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River water temperature patterns in England and Wales

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River water temperature patterns in England and Wales
Surface water temperature archive for UK fresh water and estuarine sites — Phase II

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Executive Summary

The Water Temperature Archive project was commissioned to collate historical surface-water temperature data and organise these records into a relational database, and to indicate recent trends in water temperatures across England and Wales. A subsequent programme of work was commissioned to aid interpretation of the results arising from analysis of the full archive. A major difficulty in interpreting the modelled trends and changes in temperature for sites in the Archive across the whole of England and Wales is that at such a large scale of analysis little validation of site temperature data can be performed. Furthermore, the particulars of individual sites as to changes upstream of the sampling location, such as construction of sewage outfalls, etc. could not be investigated for the entire Archive. This report details the findings of this second work programme, which aimed to address these difficulties by focussing analysis effort on sites located within the Benchmark Network catchments where existing flow data could be used to select sites with minimal disruptions.

This subsequent work programme was commissioned to; i) assess water temperature trends at sites within the Benchmark Network, ii) assess changes in the seasonal pattern of water temperatures at the selected sites, iii) explain the spatial pattern of water temperature change using national hydroclimatic and land-use data sets, iv) indicate trends in flow at Benchmark sites and relate these to trends in water temperature, v) compare rates of change in air and water temperatures, and vi) assess the influence of spot sampling on fitted trends and change statistics.

Approximately 80% of the 231 Archive sites located within Benchmark catchments exhibit an increase in water temperature over the period January 1990–December 2006. The distribution of water temperature change and the spatial pattern of change at the Benchmark sites are similar to those observed for the Archive as a whole. This suggests that the patterns described in the earlier phase of the project reflect real changes in water temperatures, irrespective of uncertainties surrounding data quality at individual sites, when viewed on the national scale.

Water temperatures have also changed seasonally, with most sites in Benchmark catchments showing increased temperatures in autumn and winter, and to a lesser extent in spring. Summer temperatures remained, on average across the 231 Benchmark sites, stable (mean temperature change $\sim$ 0℃) with consequently a greater proportion of sites showing decreased summer temperatures between 1990 and 2006. In addition, the seasonal pattern of temperature at individual sites has changed at approximately 20% of the Benchmark sites, suggesting widespread changes in seasonality superimposed upon long-term seasonal trends in water temperature.

No obvious spatial relationship between river flow and water temperature change could be detected at the Benchmark sites despite a tendency towards both increasing flows and temperatures. This pattern is repeated for seasonal changes in both flows and temperatures, with the exception of a negative correlation between temperature and flow changes in winter, where flows decrease and temperatures increase. The results support the general conclusion that river flow changes over the period of study are not likely to have strongly influenced the observed positive temperature trends.

Changes in water temperature have outpaced increases in air temperature at many Benchmark sites. Modelling at the catchment scale indicates that climatic factors, such as precipitation and potential evaporation, are better predictors of water temperature change. This suggests that the increase in water temperatures observed at the majority of sites are not simply a direct function of heat transfer from the atmosphere to waters.

Spot sampling was the predominate sampling method for sites in the Archive. This type of sampling could potentially bias the trends fitted to data relative to those that might result if the data had been collected daily and evenly over a 24-hour period. A simulation exercise using hourly-sampled data from an automated sampling location demonstrated that i) trends fitted to spot sampled data are broadly similar to that fitted to the full data set, and ii) temperature change statistics reported here and in the previous report are robust to the effects of spot sampling. However, trends fitted to spot sampled data exhibited lower multi-year variance than the trend observed from the full time series, with lower degrees of non-linearity favoured by trends fitted to spot sample simulations.

Combined, the results presented in this report indicate strong and rapid increases in water temperatures throughout England and Wales that are consistent with those reported for the whole Archive. These increases show little relationship to air temperature and flow trends at the Benchmark sites over the same period. Instead, the observed changes are more strongly related to a suite of climate-related factors.

