipitation characteristics were highly correlated ( $>0.8$ ), the one with the highest average correlation with the variogram parameters was selected (i.e. the precipitation characteristic which was likely to explain the most temporal variability). As in section 4.4.1.1, the results are plotted as box plots grouped by cluster.

The generic equation for multiple linear regression is shown in Equation 4.1:

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + \dots + b_pX_p \quad (\text{Equation 4.1})$$

Where  $\hat{Y}$  is the predicted or expected value of the dependent variable,  $X_1$  through  $X_p$  are  $p$  distinct independent or predictor variables,  $b_0$  is the value of  $Y$  when all of the independent variables ( $X_1$  through  $X_p$ ) are equal to zero, and  $b_1$  through  $b_p$  are the estimated regression coefficients. The model is fitted by minimising the Residual Sum of Squares (RSS) shown in Equation 4.2:

$$RSS = \sum_{i=1}^p e_i^2 \quad (\text{Equation 4.2})$$

Where  $e$  is the difference between the predicted  $Y$  and the measured  $Y$  shown in Equation 4.3 (the residuals):

$$e_i = Y_i - \hat{Y}_i \text{ with } i = 1, \dots, p \quad (\text{Equation 4.3})$$

There are four principal assumptions which justify the use of linear regression models:

- 1) Linearity and additivity of the relationship between the dependent and independent variables.
- 2) Statistical independence of the errors (i.e. the values of  $e_1$  to  $e_p$  from equation 4.3 should be independent of each other). In particular, no correlation between consecutive errors in the case of time series data.
- 3) Homoscedasticity (constant variance) of the errors resulting from equation 3.
- 4) Normality in the error distribution (i.e. the values of  $e_1$  to  $e_p$  from equation 4.3 should form a normal distribution).

These were investigated by:

- 1) Non-linearity in the residuals was assessed by creating a plot of the residuals versus the predicted values. The results were checked to ensure that they surrounded a horizontal line.
- 2) The independence of the errors (i.e. correlation between errors separated by the same number of lags) was investigated using the Durbin-Watson test (as in Chapter 3).
- 3) The assumption of constant variance (homoscedasticity) of errors is also investigated by plotting the residuals versus the predicted values. The results were checked to ensure that there is an even spread of values surrounding the horizontal line.
- 4) The assumption of normality can be overlooked if the model equation is assumed to be correct and the only goal is to explain as much of the data as possible (e.g. maximise the  $R^2$  value). However, non-normal residuals can create problems in determining if the model coefficients are significant. In order to investigate the normality of the residuals both a histogram and a normal quantile plot of the residuals were created. The normal quantile plot shows the quantiles of the error distribution against the quantiles of a normal distribution with the same mean and variance. The normal quantile plot was checked to ensure that the points are approximating a diagonal and the histogram was checked to ensure it was approximately Gaussian.
- 5) Although not a principal assumption of a multiple linear regression model, the influence that individual points have on the regression line was investigated. This was done by plotting residuals against leverage (the distance along the X axis from the middle of the data points) and calculating Cook's distance (how far the predicted values would change if the value was removed). The results were checked to ensure that no value had a large affect (at the 95% confidence interval) on the fit of the regression line.

## **4.4.2 Investigate the drivers behind temporal stability in the variogram parameters (questions 2 and 3)**

Section 4.4.2 investigates how temporally stable the variogram parameters are (section 4.4.2.1) and their relationship with the potential drivers (sections 4.4.2.2 and 4.4.2.3). As the variogram parameters provide an indication of the precipitation-to-river flow relationship, this enables the resilience of the precipitation-to-river flow relationship to be investigated. If this relationship is temporally resilient then a river's response will be more predictable. Furthermore, the less variability in the flow of a river, the sooner a trend will be detectable.

### **4.4.2.1 Coefficient of Variation (CV) for variogram parameters in each catchment**

The stability of the variogram parameters was analysed by calculating their inter-annual Coefficient of Variation (CV) for each catchment and grouping the results into the four different clusters identified in Chapter 2. For each catchment the CV is calculated by dividing the standard deviation of the 29 variogram values (resulting from the moving window analysis in Chapter 3) by the mean.

### **4.4.2.2 Relationship between the CV of the variogram parameters and the potential drivers**

Section 4.4.2.1 produces one value per catchment, enabling the correlation with the location (Northing and Easting) and catchment characteristics to be calculated. Location is included as a way of providing an indication of other meteorological characteristics as well as combinations of characteristics which will vary spatially and could influence the temporal changes in the variogram parameters. The catchment characteristics are included as these are likely to modulate how the river responds to changes in precipitation and hence will influence the variability. They are treated as being temporally stable, however, land use may not be stationary over the time period investigated (discussed in Chapter 2).

The correlation between the CV of the Sill and the Range and the potential drivers (catchment characteristics, location, the Coefficient of Variation in the Precipitation (CVP) and the Coefficient of Variation for the potential Evapotranspiration (CVE)) is calculated. The relationship between the CV of the variogram parameters and the CV of the climatic characteristics (evapotranspiration and precipitation) will show how closely the climatic characteristics and variogram parameters are coupled (Post and Jones, 2001). It would be expected that if there is more variability in the climatic characteristics then there would be more variability in the river flow (Wolock and McCabe, 1999), and hence the variogram parameters. CVP refers to the inter-annual coefficient of variation which was calculated for each of the 12 precipitation characteristics that were investigated in Chapter 3. CVE incorporates the inter-annual coefficient of variation for each of the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentiles of the catchment's averaged daily potential evapotranspiration. The evapotranspiration data was only available for catchments in GB, therefore the 11 catchments in NI were excluded when calculating the relationship with the CVE. The antecedent conditions are related to evapotranspiration. However, CVE provides information about inter-annual variability in evapotranspiration and will not provide information about the antecedent conditions before any particular event. The CVP and CVE are calculated using the same method as the CV (section 4.4.2.1). This method enables the relationship with all the potential drivers (for which data is available) to be assessed simultaneously.

#### **4.4.2.3 Multiple linear regression between the CV of the variogram parameters and the potential drivers**

A multiple linear regression model is created between the CV of the variogram parameters (from section 4.4.2.1) and the catchment characteristics, CVE, CVP and location (Northing and Easting as an interaction term). This provides an indication as to how much of the difference in the CV between the catchments can be explained by the potential driving characteristics. As in Chapter 3, to avoid the model being over-parameterised, stepwise selection (both forwards and backwards) based on Akaike's Information Criterion (AIC) was used to select the characteristics in the final linear regression model. The model was checked using the same steps outlined in section 4.4.1.2.

## 4.5 Results

### 4.5.1 Correlation between the CV of the Sill and the Range, and the precipitation regime

It is likely that each catchment is susceptible to changes in different aspects of precipitation. In order to investigate this, the correlation between each precipitation characteristic and variogram parameter are plotted in box plots grouped by the cluster number assigned in Chapter 2 (Figure 4.2).

The only clear pattern (i.e. increase or decrease in the mean from catchments in Cluster 1 through to catchments in Cluster 4) is for the length of dry periods for which, on average, the temporal variability in the Range is better explained for catchments in Cluster 1 than catchments in Cluster 4 (Figure 4.2). However, the same pattern is not seen for the Sill, with the length of dry periods having a low correlation with catchments in all clusters. The other box plots do not show a clear pattern from catchments in Cluster 1 through to catchments in Cluster 4 although there are some weak patterns e.g. the mean and standard deviation for the Range. Furthermore, there are differences in the spread of the correlations between different box plots e.g. winter to summer ratio for the Sill where the catchments in Cluster 4 have a smaller correlation than catchments in the other Clusters.

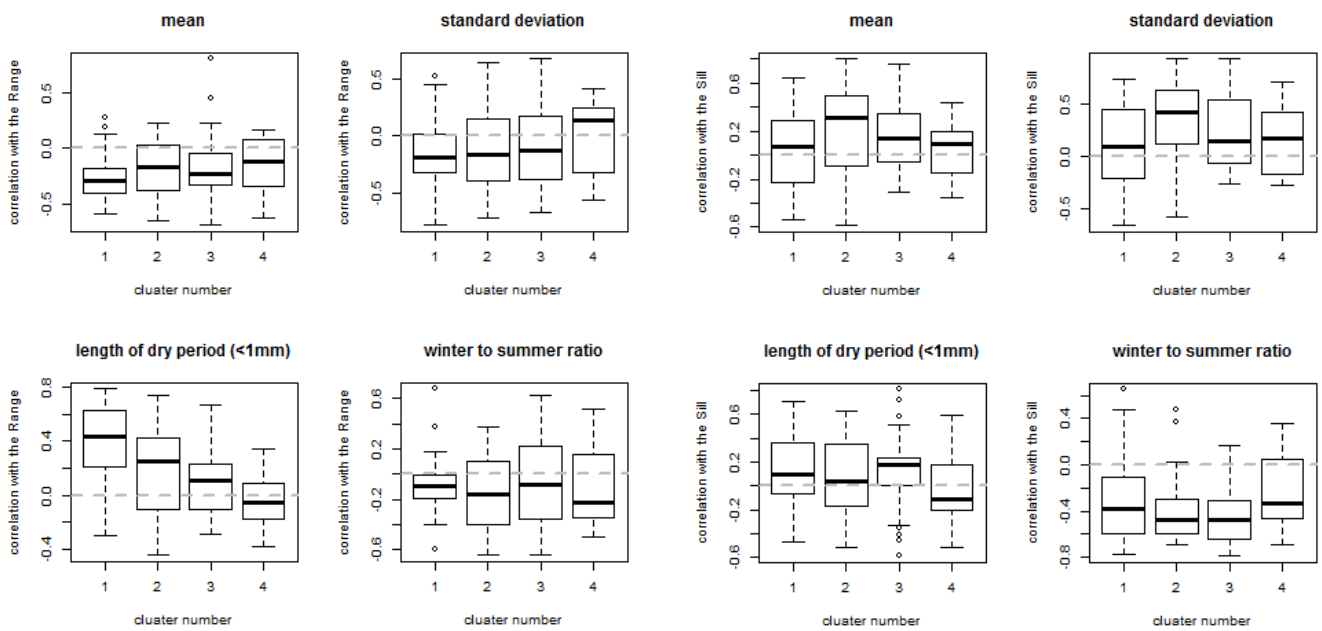


Figure 4.2: Correlation of the Range and the Sill with different precipitation characteristics, the grey dashed line shows the zero line.

#### 4.5.2 Calculate the amount of temporal variability explained by the uncorrelated precipitation characteristics

The six precipitation characteristics included in the multiple linear regression model were: winter to summer ratio, autumn to spring ratio, standard deviation, median, length above and length below 1mm. The amount of temporal variability these precipitation characteristics explained for the Range and Sill are shown in Figure 4.3.

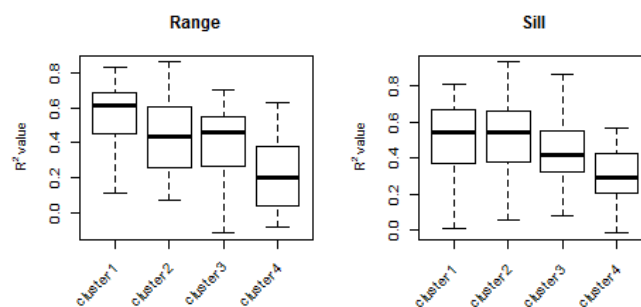


Figure 4.3: The amount of temporal variability explained for the Range and the Sill by the six uncorrelated precipitation characteristics (adjusted  $R^2$  value).

The adjusted  $R^2$  values range from around 0 to over 0.8 showing that the precipitation characteristics explain the variability in the variogram parameters well for some catchments, but poorly in others, where it is possible that other factors (e.g. other climate variables or catchment characteristics) are more important. Figure 4.3 shows that, in general, catchments in Cluster 1 have more of their temporal variability in the Range and the Sill explained by the six precipitation characteristics, than catchments in Cluster 4. However, there is a large overlap between the box plots for each cluster. The significance between the differences in neighbouring box plots was calculated using a t-test. There was a significant difference between Clusters 1 and 2 for the Range (95 % CI) and Clusters 3 and 4 for the Range and the Sill (99% CI). The large spread of values, within each of the clusters, highlights the fact that factors which influence the amount of variability explained is more complex than the differences in the way precipitation is typically transformed into river flow, as characterised by the four clusters.

### **4.5.3 Investigating the CV of the Range and the Sill for each catchment**

Figure 4.4 shows the CV of each catchment, grouped by cluster number, and Figure 4.5 shows the CV of the Range plotted against the CV of the Sill. Figure 4.4 highlights that, on average, catchments in Cluster 4 exhibit a larger CV of the Sill and the Range than catchments in the other Clusters. Furthermore, Figure 4.4 and Figure 4.5 identify that there is a larger CV of the Range than the Sill. The catchments in Cluster 1 have a smaller CV and less variability between their CV, through to catchments in Cluster 4 which have the largest CV and the most variability between them. There is less difference in the variability of the values of the CV between clusters for the Range. In addition there is more overlap between the box plots for the Range, particularly between Clusters 1 and 2. Only the difference between Cluster 1 and Cluster 2 for the Range was not significant (at the 95% CI). The difference between the other box plots for the Range were significant at the 99% CI and the difference between all box plots for the Sill were significant at the 99.9% CI.

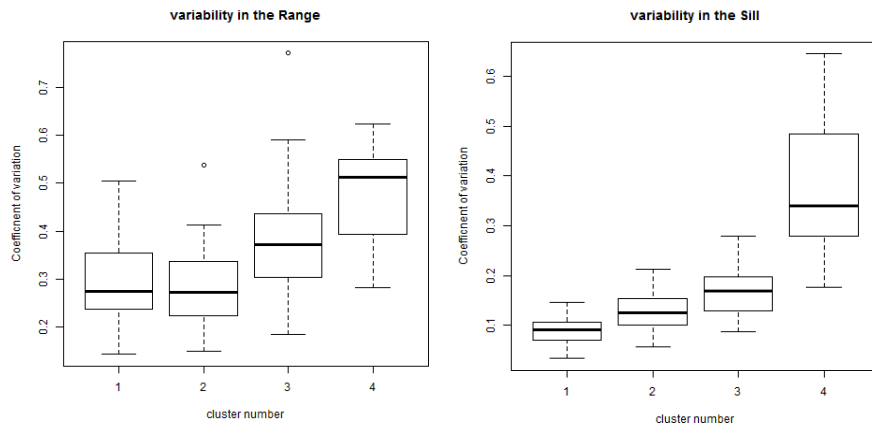


Figure 4.4: The CV of the Range and Sill for each catchment respectively, grouped by cluster.

The relationship between the CV of the Range and the Sill is shown in Figure 4.5, identifying a weak positive correlation. This means that although the Sill and Range are related, the amount of CV of the Sill is not dependent on the amount of CV of the Range and vice versa. Figure 4.4 and Figure 4.5 also highlight that there is a larger spread in the values of the CV within a cluster for the Range than the Sill, for Clusters 1 to 3.

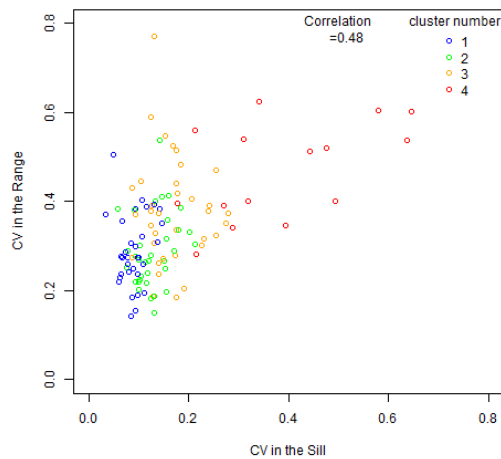


Figure 4.5: Scatter plot between the CV of the Sill and the CV of the Range.

#### 4.5.4 The correlation between the CV and the potential drivers

The relationship between the potential drivers (catchment characteristics, location, CVE and CVP) which could be influencing the CV of the variogram parameters are investigated (Table 4.1). In general, the Sill has larger correlations with the catchment and precipitation characteristics than the Range. The catchment characteristics which indicate a long lag time between a precipitation event and a river's response (e.g. deep gleying soils and the amount of highly productive fractured rock) have a positive correlation with the CV of both the Sill and the Range. This suggests that the CV is largest in catchments which are permeable and have a large amount of storage. The difference in



the CV of the Sill has a particularly strong correlation with the percentage of highly productive fractured rock and PROPWET. The location is also correlated with the CV, with catchments in the South East of the UK having a larger CV of the Range (negative correlation with Northing and positive correlation with Easting). There is a positive relationship between the CV and the CVP (Table 4.1). Both the Range and the Sill have a significant correlation with the 25<sup>th</sup> (negative) and 75<sup>th</sup> (positive) percentiles of the evapotranspiration. Finally, there is a positive correlation between the CVP and the catchment characteristics which are related to the permeable catchments (not shown).

*Table 4.1: Correlation coefficients for the characteristics which have a significant correlation (>95% CI) with the CV for the Range and the Sill.*

<b>Characteristic</b>	<b>Range</b>	<b>Sill</b>
<b>Percentage of arable land</b>	0.54	0.53
<b>Grassland</b>	-0.37	-0.35
<b>Median elevation</b>	-0.30	-0.31
<b>PROPWET</b>	-0.46	-0.61
<b>Mean drainage path slope</b>	-0.40	-0.31
<b>Highly productive fractured rock</b>	0.47	0.78
<b>Shallow gleyed soil</b>	-0.36	-0.56
<b>Deep gleyed soil</b>	0.28	0.61
<b>Easting</b>	0.47	0.36
<b>Northing</b>	-0.27	-0.28
<b>CV of the mean of precipitation</b>	0.31	0.47
<b>CV of the standard deviation of precipitation</b>	0.25	0.36
<b>CV of the length of precipitation &gt;1mm</b>	0.35	
<b>CV of the 25<sup>th</sup> percentile of evaporation</b>	-0.41	-0.31
<b>CV of the 75<sup>th</sup> percentile of evaporation</b>	0.37	0.37

#### **4.5.5 The CV which can be explained by the potential driving characteristics**

A multiple linear regression model was created to investigate how much of the difference in the CV between the catchments (Figure 4.4) could be explained by the driving characteristics (catchment characteristics, location and amount of CVP and CVE). Table 4.2 shows that different characteristics best explain the difference in the CV between the catchments for the Range and the Sill. The amount of variability in the CV which is

explained by the characteristics is higher for the Sill than the Range with values of 0.74 and 0.48 respectively.

*Table 4.2: The P values for each of the characteristics which are included in each model to describe the differences in the CV between each catchment and the resulting R<sup>2</sup> value.*

Characteristics	Range	Sill
Northing	99.9	
Easting	99	
Northing and Easting interaction (Northing * Easting)	99	
Arable	99.9	
No gleying soil	99.9	
Shallow gleying soil (<40cm)	99.9	
Medium gleying (40 to 100cm)	99.9	
Deep gleying soil (>100 cm)	99.9	
PROPWET		99
Highly productive fractured rock		99.9
CV of the length of time precipitation is >1mm	95	
CV of the magnitude of precipitation		99
CV of the standard deviation of precipitation		99
R <sup>2</sup> value	<b>0.48</b>	<b>0.74</b>

## 4.6 Discussion

This chapter investigated two aspects of how the Range and the Sill vary through time: 1) the amount of temporal variability in the Range and Sill explained by precipitation characteristics, 2) the relationship between the Coefficient of Variation (CV) of the Sill and the Range in each catchment and the potential driving characteristics (location, catchment characteristics and the CV of precipitation and evapotranspiration).

### 4.6.1 The amount of temporal variability in the Range and Sill explained by precipitation characteristics

Chapter 3 showed that different aspects of the precipitation have more influence on the Sill than the Range and vice versa. As previously mentioned, it is possible that the catchment characteristics influence how the river flow responds to each aspect of the

precipitation regime differently. Therefore the amount of temporal variability in the variogram parameters which could be explained by individual precipitation characteristics was investigated.

The analysis in this chapter showed relatively few significant differences between the four clusters in the amount of temporal variability in the Sill or the Range that could be explained by the different precipitation characteristics. The only precipitation characteristic which demonstrated a pattern from Cluster 1 (best explained) to Cluster 4 (least well explained) is the length of dry periods for the Range. This pattern is likely to be because the more permeable catchments (Cluster 4) either mitigate or exacerbate the influence of the dry periods. The river flow will be maintained during a short dry period due to release from catchment storage. Following a long dry period it will take more rainfall to return the catchment, and hence the river, to normal conditions because greater storage deficits will need to be replenished (Van Loon and Laaha, 2014, Bloomfield and Marchant, 2013). In a dry spell the extended time before the catchment conditions return to normal increases the time in which water is flowing through a slower pathway (i.e. from groundwater release). This will influence the variability in the river flow for longer, creating a larger change in the variogram parameters.

The precipitation characteristics which were not highly correlated (correlation  $\leq |0.8|$ ) with each other were selected to investigate the amount of temporal variability in the Range and the Sill explained by a combination of precipitation characteristics (Figure 4.3). In general, the temporal variability was significantly ( $>99.9\%$  CI) better explained for catchments in Cluster 1 than catchments in Cluster 4. This is because catchments in Cluster 4 have a lot of storage and therefore mitigate or exacerbate a river's response to precipitation events, creating a non-linear precipitation-to-river flow relationship.

Even though there are significant differences in the amount of variability explained by precipitation between catchments in some of the clusters, there are overlaps between the box plots for each cluster. Therefore, there are other factors in addition to the catchment characteristics (shown to vary between the clusters) which will influence how a river responds to changes in precipitation. The previous precipitation events and the amount of evapotranspiration will influence the antecedent conditions. This in turn will influence the rate at which a precipitation anomaly propagates through the catchment and hence the

river's response. In addition, the type (e.g. an increase or decrease in variability, intensity, magnitude) and scale of the precipitation change will influence the extent to which the catchment characteristics moderate the river's response.

#### **4.6.2 The drivers behind the amount of temporal variability (CV) of the variogram parameters**

The CV of the variogram parameters provides an indication as to the variability in the precipitation-to-river flow relationship. A low CV is an indication that water travels via a relatively stable pathway through the catchment (hence a change in precipitation is propagated through the catchment in a similar way throughout the whole time series). This section discusses the drivers behind the CV of the variogram parameters.

The amount of variability in river flows over a time period will depend on the meteorological conditions and the catchment characteristics (Arnell et al., 1990). However, catchments which have large CV in the Range do not necessarily have a large CV in the Sill and vice versa (Figure 4.5). Figure 1.4 highlights that the Sill and Range are characterising different aspects of the river flow regime. Moreover, the fact that catchments can exhibit large temporal changes in the Sill or Range and small changes in the other, suggests that the temporal variability in the Range and the Sill are driven by different processes. Therefore, changes in the Sill and the Range are likely to be influenced by different catchment characteristics.