Chapter 1

Introduction

The first phase of the Water Temperature Archive project collated Environment Agency (EA) water temperature data and fitted time series models to these data to investigate recent patterns in water temperatures in rivers in England and Wales. This analysis consisted of data from 3136 sampling locations. One difficulty in interpreting the outputs from this large modelling exercise is that little information is readily to hand with which to evaluate the observed changes in water temperatures. Without extensive research we are unlikely to be able to confirm whether any of the 3136 sampling locations has been disturbed through changes in abstraction or flow, or from new infrastructure works such as installation of power station outflows.

Subsequent to this first phase of analysis, additional work was specified to investigate trends in water temperatures in a subset of the original sites where additional information on catchments and flows was available. Here we summarise model fits and describe the patterns in water temperatures at a subset of the original sampling location that are located within (or near to) Benchmark Catchments. 231 of the original sampling locations are also located in the Benchmark catchments. These sampling locations are shown in Figure 1.1.

The work programme for this phase of the project consisted of several stages of analysis;

1. a description of trends fitted to the study sites,
2. modelling seasonal trends and changes in the seasonal distribution of temperatures in benchmark catchments,
3. an examination of river flow trends in the benchmark network to allow comparison with water temperature trends,
4. an investigation of factors related to changes in annual and seasonal trends across the benchmark catchments,
5. a comparison of changes in air and water temperatures at benchmark sites, and
6. an evaluation of the effects of spot sampling on the extracted water temperature trends.

This report describes the results of the above analyses and provides a comprehensive account of changes in water temperatures in rivers in England and Wales. Each of the above parts of the work programme will be described in turn in the report.

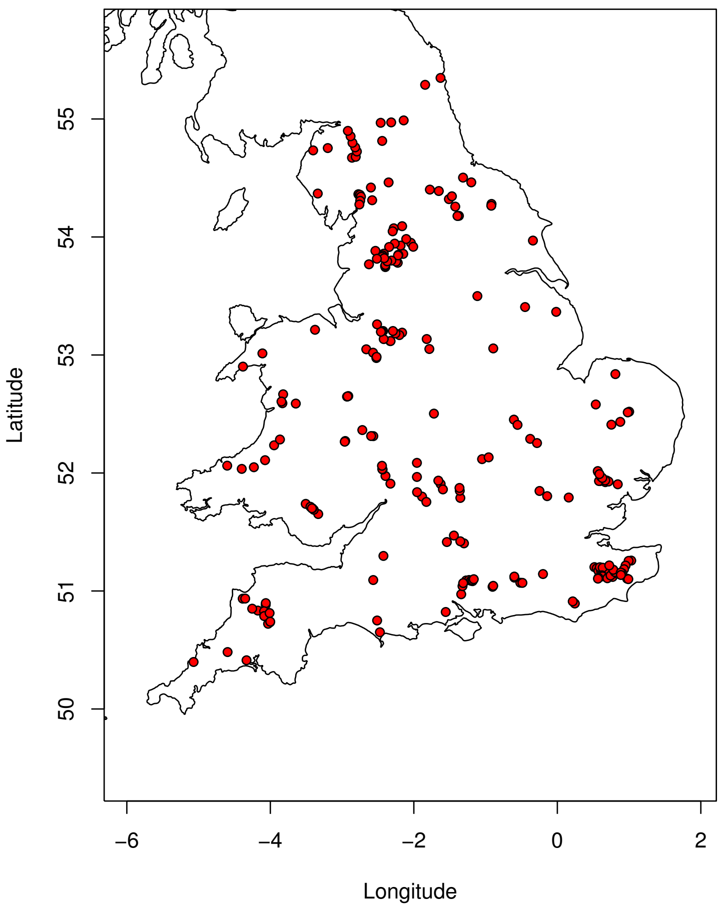

Figure 1.1: Map showing the locations of the 231 sampling stations within Benchmark Catchments.