In general, the Range has a higher CV than the Sill, demonstrating that it is less temporally stable. Furthermore, there is a general decrease in the CV from catchments in Cluster 4 through to catchments in Cluster 1 (Figure 4.4), particularly for the Sill. The catchment characteristics differ between the catchments in each cluster (in general, catchments in Cluster 1 have the steepest topography, are most impermeable and have the least storage through to catchments in Cluster 4). This indicates that the catchment characteristics may be having an influence on the temporal stability of the variogram parameters.

The catchments which have the lowest  $R^2$  value from the multiple linear regression between the precipitation characteristics and the variogram parameters have the largest CV (Figure 4.3 and Figure 4.4), echoing a result found by Carey et al. (2010) (although for variability expressed by the CV in monthly river flow data rather than variogram

parameters). This shows that the response of rivers to changes in precipitation in Cluster 1 are the least influenced by the catchment characteristics, and Cluster 4 the most. The larger CV for catchments in the South East (Clusters 3 and 4) could be caused by an increase in climatic variability in the South East or the difference in catchment characteristics. Increased climate variability would cause an increase in the CV of the Sill and the Range (as also found for river flow variability by Carey et al. (2010)). However, the large difference in the values between catchments in Clusters 3 and 4 for the Sill and Range and Clusters 1 and 2 for the Sill (some of which are in close spatial proximity to each other, Figure 2.4) suggests that catchment characteristics are having an influence. Catchments with characteristics enabling water to travel via a deep (slower) pathway (e.g. shallow gradients, permeable soils and a large amount of storage) create a larger CV of the Sill and Range. This is because these modulate a river's response more than catchment characteristics which result in a fast precipitation-to-river flow relationship.

Table 4.1 shows that there are several characteristics which have a significant correlation with the CV of the variogram parameters. In general, the Sill has a higher correlation than the Range with the precipitation and catchment characteristics, particularly rock type (which provides an indication as to the amount of groundwater storage in the catchment). The Range has a higher correlation with the length of wet periods, the 25<sup>th</sup> percentile in the evapotranspiration, location and slope of the catchment, than the Sill. The positive relationship between the CV of the Sill and storage is because catchments with a lot of storage are able to modulate a river's response to precipitation events more than upland catchments (Tallaksen et al., 2009). For example, prolonging of long-term precipitation anomalies, as shown by Lange and Haensler (2012) who demonstrate that the deeper flow pathways take longer to recover after a drought. The Range may be more susceptible to temporally localised precipitation events and less influenced by the catchment characteristics or climatic characteristics. The response of the river to individual precipitation events will be influenced by the antecedent conditions which will alter the propagation of the precipitation signal through the catchment (Pfister et al., 2004). The antecedent conditions will be influenced by the evapotranspiration and length of wet periods.

Multiple linear regression was used to calculate which combination of the potential drivers (CVP, CVE, catchment characteristics and location) best explain the difference in the CV of the Sill and the Range between the catchments. These findings (Table 4.2) agree with the findings in Chapter 3 which show that the temporal variability in the Sill and the Range are related to different precipitation characteristics (magnitude and variability for the Sill, and length of wet and dry periods and seasonality for the Range). The analysis in this chapter went further than Chapter 3 and identified the other potential drivers (location, evapotranspiration and catchment characteristics) which are most correlated with the CV of the Sill and the Range.

The difference in the CV between the catchments is better explained for the Sill than the Range (74% and 48% respectively). This shows that variability in the Sill can be better characterised by the temporally averaged and temporally static characteristics than the Range. The difference in the CV of the Sill between catchments is explained well by four characteristics: the percentage of highly productive fractured rock, proportion of time the soil spends wet (PROPWET) and the CV of the standard deviation and magnitude of the precipitation. Table 4.1 identified that the percentage of highly productive fractured rock has the largest correlation (positive) with the CV of the Sill. The amount of groundwater will control how long an anomalous precipitation event influences the river flow for (as it will take longer to return to average conditions). PROPWET also has a large (negative) correlation with the CV of the Sill. PROPWET provides an indication as to the amount of infiltration which is likely to occur (Woods, 2014), this will influence the amount of water which can reach the rock / deep soil and hence the storage. In addition, the larger the CV of the magnitude and standard deviation in the precipitation, the larger the CV of the Sill. The percentage of highly productive fractured rock distinguishes catchments in Cluster 4 from the other catchments (Figure 2.7). However, it will not distinguish between catchments in the other three clusters. PROPWET (Figure 2.6) and the precipitation characteristics will distinguish between the catchments which are not groundwater dominated.

The difference in the CV of the Range between catchments is best explained by: Northing and Easting, percentage of arable land, depth to gleyed layer in the soil and the CV of the length of wet periods. Northing and Easting are likely to be capturing combinations of

catchment and climatic characteristics which vary spatially and describe the CV of the Range better than individual characteristics. Table 4.1 shows that catchments in the South East (negative correlation with Northing and positive with Easting) have the largest CV. The South East is also the part of the UK which experiences highest evapotranspiration (Hulme and Barrow, 1997). Evapotranspiration will influence both the amount of precipitation reaching the river and the antecedent conditions (which in turn also influence the evapotranspiration) (Delworth and Manabe, 1988). Some papers argue that the antecedent wetness conditions are the most important factor in determining a river's response to a precipitation event (e.g. Noto et al. (2008) and Michele and Salvadori (2002)). The fact that evapotranspiration only has a moderate correlation with the CV of the variogram parameters could be because of the time scale being investigated (i.e. inter-annual). Therefore, the evapotranspiration will provide an indication as to whether more or less water is leaving the catchment before the gauging station but it will not capture the conditions of the catchment before a single precipitation event.

Northing and Easting are characteristics which have been shown to have an effect on the CV in the variogram parameters. These are characteristics which integrate a number of factors (catchment and meteorological characteristics). However, these factors cannot be separated to provide the actual driver. Wetter antecedent conditions (less evapotranspiration and an increase in the length of wet periods) will increase the rate at which water moves through the catchment and hence is likely to decrease the Range as more variability in precipitation will reach the river, causing the river flow time series to be less 'smooth'. The soil type (indicated by the depth to gleyed layer) will have an influence on how long the catchment stays wet after a precipitation event and therefore also influences the antecedent conditions of the catchment.

#### **4.6.3 How do catchment characteristics influence a river's response to temporal changes in precipitation?**

In the UK there is a north-west to south-east gradient in precipitation, evapotranspiration and catchment characteristics (e.g. the productivity of rock type, depth to gleyed layer and elevation). Therefore, this chapter cannot identify the exact drivers and can only provide educated inferences about the likely drivers behind the CV of the Sill and the Range. This chapter has demonstrated that each catchment type will respond differently

to given change in meteorological conditions. Firstly, upland catchments with low storage and infiltration respond in a way which is closer to a linear relationship with the precipitation characteristics. The response of the river is dependent on the type of meteorological change. Changes in the standard deviation and / or magnitude of precipitation are more likely to result in changes in the overall variability of the river flow (indicated by the Sill). However, the amount of change will be heavily modulated by the amount of storage (catchment specific). A change in the length of wet periods and evapotranspiration are likely to influence the Range. Overall the CV of the Range (an indicator of smoothness in the river flow time series) is not very well explained, in comparison to the Sill. It is likely that the Range is more event-specific and influenced by the antecedent conditions. The antecedent conditions will be partly controlled by the soil type, length of wet periods and evapotranspiration.

The change in the resilience of the precipitation-to-river flow relationship from catchments in Cluster 1 (highest) through to catchments in Cluster 4 (lowest) is an important finding. It highlights that propagation of precipitation signals through the catchment is more variable in the catchments in Cluster 4 due to the response being more non-linear and dependent on thresholds, rather than a relationship which is closer to linear. Therefore, a more cautionary approach in terms of estimating a river's response to predicted precipitation change is recommended for the rivers with a larger CV of the Sill and the Range. Furthermore, a larger CV means that the catchment characteristics are having a larger influence on how a river responds to changes in precipitation. Consequently, larger signal or a longer time period would be needed before monotonic changes in precipitation could be detected in the river flow.

## **4.7 Conclusion**

This chapter investigated the relationship between the temporal variability in the variogram parameters (Range and Sill) and characteristics of the potential drivers (precipitation, evapotranspiration and catchment characteristics as well as spatial location). The chapter addressed three questions: 1) how much of the temporal variability in the variogram parameters can be attributed to precipitation characteristics? 2) which catchments have the most temporally stable variogram parameters? 3) what are the drivers



behind the temporal stability in the variogram parameters (e.g. climate, catchment characteristics and spatial location)?

On average the precipitation characteristics explain a large proportion of the temporal variability in the variogram parameters (question 1). Furthermore, the 30-year average variogram was found to provide a good indication as to the relationship between the variogram parameters and precipitation. In general, upland catchments (variograms with a large Sill and small Range) were significantly better explained than lowland catchments with a large amount of groundwater storage (variograms with a small Sill and large Range). This demonstrated that the lowland catchments modify a river's response more than the upland catchments and that upland catchments have a relationship with precipitation which is closer to a linear relationship. However there was a large range in the amount of variability which was explained between catchments. This demonstrates that the amount of variability explained by precipitation is also dependent on temporally localised conditions e.g. antecedent conditions.

The temporal stability of the variogram parameters was analysed by calculating the Coefficient of Variation (CV) (question 2). The results showed that the catchments with a large amount of storage (in the South East) had a significantly larger CV than the upland catchments with no storage (in the North West). This pattern was particularly strong for the Sill. The drivers behind the CV of the Range and the Sill for each catchment were investigated (question 3). The CV of the Sill has a larger correlation with the catchment characteristics (particularly the percentage of highly productive fractured rock and PROPWET) and the CV of the magnitude and standard deviation of precipitation than the Range. The CV of the Range had a larger correlation with the length of wet periods, evapotranspiration and location than the Sill. The difference in the CV between the catchments for the Sill is well explained (74%) by the temporally static and temporally averaged characteristics compared to the Range (48%). The CV of the Sill is dependent on the amount of storage in the catchment, whereas the Range is related to individual precipitation events which will be modulated by the antecedent conditions and the soil type. These findings show that the variogram parameters (which characterise the precipitation-to-river flow relationship) are less temporally stable in the permeable catchments with a large amount of storage. Therefore, these catchments are likely to have

a larger signal to noise ratio. This means that detection times for changes in the variability on the scale of weeks to months (characterised by the Sill and the Range) are likely to be longer for the permeable catchments with a large amount of storage.

Overall there is larger moderation of the precipitation-to-river flow relationship in the permeable, lowland catchments (question 1) and these catchments also have a larger CV (questions 2 and 3). This demonstrates that the permeable catchments are modulating a river's response to changes in precipitation more than the upland catchments, and hence have a less stable precipitation-to-river flow relationship. Consequently, their response to a precipitation change is likely to be non-linear and harder to predict.

## 4.8 References

- ARNELL, N. W., BROWN, R. P. & REYNARD, N. S. 1990. Impact of climatic variability and change on river flow regimes in the UK. Wallingford, UK: Centre for Ecology and Hydrology (formally the Institute of Hydrology).
- BEVEN, K. J. 2000. Uniqueness of place and process representations in hydrological modelling. *Hydrol. Earth Syst. Sci.*, 4, 203-213.
- BIRSAN, M.-V., MOLNAR, P., BURLANDO, P. & PFAUNDLER, M. 2005. Streamflow trends in Switzerland. *Journal of Hydrology*, 314, 312-329.
- BLACK, P. E. 1997. WATERSHED FUNCTIONS. *JAWRA Journal of the American Water Resources Association*, 33, 1-11.
- BLOOMFIELD, J. P. & MARCHANT, B. P. 2013. Analysis of groundwater drought using a variant of the Standardised Precipitation Index. *Hydrol. Earth Syst. Sci. Discuss.*, 10, 7537-7574.
- BLOSCHL, G., SIVAPALAN, M., WAGENER, T., VIGLIONE, A. & SAVENIJE, H. 2013. *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales*, Cambridge, UK, Cambridge University Press.
- BRADFORD, R. B. & MARSH, T. J. 2003. Defining a network of Benchmark catchments for the UK. *Proceedings of the ICE - Water and Maritime Engineering*, 156, 109-116.
- BUDYKO, M. I. 1974. *Climate and life, translated from Russian by D.H. Miller*, San Diego, CA, Academic Press, Available from <http://books.google.com/books?id=Ln89Y-6KwZYC>.
- CAREY, S. K., TETZLAFF, D., SEIBERT, J., SOULSBY, C., BUTTLE, J., LAUDON, H., MCDONNELL, J., MCGUIRE, K., CAISSIE, D., SHANLEY, J., KENNEDY, M., DEVITO, K. & POMEROY, J. W. 2010. Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience. *Hydrological Processes*, 24, 3591-3602.
- CHANDLER, R. & SCOTT, M. 2011. *Statistical Methods for Trend Detection and Analysis in the Environmental Sciences*, Chichester, UK, John Wiley & Sons Ltd.

- DAI, A., QIAN, T., TRENBERTH, K. E. & MILLIMAN, J. D. 2009. Changes in Continental Freshwater Discharge from 1948 to 2004. *Journal of Climate*, 22, 2773-2792.
- DELWORTH, T. L. & MANABE, S. 1988. The Influence of Potential Evaporation on the Variabilities of Simulated Soil Wetness and Climate. *Journal of Climate*, 1, 523-547.
- GAÁL, L., SZOLGAY, J., KOHNOVÁ, S., PARAJKA, J., MERZ, R., VIGLIONE, A. & BLÖSCHL, G. 2012. Flood time scales: Understanding the interplay of climate and catchment processes through comparative hydrology. *Water Resources Research*, 48, W04511.
- HANNAFORD, J. 2015. Climate-driven changes in UK river flows: A review of the evidence. *Progress in Physical Geography*, 1-20.
- HRACHOWITZ, M., SAVENIJE, H. H. G., BLÖSCHL, G., MCDONNELL, J. J., SIVAPALAN, M., POMEROY, J. W., ARHEIMER, B., BLUME, T., CLARK, M. P., EHRET, U., FENICIA, F., FREER, J. E., GELFAN, A., GUPTA, H. V., HUGHES, D. A., HUT, R. W., MONTANARI, A., PANDE, S., TETZLAFF, D., TROCH, P. A., UHLENBROOK, S., WAGENER, T., WINSEMIUS, H. C., WOODS, R. A., ZEHE, E. & CUDENNEC, C. 2013. A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal*, 58, 1198-1255.
- HULME, M. & BARROW, E. 1997. *Climates of the British Isles; present, past and future*, London, UK, Routledge.
- JEFFERSON, A., GRANT, G. E., LEWIS, S. L. & LANCASTER, S. T. 2010. Coevolution of hydrology and topography on a basalt landscape in the Oregon Cascade Range, USA. *Earth Surface Processes and Landforms*, 35, 803-816.
- LAAHA, G. & BLÖSCHL, G. 2007. A national low flow estimation procedure for Austria. *Hydrological Sciences Journal*, 52, 625-644.
- LAIZÉ, C. L. R. & HANNAH, D. M. 2010. Modification of climate–river flow associations by basin properties. *Journal of Hydrology*, 389, 186-204.
- LANGE, J. & HAENSLER, A. 2012. Runoff generation following a prolonged dry period. *Journal of Hydrology*, 464-465, 157-164.
- LVOVICH, M. I. 1979. World water resources, present and future. *GeoJournal*, 3, 423-433.
- MCDONNELL, J. J. & WOODS, R. 2004. On the need for catchment classification. *Journal of Hydrology*, 299, 2-3.
- MERZ, R. & BLÖSCHL, G. 2009. A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. *Water Resources Research*, 45, W01405.
- MICHELE, C. D. & SALVADORI, G. 2002. On the derived flood frequency distribution: analytical formulation and the influence of antecedent soil moisture condition. *Journal of Hydrology*, 262, 245-258.
- MILLIMAN, J. D., FARNSWORTH, K. L., JONES, P. D., XU, K. H. & SMITH, L. C. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change*, 62, 187-194.
- MONK, W. A., PETERS, D. L., ALLEN CURRY, R. & BAIRD, D. J. 2011. Quantifying trends in indicator hydroecological variables for regime-based groups of Canadian rivers. *Hydrological Processes*, 25, 3086-3100.

- NOTO, L. V., IVANOV, V. Y., BRAS, R. L. & VIVONI, E. R. 2008. Effects of initialization on response of a fully-distributed hydrologic model. *Journal of Hydrology*, 352, 107-125.
- PFISTER, L., KWADIJK, J., MUSY, A., BRONSTERT, A. & HOFFMANN, L. 2004. Climate change, land use change and runoff prediction in the Rhine–Meuse basins. *River Research and Applications*, 20, 229-241.
- POST, D. A. & JONES, J. A. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Advances in Water Resources*, 24, 1195-1210.
- ROBINSON, E. L., BLYTH, E., CLARK, D. B., FINCH, J., and RUDD, A. C. in prep. Trends in evaporative demand in Great Britain using high-resolution meteorological data.
- ROBINSON, E. L., BLYTH, E., CLARK, D. B., FINCH, J., and RUDD, A. C. 2015. Climate, Hydrology and Ecology research Support System dataset (1961-2012) [CHESS]. NERC Environmental Information Data Centre.
- SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrol. Earth Syst. Sci.*, 15, 2895-2911.
- SIVAPALAN, M. 2006. Pattern, Process and Function: Elements of a Unified Theory of Hydrology at the Catchment Scale. *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd.
- SIVAPALAN, M., TAKEUCHI, K., FRANKS, S. W., GUPTA, V. K., KARAMBIRI, H., LAKSHMI, V., LIANG, X., MCDONNELL, J. J., MENDIONDO, E. M., O'CONNELL, P. E., OKI, T., POMEROY, J. W., SCHERTZER, D., UHLENBROOK, S. & ZEHE, E. 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrological Sciences Journal*, 48, 857-880.
- SPEARMAN, C. 1904. General intelligence, objectively determined and measured. *American Journal of Physiology*, 15, 201 - 293.
- STAHL, K., HISDAL, H., HANNAFORD, J., TALLAKSEN, L. M., VAN LANEN, H. A. J., SAUQUET, E., DEMUTH, S., FENDEKOVA, M. & JÓDAR, J. 2010. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrol. Earth Syst. Sci. Discuss.*, 7, 5769-5804.
- STAHL, K., TALLAKSEN, L. M., HANNAFORD, J. & VAN LANEN, H. A. J. 2012. Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrol. Earth Syst. Sci.*, 16, 2035-2047.
- STOCKER, T. F., QIN, D., PLATTNER, G.-K., TIGNOR, M. M. B., ALLEN, S. K., BOSCHUNG, J., NAUELS, A., XIA, Y., BEX, V. & MIDGLEY, P. M. 2013. *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment report of the Intergovernmental Panel on Climate Change* Cambridge, UK, Cambridge University Press.
- TALLAKSEN, L. M., HISDAL, H. & LANEN, H. A. J. V. 2009. Space–time modelling of catchment scale drought characteristics. *Journal of Hydrology*, 375, 363-372.
- THORNTHWAITE, C. W. 1931. The climates of North America according to a new classification. *Geographical review*, 21, 633-655.

- THOMPSON, N., BARRIE, I. A., and AYLES, M.: The Meteorological Office rainfall and evaporation calculation system: MORECS, Meteorological Office, Bracknell, 1981.
- VAN LOON, A. F. & LAAHA, G. 2014. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*.
- VIGLIONE, A., PARAJKA, J., ROGGER, M., SALINAS, J. L., LAAHA, G., SIVAPALAN, M. & BLÖSCHL, G. 2013. Comparative assessment of predictions in ungauged basins &ndash; Part 3: Runoff signatures in Austria. *Hydrol. Earth Syst. Sci.*, 17, 2263-2279.
- WILBY, R. L. 2006. When and where might climate change be detectable in UK river flows? *Geophysical Research Letters*, 33, L19407.
- WOLOCK, D. M. & MCCABE, D. M. 1999. Explaining Spatial Variability in Mean Annual Runoff in the Conterminous United States. *Climate Research*, 11, 149 - 159
- WOODS, A. 2014. Using climate change projections in UK flood risk assessment.
- YOUNG, A. R. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. *Journal of Hydrology*, 320, 155-172.

## 5 Synthesis

### 5.1 Introduction

Understanding the influence that the catchment characteristics have on a river's response to temporal changes in precipitation is important for future water resource planning e.g. for flood forecasting (Reynard et al., 2009). Knowledge of how catchment characteristics modulate a river's response to changes in precipitation will enable future predictions in water quantity to be catchment specific, based on the predicted change in precipitation (driver of change) and the catchment characteristics (secondary influence of the change). Furthermore, knowledge of how the catchment characteristics transform precipitation into river flow will assist with the transfer of data from gauged to un-gauged catchments.

This thesis analyses how changes in temporal dependence (as characterised by the variogram) over time can be explained by precipitation and/or catchment characteristics. A variogram captures aspects of the river flow which are largely controlled by the pathway water has taken through the catchment; the variability at a range of temporal scales and the 'smoothness' of the river flow time series. Being able to investigate a range of aspects of the river flow regime is essential to understanding average catchment behaviour, because river flow is a result of multiple interacting processes which occur over multiple spatial and temporal scales. At the event time scale, topography controls the direction of surface and sub-surface flows as well as the forces which control the rate of water moving through the catchment. The soil structure and texture will influence: the amount of resistance that water encounters when moving through the catchment, the accessibility to preferential flow paths, the partitioning between overland and sub-surface flow, and the depth of percolation. The patterns of soil moisture are seasonally dependent and will have an influence on the seasonality of the river flow. At seasonal and inter-annual time scales the influence of groundwater storage, transport and release becomes more important to the river flow. During periods of low rainfall and / or high evapotranspiration, water stored in the catchment makes up a high proportion of the river flow.

When the variogram is calculated over long time periods (decades) it will capture the temporal dependence in the river flow which is controlled by the processes which

transform precipitation into river flow. This characterises the relative roles of the different pathways – both long-term (groundwater) and short-term (runoff). The slower pathways (i.e. through deep soil or the rocks) will reduce (or ‘smooth out’ the amount of short-term variability in the precipitation reaching the river, relative to the faster pathways (i.e. shallow sub-surface or surface runoff).

The variogram can also be calculated over shorter time scales, as conducted in Chapter 3 using the TSV methodology. Over shorter time scales (< 10 years) the variogram parameters will capture variability in the precipitation-to-river flow relationship. These could be caused by changes in atmospheric conditions and / or changes in the catchment. For example: land cover change influencing the amount of interception; a decrease in winter recharge reducing the amount of water in groundwater storage or an increase in persistent rain events which will increase the antecedent wetness in the catchment and hence increase water travelling via a fast pathway. The changes in the variogram parameters will depend both on the type of change (e.g. change in the intensity or duration of precipitation) and how it is modulated by the catchment characteristics.

This chapter discusses the key findings in Chapters 2 to 4 in the context of wider work and identifies how the information generated in this thesis could pave the way for further research on this topic, and could potentially inform future improvements in water resource management. Section 5.2 gives an overview of the methods and key findings from chapters 2 to 4 which address the objectives of the thesis outlined in section 1.1.1. Section 5.3 discusses the influence individual precipitation and catchment characteristics could have on the results before providing a discussion about how the interactions are important (3.1). Section 4 identifies areas of potential further work. Section 5 identifies the major research findings.

## **5.2 Summary of methods and key results**

### **5.2.1 Characterising the influence that the catchment characteristics have on the precipitation-to-river flow relationship**

Throughout this thesis variograms were created using the standardised daily river flow data in order to characterise the dynamics of the river flow. The variogram was found to have several advantages over other techniques for understanding the role that catchment



characteristics have on modulating a river's response to meteorological variability. Firstly, the variograms are calculated using the whole of the river flow time series as opposed to a specific aspect (e.g. annual maximum or minimum). Secondly, the variogram can be calculated relatively accurately even with limited amounts of missing data. Furthermore, the variogram has several parameters which will vary depending on the pathway water has taken through the catchment. Each parameter provides information about a different aspect of the river flow regime meaning that the variogram provides a detailed overview about the daily river flow data time series. Finally the variogram parameters were shown to be influenced by the dominant pathway water takes through the catchment and therefore is related to the catchment characteristics.

### **5.2.2 Which catchment characteristics control the temporal dependence structure of daily river flows? (Chapter 2)**

A semi-variogram was created using a fixed 30-year time period (1980 to 2010) for each of the 116 catchments within the UK Benchmark group. The catchments were then clustered based on the shape of their variogram. Four distinct groups of catchments were identified. Catchments in Cluster 1 had a variogram which began relatively steeply and started to level off after a few days. The shapes of the variograms changed through to the catchments in Cluster 4 which were approaching a linear line with a relatively shallow gradient. This demonstrated that there is a change in the amount of temporal dependence from the catchments in Cluster 1 which have a short temporal dependence structure through to the catchments in Cluster 4 which have a longer temporal dependence structure. Catchments in Cluster 1 were predominantly upland catchments which were relatively impermeable whilst catchments in Cluster 4 were found to overlay highly productive fractured aquifers. Geology, depth to gleyed layer in soils, slope of the catchment and the percentage of arable land were significantly different between the clusters. These characteristics are significantly correlated with the temporal dependence structure and it is likely that they influence the rate at which water moves through the catchment and/or the storage in the catchment.



### **5.2.3 Using variograms to detect and attribute hydrological change (Chapter 3)**

Variograms were created using river flow data from 5-year overlapping moving windows, each window overlapping the previous window by four years (i.e. 1980 – 1984, 1981 – 1985 ... 2008 – 2012). Upper and lower thresholds were created by calculating the 5<sup>th</sup> and 95<sup>th</sup> percentiles from 1,000 realisations of the variogram calculated over the entire study period (33 years). This is a new change detection method (called Temporally Shifting Variograms, TSV) and therefore was tested against a river flow time series with imposed changes. The river flow time series was created by artificially manipulating a 7-year section of the 33 year time series to represent changes which could occur in the natural environment (e.g. change in: seasonality, magnitude or the length of wet and dry periods). Altering a raw river flow time series was viewed as a tougher test of the method as opposed to detecting a signal in a time series which had no background variability. The method was found to perform well and highlighted that each variogram parameter is sensitive to a change in a different aspect of the river flow time series.

The changes detected by the TSV method were then attributed to potential drivers. It was found that each variogram parameter had a different relationship with the precipitation characteristics. The Range had a larger correlation with the length of wet and dry periods than the other variogram parameters (Sill, 3DASV and HRASV, see Chapter 3 for a description). The other variogram parameters had larger correlations with the magnitude, seasonality (winter to summer ratio) and the standard deviation of the precipitation. Two prominent periods of change were identified: 1995–2001 and 2004–2012. The first period of change is attributed to an increase in the magnitude of rainfall whilst the second period is attributed to an increase in variability of the rainfall.

### **5.2.4 How do the catchment characteristics influence the temporal variability in the river flow? (Chapter 4)**

Two aspects of the temporal variability in the variogram parameters were investigated. Firstly, the relationship between the average variogram (Chapter 2) and the amount of temporal variability in the variogram parameters which could be explained by precipitation (Chapter 3) was analysed. Secondly, the relationship between the

Coefficient of Variation (CV) in the variogram parameters and the potential drivers (spatial location of the catchment, variability in precipitation, variability in the evapotranspiration and catchment characteristics) was assessed. The temporal variability in the variogram parameters was found to be better explained for the relatively impermeable catchments with short lag times between precipitation and river flow than the permeable catchments. However, there was a large amount of overlap in the amount of variability explained between the catchments in each of the clusters (assigned in Chapter 2). This shows that the amount of temporal variability in the variogram parameters is also dependent on temporally localised factors e.g. antecedent conditions. It was found that temporal changes in the Sill are more dependent than the Range on the catchment characteristics, particularly the amount of groundwater storage present in the catchment. The Range was more influenced than the Sill by individual precipitation events which are modulated by the antecedent conditions and soil composition in the catchment.

### **5.3 Discussion**

This work demonstrated the link between catchment characteristics and the temporal dependence structure in river flow time series. Furthermore, the influence that the catchment characteristics have on how changes in the temporal dependence structure in river flows are related to changes in precipitation was investigated. In order to summarise the key findings of how catchment characteristics influence river flow variability, Table 5.1 first breaks down how the individual catchment characteristics may have influenced the variogram parameters before section 5.3.1 gives an integrated overview, including consideration of the interactions between catchment characteristics.

Table 5.1: Description of the influence that the characteristics have on the precipitation-to-river flow relationship.

Characteristic	Conceptual understanding of the influence the characteristics have on the precipitation-to-river flow relationship	Observations in the thesis	Supporting literature
<b>Precipitation</b>	<p>The intensity of the precipitation will influence the partitioning of the rainfall into the different flow pathways.</p>	<p>An increase in magnitude of precipitation was found to increase the variability (the Sill), which is likely to be due to water flowing via a faster pathway through the catchment.</p>	<p>A change in the intensity of rainfall increased the river flow more than a change in the number of wet days (e.g. Pruski and Nearing (2002) and Nearing et al. (2005)). Higher intensity rainfall is more likely to exceed infiltration capacity of soils and thus a larger proportion reaches the channel (Boughton and Chiew, 2007) rather than entering storage.</p>
	<p>During a dry period a higher proportion of the water will come from storage (soil water during the short-term and groundwater over the longer period).</p>	<p>The length of wet and dry periods was a good predictor of the Range (i.e. the length of wet and dry periods has a large correlation with the Range, Table 3.3) of river flow series.</p>	<p>Water released from storage has less variability than water traveling via the surface / shallow sub-surface after a precipitation event (Bradford, 2002).</p>
	<p>A change in the precipitation dynamics will result in a change in the river flow regime. For example, it would be expected that a large precipitation event would propagate through the catchment quickly and hence the catchment characteristics would modulate a river's response less than a moderate or small precipitation event.</p>	<p>The CV of the precipitation characteristics were found to have significant correlations with the CV of the Sill and the Range. The length of wet periods is the best precipitation characteristic for explaining the CV of the Range whilst the Sill is most correlated with the magnitude and standard deviation of the precipitation (Table 4.1 and Table 4.2).</p>	<p>Carey et al. (2010) found a positive correlation between the CV of the precipitation characteristics and the CV of the river flow data.</p>

<p><b>Other meteorological characteristics</b></p>	<p>Evapotranspiration varies spatially across the UK and has a large influence on the antecedent conditions. The influence of evapotranspiration will be dominant for catchments in the South East of the UK.</p> <p>The amount of evapotranspiration will also affect the antecedent conditions which will influence the river's response to subsequent precipitation events. If the amount of evapotranspiration is large then there will be more infiltration and therefore there will be more modulation of the change in precipitation before it reaches the river.</p>	<p>Chapter 4 identified a significant relationship between the CV (particularly for the Range) and the location of the catchment as well as the amount of variability in the evapotranspiration. Catchments in the South East were identified as having the largest CV of the Range (negative correlation with Northing and positive correlation with Easting).</p> <p>Evapotranspiration had a larger correlation with the Range than the Sill (Table 4.1). Increased evapotranspiration could reduce the influence of subsequent rainfall events, increasing the Range. However, the variability in the Sill was found to be more correlated with the precipitation.</p>	<p>Evapotranspiration is a greater component of the water balance in the South East of the UK because of the higher temperatures and lower precipitation totals (Perry and Hollis, 2005), which means that evapotranspiration in water limited in the South East (Kay et al., 2013). Evapotranspiration is the dominant process during the drying phase, moderated by the catchment characteristics which determine the release of water (e.g. topography (McVicar et al., 2007) and soil type (El Maayar and Chen, 2006)).</p> <p>Evapotranspiration will increase the amount of pore space in the soil for which water can infiltrate and percolate into, dampening the influence of the next precipitation event (Tromp-van Meerveld and McDonnell, 2006).</p>
<p><b>Topography</b></p>	<p>Topography controls the direction of movement and the magnitude of forces which control the velocity of water through the catchment. Furthermore, the topography also influences the connectivity of the catchment and hence</p>	<p>Chapter 2 showed that the catchments with the steeper slopes had more day-to-day variability in the river flow (steep variogram levelling off relatively quickly). Furthermore, the slope of the catchment was one of the five variables which were found to best cluster un-gauged catchments.</p>	<p>In higher (and hence steeper) catchments, water travels through the catchment faster (McGuire et al. (2005) and Tetzlaff et al. (2009a)) as there is more shallow subsurface flow and the pathways are better connected (Mayor et al., 2008).</p>

---

the rate at which water can move through the catchment.

Topography will have the largest influence in upland, impermeable, catchments as the movement of water will be driven by gravity and less influenced by sub-surface factors (e.g. the size of pore spaces).

Chapter 4 identified that the catchments which exhibit the largest CV of the variogram parameters were relatively flat. However, it is not clear if topography is the driver as it is correlated with other characteristics (e.g. precipitation and soil characteristics).

In flatter catchments the topography has been found to have less of an influence on the mean transit time because mean transit time is influenced by sub-surface processes (Tetzlaff et al., 2009a).

#### **Land cover**

The land cover will influence the amount of interception, the localised wind speed and temperature of the soil, and hence the amount of evaporation. Furthermore the plant roots will make water, which would otherwise be inaccessible, available to the atmosphere through transpiration.

Chapter 2 identified that land cover apparently influences temporal dependence structure, with the percentage of arable land being a key characteristic for differentiating between clusters. However, it is likely that arable land is a surrogate for a range of other catchment properties; put simply, arable operations are typically conducted in flat, well drained catchments, as found in Clusters 3 and 4.

Although the vegetation cover does influence the precipitation-to-river flow relationship, other catchment characteristics have a larger influence (Hundecha and Bárdossy, 2004).

Land cover is not likely to be stationary over the time period being investigated (1980 – 2012). Firstly, there is inter-annual variability in the vegetation due to the changes between the seasons (in general there is more vegetation cover in summer). Secondly, land cover will change due to changing demands for produce. Finally the management of the land will change as different technology

It is highly unlikely that the change in land cover was spatially extensive and spatially uniform enough to be influential in driving the changes reported in this thesis (e.g. the significant changes exhibited in over 70 % of the catchments for the Range or the Sill around 1995 and 2007 respectively (Figure 3.6).

Brown et al. (2005) investigated 166 paired catchment studies and found that the time taken before the hydrological regime reaches a new equilibrium following a change in land cover varies considerably between catchments, identifying that a similar response is unlikely across many catchments.

becomes available (e.g. larger machines), this can alter the amount of: wetlands, trees and hedges, compaction of the soil, etc.

### Soil type

The soil type will particularly influence how a river responds to precipitation events which have low to medium intensity and hence are below the infiltration capacity of the soil. The soil will influence the partitioning of water as well as the rate at which water travels through the shallow sub-surface.

The larger proportion of water infiltrating into the soil in the permeable catchments will increase the mean transit time through the catchment. An increased transit time is likely to lead to increased modulation by the catchment characteristics and hence increased non-linearity in the precipitation-to-river flow relationship.

The soil type was found to be crucial for clustering catchments, based on their variogram shape, without using the river flow data. Soil type is particularly important when distinguishing between catchments which are not groundwater dominated.

Chapter 4 identified that catchments which have permeable soils have a larger CV of the Range and the Sill. This could be because permeable soils increase the non-linearity in the precipitation-to-river flow relationship. This would explain why catchments in Cluster 4 are not as well explained by precipitation when using a multiple linear regression model.

Freely draining soils modulate a river's response more than relatively impermeable soils, because they have a higher infiltration capacity (hence soil storage) and will thus accommodate a greater range of magnitude of precipitation events (Castillo et al., 2003).

The Hydrology Of Soil Types classification (Boorman et al., 1995) identified that the soil properties are related to indicators which represent the partitioning of water between slow and fast pathways (e.g. base flow index and standard percentage runoff). Furthermore, Tetzlaff et al. (2009b) showed that the mean transit time is related to the soil properties for catchments in Scotland, highlighting that the soil properties are also important in determining the transit time in relatively impermeable catchments.

### Geology

River flow responses attenuated via long lag times resulting from groundwater storage will have less short-term variability than responses resulting from

The shape of the variograms for the catchments in groundwater dominated catchments were distinct. This characterises the relatively smooth river flow time series with little short-term

Bloomfield and Marchant (2013) used autocorrelation to show that the temporal dependence structure lasts between months and years for groundwater. Furthermore, they

surface / shallow sub-surface flow paths. During dry periods, water from storage will provide a higher proportion of the river flow. Therefore, the more storage there is in a catchment, the less the river flow will be affected by short dry periods.

Although groundwater storage will mitigate against the influence that short precipitation anomalies have on the river flow regime, a large amount of storage may increase the length of time before the catchment returns to normal conditions following a large precipitation anomaly.

variability (over short time scales, <3 months). The uniqueness of the variogram for catchments in Cluster 4 is demonstrated by Table 2.6, which shows that all the catchments in Cluster 4 were successfully clustered without the use of the river flow data.

Analysis of the CV of the variogram parameters (Chapter 4) demonstrated that the CV, particularly in the Sill, is positively related to the amount of groundwater storage in the catchment. This is likely to be because the catchments with a lot of storage take longer to recover after a large precipitation anomaly.

identify that the autocorrelation structure is related to the aquifer properties (e.g. transmissivity and storage).

Van Loon and Laaha (2014) identified that the amount of storage influences the duration and severity of the drought. This is because after a prolonged dry period groundwater dominated systems will take longer to return to average conditions (Fiorillo and Guadagno, 2010).

### 5.3.1 Integrated overview

Table 5.1 focused on the individual meteorological and catchment characteristics, the processes they influence and how they relate to the findings in Chapters 2 to 4. Table 5.1 demonstrated how there are several catchment characteristics which will influence the partitioning, transmission, storage and release of water which occur within a catchment. The table also discussed the influence of temporally varying meteorological characteristics, and how individual catchment characteristics can modulate changes in precipitation. However, catchment characteristics interact with one another in their effect on river flow, and it is this interaction that gives rise to the complex spatial and temporal patterns of river flow variability that have been the subject of this thesis. This section provides a more integrated overview of the study finding.

Figure 2.9 shows the correlation between the catchment characteristics used in this thesis. It highlights that there are large correlations between several of the catchment characteristics. For example, elevation is negatively correlated with the percentage of arable land and the percentage of no gleying soils is positively correlated with the percentage of highly productive fractured rock. The combination of catchment characteristics will influence the pathway water takes through the catchment and the connectivity of the catchment (which is driven by vegetation, soil type and topography (Mayor et al., 2008)). The pathway water takes through the catchment will influence the propagation of the precipitation signal through to the river flow. Furthermore, there is a correlation between climate characteristics and catchment characteristics. For example, precipitation is positively correlated with elevation, and latitude is positively correlated with temperature and hence evaporation. The multiple correlations result in a north-west to south-east gradient in the UK. Northern and western areas are generally wetter, cooler and contains catchments which are predominantly upland, impermeable and have a small amount of groundwater storage compared to the more lowland settings in southern and eastern England.

The finding that the transformation of precipitation variability into river flow variability depends on the catchment characteristics is important for future regionalisation studies. The results in this thesis identified that the dynamics of the river flow time series are



dependent on the catchment characteristics. However, the impact that the catchment characteristics have is likely to be dependent on the aspect of the river flow regime which is investigated. This is demonstrated by the different relationship between the CV in the Sill and the Range, and the catchment characteristics (Table 4.1 and 4.2). The impact that the catchment characteristics have is likely to be exacerbated for studies assessing low flows (e.g. Van Loon and Laaha (2014)) as this is highly dependent on the amount of storage. Whereas the catchment characteristics are likely to have less of an influence on high flows which are likely to be driven by heavy precipitation causing the precipitation signal to propagate through the catchment quickly.

The difference in the flow pathway between the catchments in Clusters 1 to 3 is likely to be driven by the interactions between climate, soils and topography. The variograms for the catchments in Cluster 4 are distinct with Ranges of years rather than weeks. The shape of the variograms in Cluster 4 are driven by the increased storage which is a result of the freely draining soil overlaying highly productive fractured rock.

There are also implications for transferring data from gauged to un-gauged catchments. As shown by Viglione et al. (2013), transferring a specific aspect of the river flow regime to an un-gauged catchment is more accurate than transferring the whole river flow time series. The results from this thesis indicate that studies which are aiming to transfer data which is related to medium / low flows should take into account the catchment characteristics. Whereas, studies transferring high flows are likely to use less or no information about the catchment characteristics and could focus on other aspects e.g. location.

As well as identifying how the catchment characteristics influence the dominant pathway through the catchment, the influence that the catchment characteristics have on the temporal changes in the variability was also investigated. The catchment characteristics influence both the resilience and resistance of the catchment (two terms taken from ecology; Folke et al. (2004) and Potts et al. (2006)). From a catchment perspective, resistance is the amount of change in river flow following a unit change in precipitation (also termed elasticity e.g. Sankarasubramanian et al. (2001)). Therefore, resistance provides information as to what will happen to the river if the precipitation increases or decreases. Catchments with a lot of long-term storage with a large base flow index will

have a high resistance, whereas catchments which have a quick precipitation-to-river flow relationship will have a low resistance (Figure 4.4). This was also found by (Tague et al., 2008, Tague and Grant, 2009) who showed that the resistance of a catchment relates to its storage and drainage efficiency. The resilience of a catchment characterises the magnitude and time for which the precipitation-to-river flow relationship will deviate from the average, following a precipitation anomaly. This characterises the amount of time it takes for a river to return to normal conditions following a precipitation anomaly. A resilient catchment will exhibit little change in the precipitation-to-river flow relationship. Table 4.1 and Figure 4.4 identify that the lowland, permeable catchments have the least resilient precipitation-to-river flow relationship.

In order to detect changes in the variogram parameters, a new change detection method was developed (in Chapter 3). The new method (Temporally Shifting Variograms, TSV) was tested against an artificially perturbed time series to identify if the technique could detect artificial changes beyond the background variability. The TSV method was shown to be able to detect several different types of change in the river flow regime (e.g. change in magnitude or seasonality). The TSV method has several advantages compared to other change detection methods. Firstly, it is not influenced by the start and end points of the record (and can detect changes at the start or end of the record). Secondly, the method identifies when in the record the change occurred. In addition, multiple types of changes can be detected (e.g. linear, step change and non-linear). In addition, the method provides information about the temporal location and magnitude of the change; this enables the changes to be compared with potential drivers to enable attribution. Finally, the variogram parameters have been shown to be influenced by the rate at which water propagates through the catchment and hence enables the analysis to assess the influence that the catchment characteristics have on the amount / type of change.

Chapter 3 identified that the majority of the catchments exhibit significant changes in the short-term variability in the river flow (characterised by the variogram parameters) which indicates that the propagation of precipitation through the catchment changes through time. It was found that each variogram parameter is related to different precipitation characteristics and that a large proportion of the temporal variability in the variogram parameters could be explained using precipitation characteristics (on average over 70%).

This demonstrates that the type of change in the river flow dynamics is dependent on the type of change in the precipitation. Therefore, studies which aim to investigate if and why a river flow regime has changed through time should look at multiple aspects of both the river flow regime and the potential drivers.

Chapter 4 investigated the influence of the catchment characteristics on the amount of temporal variability in the variogram parameters (resilience). The chapter identified that permeable catchments with large amounts of storage exhibit more temporal variability in their variogram parameters (indicating more variability in the way precipitation signals propagate through the catchment). This could be for a combination of two factors. Firstly, when an anomaly in catchments with a large amount of storage occurs, it will take longer for the amount of water in storage and hence the precipitation-to-river flow relationship to return to normal. Secondly, there are a wider range of pathways water can take through a highly permeable catchment and therefore there can be a larger change in the precipitation-to-river flow relationship than in impermeable catchments. Therefore, water flows via a relatively constant pathway for the catchments in Cluster 1 compared to the catchments in Cluster 4. Catchments which maintain a relatively stable precipitation-to-river flow relationship are likely to respond to precipitation events in the same way in the future. The response of the catchments in Cluster 1 to changes in precipitation is dependent on the precipitation and less on thresholds within the catchment (e.g. when precipitation exceeds the infiltration capacity) which will be influenced by the antecedent conditions.

The catchment characteristics were found to influence the Coefficient of Variation (CV) in the variogram parameters. The CV of the Sill is influenced by the amount of storage in the catchment. Groundwater dominated catchments take longer to return to normal conditions after a severe precipitation anomaly, hence it takes longer before the river returns to normal. This means that the change will have more influence on the shape of the 5-year variogram and therefore is more likely to be detected using the TSV approach (Chapter 3). The CV of the Sill is also dependent on the magnitude and standard deviation of the precipitation. An increase in the magnitude (which has a significant positive correlation with the standard deviation) will influence the peak flows. There is also a larger CV of the Range for the catchments in Cluster 4. However, the difference in the

CV between the catchments was not as well explained by the temporally static and temporally averaged catchment and climatic characteristics (precipitation and evapotranspiration, averaged over five years) for the Range as for the Sill. This suggests that changes in the Range are more event specific. The difference in the CV for the Range between catchments is best characterised by location, soil type and the length of wet and dry periods. The influence of the characteristics on a river's response to an individual precipitation event will depend on the antecedent conditions of the catchment which will influence the connectivity of the catchment (Smith et al., 2013) and hence the rate at which precipitation signals propagate through the catchment. This will determine the amount of variability in precipitation which will reach the river and therefore the smoothness of the river flow time series.

The difference in the relationship between the driving characteristics and the CV of the Sill and Range demonstrates that each part of the river flow regime is influenced by different processes in the catchment. This was also found in Carrillo et al. (2011) who investigated the influence that climate and catchment characteristics have on hydrological signatures (base flow index, runoff coefficient and the slope of the flow duration curve). Furthermore, Harman et al. (2011) investigated the elasticity of the slow and fast river flow pathways and identified that fast pathways are more sensitive to a change in precipitation. This is because the catchment characteristics will have a larger influence on the precipitation-to-river flow relationship when the catchment is relatively dry and water is infiltrating into soil and groundwater stores.

Chapter 4 also showed that temporal changes in the variogram parameters for the permeable catchments with a lot of storage (i.e. catchments in Cluster 4) had the least amount of variability explained by the precipitation characteristics. However, the opposite relationship is found with regards to resilience, with the more permeable catchments having a larger CV (Figure 4.5).

The relationship between the catchment characteristics and the amount / type of change detected has important implications for change detection studies and data transfer. With regards to change detection studies, this work has shown that catchments with different characteristics will have a different susceptibility to change. Therefore, studies aimed at detecting and attributing change should encompass the physical attributes of the

catchment; they should also not focus on a single value of change (i.e. a monotonic trend) and identify periods of change throughout the record, as carried out here using TSV, as this could reveal important non-linearities in catchment response over time. Including the catchment characteristics and providing more detail on temporal changes may help to explain why catchments in similar geographical locations have been shown to exhibit different amounts of change (e.g. Hannaford and Buys (2012)).

There are multiple implications for transferring data from gauged to un-gauged catchments. Firstly, if the climate projections are realised then the meteorological conditions will change in the future. These changes will manifest themselves differently between catchments depending on the combination of catchment characteristics as these will modulate the propagation of precipitation through the catchment to the river differently. Therefore, catchments which are currently a good donor site may not be in the future. Secondly, the finding that the upland catchments which are relatively impermeable have the most resilient precipitation-to-river flow relationship suggest that data transfer may be more successful in upland catchments. This is because the precipitation-to-river flow relationship is closer to a linear relationship in the upland catchments and less dependent on thresholds within the catchment.

In general the results in this thesis agree with Merz and Blöschl (2009) who investigated several runoff signatures (mean, standard deviation, Coefficient of Variation (CV), and Coefficient of Skewness) for 459 catchments in Austria. These were correlated against multiple atmospheric and catchment characteristics. Merz and Blöschl (2009) found a positive correlation between the CV and storage (BFI), agricultural land and relatively impermeable soils (luvisols). There was a negative correlation between the CV and elevation, slope and permeable soils (endzinas and podzols). The difference in the relationship between soil and the CV in Merz and Blöschl (2009) compared to the findings in this thesis could be caused by several reasons. Firstly, several of the upland catchments used in Merz and Blöschl (2009) experience a large amount of snow cover during winter which provides relatively constant river flow throughout the melting period. A change in the temperature would influence the accumulation and melting period and hence the CV. Secondly, the combinations of the catchment characteristics will be different and other characteristics (e.g. elevation) may be more influential than in the UK.

Another reason could be the variability of the atmospheric conditions. Finally, the CV was calculated using different aspects of the river flow, Merz and Blöschl (2009) used hourly discharge data whereas this thesis has investigated the CV of the variogram parameters calculated from daily river flow data. These different aspects of the river flow time series which have been calculated over different times will be influenced by different aspects of the precipitation-to-river flow relationship and hence different catchment processes.

The finding that more permeable catchments are more resistant but less resilient to changes in precipitation was also found in (Carey et al., 2010) who investigates temporal changes in catchment resilience for ten catchments spanning Scotland, Canada, Sweden and the USA. This demonstrates that on average there will be a larger change in river flow per unit change in precipitation for upland catchments. However, the precipitation-to-river flow relationship is more likely to change (as it exhibits non-linear, threshold-based behaviour) in well drained, groundwater dominated catchments.

The information gained from this thesis identifies how the catchment characteristics influence the propagation of precipitation signals through the catchment as well as showing that the resilience in this propagation is dependent on the catchment characteristics. This has important implications for water management plans which, in the UK, are created at the catchment scale. This research showed that the precipitation-to-river flow relationship in the permeable catchments which have a lot of storage in the South East of the UK are the least resilient to change (i.e. their flow regimes deviate from the normal conditions for longer). This is because the propagation of the climate signal through to the river flow is more non-linear and dependent on thresholds than upland catchments which have a closer to linear precipitation-to-river flow relationship. Catchment management plans should take this into account and leave a larger safety margin when using climate projections to predict changes in water quantity in the future. This is particularly the case when considering low flow because the catchment characteristics have a greater influence on the low flows than the high flows. Therefore, the response of a river to a projected decrease in precipitation in a permeable catchment may be harder to predict (e.g. the change may be less severe but last for longer).

## **5.4 Recommendations for further work**

### **5.4.1 Analysing the influence of groundwater storage**

As the amount of highly productive fractured rock (an indication of the amount of groundwater storage) was found to be highly influential in modulating the amount of variability in the variogram parameters, the temporal change in groundwater levels should be brought into future analyses. Observation boreholes within (or hydrologically connected to) Benchmark catchments could be identified, particularly over the highly productive fractured aquifers in the South East of the UK. The change in variogram parameters could then be assessed, along with changes in the groundwater levels (work could analyse, for example, if the Range increases when the groundwater is decreasing due to lack of recharge by rainfall).

### **5.4.2 Testing the methods in a different climate**

The catchment characteristics have been found to influence both the average precipitation-to-river flow relationship and the amount of variability in the river flow time series in the UK. The UK has a temperate maritime climate which has a clear seasonal cycle in temperature (and hence evapotranspiration) with the summer months (June, July and August) being the warmest. In addition, precipitation has a strong seasonal cycle in the West (strongest in the North West) of the UK. Furthermore, there is a distinct geographical gradient with the North West being wetter and cooler than the South East. Further work should use the same method to investigate if these findings vary in different climates (e.g. is the shape of the variogram more dependent on the climate for continental or monsoon catchments).

### **5.4.3 Further evaluation of the relationships between the variogram properties and the potential drivers**

In the UK, snowmelt makes up a relatively small proportion of the river flow, although it can be important in typical winters in parts of northern Britain, especially north-east Scotland, and can be influential in more extreme winters elsewhere. The influence of large and frequent (i.e. most years) snowfall events have on the shape of the variogram

should be investigated. The snowpack will be a temporary store of water and may shift the variogram to appear more like one which is representative of a groundwater dominated catchment. This work would provide more information about the role of snow in the average precipitation-to-flow relationship. Furthermore, using the TSV technique, the influence of changing snow fall on the precipitation-to-river flow relationship can be investigated.

#### **5.4.4 Assessing the effects of artificial influences**

Using the knowledge gained about how the catchment characteristics influence the average precipitation-to-river flow relationship, the impact of artificial influences on the precipitation-to-river flow relationship could be investigated. Variograms could be created for catchments with known impacts, and compared to the expected variogram based on the catchment characteristics. This would provide an indication as to the amount of change in the average precipitation-to-river flow relationship caused by the artificial impact. This could potentially be very useful in hydro-ecology, which employs a wide range of indicators to assess anthropogenic disturbances to flow regimes. For example, Richter et al. (1996) looks at how 32 river flow indicators vary before and after the period of interest. The TSV approach could provide an efficient way of capturing changes in river flow dynamics; using indicators based on responsiveness/dependence would provide information about the changes in the precipitation-to-river flow relationship which could have impacts for the ecology in the river.

#### **5.4.5 The influence of changing land cover**

If information was available about the temporal changes in land cover then this information could be added to the attribution phase of the TSV method, although datasets such as the Land Cover Map (Fuller et al., 2002) exist, they are just for a few snapshots (1990, 2000, 2007). However, increasingly datasets are being developed which could be used to look at dynamic changes in land use and cover. Thus far, these have mainly been applied to a small number of urban catchments (e.g. urban, Miller et al. (2014)), but future studies may be able to capitalise on wider datasets. For rural catchments, such mapping approaches may not be available but known changes in land cover, land use or



management (e.g. Rust et al. (2014); Harrigan et al. (2014)) could also be used as explanatory variables. Using the TSV approach would provide inferences as to the influence that a change in land use has on the dominant pathway water takes through the catchment, and the amount of land use change which is required to cause a change in the dominant flow pathway through the catchment. Furthermore, information will also be provided about the amount of time it takes before the change in land use is identified in the river flow regime as well as the duration for which the river flow regime is influenced.

## 5.5 Conclusions

The thesis's most significant findings and advancements in scientific understanding are identified and highlighted in the five sections below:

**1) Variograms are able to detect the influence that catchment characteristics have on the precipitation-to-river flow relationship.**

The similarity of catchments based on the shape of the semi-variogram calculated from 30 years of daily flow data (1980 to 2010) for 116 near natural catchments was analysed. The semi-variograms were grouped into relatively distinct clusters, with four clusters best representing the range of semi-variogram shapes for the 116 catchments. Semi-variograms were also calculated using the daily precipitation data for each catchment. These were found not to be significantly different between the clusters. Therefore, the change in the shape of the variogram between the catchments was deemed to be driven by the catchment characteristics which control the processes within the catchment and hence the precipitation-to-river flow relationship. The more permeable catchments had semi-variograms with a longer Range and lower Sill. This shows that, over a 90-day period, there is on average a smoother river flow time series with less variability in the permeable catchments. Therefore, on average, more of the short-term variability in the precipitation is dampened by the lowland, permeable catchments with a large amount of storage than by the upland, relatively impermeable catchments. This demonstrates that the catchment characteristics influence the pathway water takes through the catchment and hence the river flow dynamics.

**2) The shape of the variogram can be estimated for un-gauged catchments using their catchment characteristics.**

Some of the catchment characteristics were found to be significantly different between the clusters. Consequently, un-gauged catchments can be clustered using their catchment characteristics. The catchment characteristics which were found to best distinguish between the clusters were: average drainage path slope, depth to gleying layer in the soil and the percentage of arable land. Using these characteristics over 70 % of un-gauged catchments could be clustered correctly. All of the predominantly groundwater-dominated (situated on highly productive fractured rock) calibration and validation catchments were clustered correctly due to their distinct variogram shape. This method is valuable for transferring information about the precipitation-to-flow relationship from gauged to un-gauged catchments. This could be expanded upon to enable predictions of regime characteristics at un-gauged sites to be made.

**3) Variograms calculated over short time scales identify changes in the river flow regime.**

A new method was developed (Temporally Shifting Variograms) in order to detect periods of significant change in the variogram parameters. The method compares the variogram parameters which are calculated from 5-year moving windows to the average variogram parameters (calculated over the whole record, 1980 to 2012) for each catchment to see if change has occurred. This shows that at different time periods more/less of the variability in the precipitation propagates through the catchment to the river. The method was tested on an artificially perturbed time series which identified that each variogram parameter is sensitive to changes in different aspects of the river flow time series. The method identified clear peaks in the time series in the percentage of catchments which have significant changes from their average value (around 1995 for the Range and 2012 for the Sill).

**4) Attributing the change in the variogram parameters to meteorological characteristics.**

The relationship between the temporal changes in the variogram parameters and the precipitation characteristics was investigated. It was found that each variogram parameter has a different relationship with each precipitation characteristic. The Range has a larger

correlation with the length of wet and dry periods whilst the Sill has a larger correlation with the magnitude of precipitation and the seasonality. The peak in the number of catchments which exceeded the lower threshold for the Range (around 1995) was attributed to an increase in the length of wet periods (as 1995 to 2001 was exceptionally wet). The length of wet periods will influence the antecedent conditions, and reduce the influence catchment characteristics have on the amount of short-term temporal variability in the precipitation reaching the river. The peak in the number of catchments exceeding the upper threshold for the Sill (around 2010 to 2012) was attributed to an increase in the variability of precipitation that caused widespread flooding and droughts between 2008 and 2013. Consequently, river flow had more overall variability which was detected by an increase in the Sill.

It was found that there was a large range in the amount of variability in the variogram parameters which could be explained by precipitation. The influence that the catchment characteristics have on this amount of variability was investigated. The results showed that the temporal variability in the variogram parameters for catchments in Cluster 4 (catchments with high infiltration and storage) was not as well explained by the precipitation characteristics as the other clusters. This indicates that the lowland, permeable catchments with a large amount of storage have a relationship with precipitation which is non-linear, in contrast to the upland, relatively impermeable catchments.

##### **5) The catchment characteristics influence how the river responds to climatic variability.**

The relationship between the Coefficient of Variation (CV) and a range of potential drivers (precipitation, evapotranspiration, catchment characteristics and location) was investigated. It was identified that the lowland, permeable catchments have the largest Coefficient of Variation (CV). This shows that the temporal dependence structure is less temporally stable in the lowland permeable catchments, indicating that the propagation of precipitation through the catchment varies more in these catchments. The difference in the CV between the catchments for the Sill was well explained (74%) by the CV of the precipitation characteristics and the catchment characteristics. Groundwater storage in the

catchment was found to influence the CV of the Sill. It is likely that groundwater dominated catchments reduce the impact of short-term precipitation anomalies but exacerbate the length of time needed before the river returns to normal levels after a long dry period. Using location (Northing and Easting), catchment characteristics and the CV of the precipitation characteristics, 48% of the variability in the CV of the Range between the catchments was explained. It is likely that the variability in the Range is more dependent on individual precipitation events which would be influenced by the soil type and the antecedent conditions.

## 5.6 Final remarks

This thesis identified (for the first time) that the variogram, calculated from daily river flow data, is dependent on the catchment characteristics which control the propagation of precipitation variability through the catchment. A novel change detection technique was developed in order to assess changes in the variogram parameters through time. Analysing the variogram parameters enabled the influence that catchment characteristics have on a river's response to climatic variability to be assessed. This improved understanding contributes significant new knowledge that can be used for both assessing how individual catchments are likely to respond to projected changes in precipitation and in informing data transfer to un-gauged catchments.

## 5.7 References

- BLOOMFIELD, J. P. & MARCHANT, B. P. 2013. Analysis of groundwater drought using a variant of the Standardised Precipitation Index. *Hydrol. Earth Syst. Sci. Discuss.*, 10, 7537-7574.
- BOORMAN, D., HOLLIS, J. & LILLY, A. 1995. *Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom. Report No 126.*, UK, Institute of Hydrology.
- BOUGHTON, W. & CHIEW, F. 2007. Estimating runoff in ungauged catchments from rainfall, PET and the AWBM model. *Environmental Modelling & Software*, 22, 476-487.
- BRADFORD, R. B. 2002. Controls on the discharge of Chalk streams of the Berkshire Downs, UK. *Science of The Total Environment*, 282–283, 65-80.
- BROWN, A. E., ZHANG, L., MCMAHON, T. A., WESTERN, A. W. & VERTESSY, R. A. 2005. A review of paired catchment studies for determining changes in

- water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310, 28-61.
- CAREY, S. K., TETZLAFF, D., SEIBERT, J., SOULSBY, C., BUTTLE, J., LAUDON, H., MCDONNELL, J., MCGUIRE, K., CAISSIE, D., SHANLEY, J., KENNEDY, M., DEVITO, K. & POMEROY, J. W. 2010. Inter-comparison of hydro-climatic regimes across northern catchments: synchronicity, resistance and resilience. *Hydrological Processes*, 24, 3591-3602.
- CARRILLO, G., TROCH, P. A., SIVAPALAN, M., WAGENER, T., HARMAN, C. & SAWICZ, K. 2011. Catchment classification: hydrological analysis of catchment behavior through process-based modeling along a climate gradient. *Hydrol. Earth Syst. Sci.*, 15, 3411-3430.
- CASTILLO, V. M., GÓMEZ-PLAZA, A. & MARTÍNEZ-MENA, M. 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *Journal of Hydrology*, 284, 114-130.
- EL MAAYAR, M. & CHEN, J. M. 2006. Spatial scaling of evapotranspiration as affected by heterogeneities in vegetation, topography, and soil texture. *Remote Sensing of Environment*, 102, 33-51.
- FIORILLO, F. & GUADAGNO, F. 2010. Karst Spring Discharges Analysis in Relation to Drought Periods, Using the SPI. *Water Resources Management*, 24, 1867-1884.
- FOLKE, C., CARPENTER, S., WALKER, B., SCHEFFER, M., ELMQVIST, T., GUNDERSON, L. & HOLLING, C. S. 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual Review of Ecology, Evolution, and Systematics*, 35, 557-581.
- FULLER, R. M., SMITH, G. M., SANDERSON, J. M., HILL, R. A. & THOMSON, A. G. 2002. The UK Land Cover Map 2000: Construction of a Parcel-Based Vector Map from Satellite Images. *The Cartographic Journal*, 39, 15-25.
- HANNAFORD, J. & BUYS, G. 2012. Trends in seasonal river flow regimes in the UK. *Journal of Hydrology*, 475, 158-174.
- HARMAN, C. J., TROCH, P. A. & SIVAPALAN, M. 2011. Functional model of water balance variability at the catchment scale: 2. Elasticity of fast and slow runoff components to precipitation change in the continental United States. *Water Resources Research*, 47.
- HARRIGAN, S., MURPHY, C., HALL, J., WILBY, R. L. & SWEENEY, J. 2014. Attribution of detected changes in streamflow using multiple working hypotheses. *Hydrol. Earth Syst. Sci.*, 18, 1935-1952.
- HUNDECHA, Y. & BÁRDOSSY, A. 2004. Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model. *Journal of Hydrology*, 292, 281-295.
- KAY, A. L., BELL, V. A., BLYTH, E. M., CROOKS, S. M., DAVIES, H. N. & REYNARD, N. S. 2013. A hydrological perspective on evaporation: historical trends and future projections in Britain. *Journal of Water and Climate Change*, 4, 193.
- MAYOR, Á. G., BAUTISTA, S., SMALL, E. E., DIXON, M. & BELLOT, J. 2008. Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in drylands. *Water Resources Research*, 44, W10423.

- MCGUIRE, K. J., MCDONNELL, J. J., WEILER, M., KENDALL, C., MCGLYNN, B. L., WELKER, J. M. & SEIBERT, J. 2005. The role of topography on catchment-scale water residence time. *Water Resources Research*, 41, W05002.
- MCVICAR, T. R., VAN NIEL, T. G., LI, L., HUTCHINSON, M. F., MU, X. & LIU, Z. 2007. Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. *Journal of Hydrology*, 338, 196-220.
- MERZ, R. & BLÖSCHL, G. 2009. A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. *Water Resources Research*, 45, W01405.
- MILLER, J. D., KIM, H., KJELDSSEN, T. R., PACKMAN, J., GREBBY, S. & DEARDEN, R. 2014. Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology*, 515, 59-70.
- NEARING, M. A., JETTEN, V., BAFFAUT, C., CERDAN, O., COUTURIER, A., HERNANDEZ, M., LE BISSONNAIS, Y., NICHOLS, M. H., NUNES, J. P., RENSCHLER, C. S., SOUCHÈRE, V. & VAN OOST, K. 2005. Modeling response of soil erosion and runoff to changes in precipitation and cover. *CATENA*, 61, 131-154.
- PERRY, M. & HOLLIS, D. 2005. The development of a new set of long-term climate averages for the UK. *International Journal of Climatology*, 25, 1023-1039.
- POTTS, D. L., HUXMAN, T. E., ENQUIST, B. J., WELTZIN, J. F. & WILLIAMS, D. G. 2006. Resilience and resistance of ecosystem functional response to a precipitation pulse in a semi-arid grassland. *Journal of Ecology*, 94, 23-30.
- PRUSKI, F. F. & NEARING, M. A. 2002. Runoff and soil-loss responses to changes in precipitation: A computer simulation study. *Journal of Soil and Water Conservation*, 57, 7-16.
- REYNARD, N. S., CROOKS, S., KAY, A., L. & PRUDHOMME, C. 2009. Regionalised Impacts of Climate Change on Flood Flows - FD2020 DEFRA: <http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=13958>.
- RICHTER, B. D., BAUMGARTNER, J. V., POWELL, J. & BRAUN, D. P. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems.
- RUST, W., CORSTANJE, R., HOLMAN, I. P. & MILNE, A. E. 2014. Detecting land use and land management influences on catchment hydrology by modelling and wavelets. *Journal of Hydrology*, 517, 378-389.
- Un Métró para Evaluar Alteraciones Hidrológicas dentro de Ecosistemas. *Conservation Biology*, 10, 1163-1174.
- SANKARASUBRAMANIAN, A., VOGEL, R. M. & LIMBRUNNER, J. F. 2001. Climate elasticity of streamflow in the United States. *Water Resources Research*, 37, 1771-1781.
- SMITH, T., MARSHALL, L., MCGLYNN, B. & JENCOSO, K. 2013. Using field data to inform and evaluate a new model of catchment hydrologic connectivity. *Water Resources Research*, 49, 6834-6846.
- TAGUE, C., GRANT, G., FARRELL, M., CHOATE, J. & JEFFERSON, A. 2008. Deep groundwater mediates streamflow response to climate warming in the Oregon Cascades. *Climatic Change*, 86, 189-210.

- TAGUE, C. & GRANT, G. E. 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. *Water Resources Research*, 45.
- TETZLAFF, D., SEIBERT, J., MCGUIRE, K. J., LAUDON, H., BURNS, D. A., DUNN, S. M. & SOULSBY, C. 2009a. How does landscape structure influence catchment transit time across different geomorphic provinces? *Hydrological Processes*, 23, 945-953.
- TETZLAFF, D., SEIBERT, J. & SOULSBY, C. 2009b. Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland. *Hydrological Processes*, 23, 1874-1886.
- TROMP-VAN MEERVELD, H. J. & MCDONNELL, J. J. 2006. Threshold relations in subsurface stormflow: 2. The fill and spill hypothesis. *Water Resources Research*, 42.
- VAN LOON, A. F. & LAAHA, G. 2014. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*.
- VIGLIONE, A., PARAJKA, J., ROGGER, M., SALINAS, J. L., LAAHA, G., SIVAPALAN, M. & BLÖSCHL, G. 2013. Comparative assessment of predictions in ungauged basins &ndash; Part 3: Runoff signatures in Austria. *Hydrol. Earth Syst. Sci.*, 17, 2263-2279.

## **APPENDIX I**

CHIVERTON, A., HANNAFORD, J., HOLMAN, I., CORSTANJE, R.,  
PRUDHOMME, C., BLOOMFIELD, J. & HESS, T. M. 2015a. Which  
catchment characteristics control the temporal dependence structure of daily  
river flows? *Hydrological Processes*, 29, 1353-1369.



## **APPENDIX II**

CHIVERTON, A., HANNAFORD, J., HOLMAN, I. P., CORSTANJE, R.,  
PRUDHOMME, C., HESS, T. M. & BLOOMFIELD, J. P. 2015b. Using  
variograms to detect and attribute hydrological change. *Hydrol. Earth Syst. Sci.*,  
19, 2395-2408.