Chapter 2

Trends in annual river water temperatures

2.1 Introduction

In this section of the report we summarise model fits and describe the patterns in water temperatures at sites in the benchmark catchments. These models were fitted under the first phase of the Water Temperature Archive project. Here, for completeness, we briefly describe the methodology used to analyse trends in the temperature data. We then collate and summarise trends for sites in the benchmark catchments.

2.2 Methods

The approach to model building and testing closely followed that of Ferguson et al. (2008), which we briefly outline here. The key feature of this approach is to model the properties of the time series using a statistical model. These properties include both the periodic or cyclical component associated with the seasonal signal plus any trend component in the observations.

A linear model that describes both the seasonal and trend components may be written as

$$y = \beta_0 + \beta_1 \text{time} + \beta_2 \text{doy} + \varepsilon, \quad \varepsilon \sim N(0, \sigma^2 \mathbf{\Lambda}).$$

The parameters in this model are the β_j, $j = 0, 1, 2$, and the variance σ^2. β_0 is the overall mean temperature, β_1 describes the rate of change in temperature for unit change in time, and β_2 describes the deviation due to the seasonal signal (doy, the day of the year). Notice that here we have added $\mathbf{\Lambda}$ to the distribution of the residuals ε. For now, $\mathbf{\Lambda} \equiv \mathbf{I}$, where $\mathbf{I}$ is an identity matrix, a matrix with diagonal values equal to one and off-diagonals equal to zero

$$\mathbf{I} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

As the diagonal values are equal to one and off-diagonals equal to 0, the residual for observation i is perfectly correlated with itself, but uncorrelated with the residuals for the other observations, i.e. the residuals ε are independently distributed. This is a major assumption of regression. We can relax this assumption by specifying a different form for $\mathbf{\Lambda}$ where the off-diagonal components are not equal to 0, and therefore represent the dependence structure in the data.

We can replace the parameters in this model with smooth functions of `time` and `doy` to allow for non-linear trends and seasonal components. The resulting model is

$$y = \beta_0 + f_1(\text{time}) + f_2(\text{doy}) + \varepsilon, \quad \varepsilon \sim N(0, \sigma^2 \mathbf{\Lambda}).$$

The degree of smoothing used within each f_j is determined from the data themselves, either via a cross validation procedure or by estimating the smoothing parameter as part of the model using maximum likelihood (ML) or restricted maximum likelihood (REML) techniques.

To test if the non-linear trend model is better supported by the observations than the linear trend model we compare the two models and determine if the extra complexity of the additive model is justified in terms of extra explanatory power. We compare the non-linear trend model with the following, simpler model

$$y = \beta_0 + \beta_1 \text{time} + f_2(\text{doy}) + \varepsilon, \quad \varepsilon \sim N(0, \sigma^2 \mathbf{\Lambda}).$$

To test if we need a trend at all, we can compare with the following null model (H_0)

$$y = \beta_0 + f_1(\text{doy}) + \varepsilon, \quad \varepsilon \sim N(0, \sigma^2 \mathbf{\Lambda}).$$

In both cases we are performing a likelihood ratio test.

2.2.1 Building additive models for time series

Additive models are a non-parametric form of regression in which the sum of regression coefficients $\times$ explanatory variables of a linear regression is replaced by a sum of arbitrary smooth functions of the explanatory variables. This allows the shape of the relationship between the response and the explanatory variables to be determined from the data themselves, rather than assigned a prescribed functional form (e.g., linear or quadratic). As a result additive models are able to model local features of the relationship between the response and the covariates; the effect of the covariate is allowed to vary across its range.

Formally, an additive model of the type discussed here has the following form

$$y_i = \alpha + \sum_{j=1}^{k} f_j(x_{ji}) + \varepsilon_i, \qquad \varepsilon \sim N(0, \sigma^2 \mathbf{\Lambda}). \tag{2.1}$$

$f_j(x_{ji})$ is a centred smooth function of the jth explanatory variable, $i = 1, \ldots, n$, the number of observations, and α is a constant representing the intercept. The errors, ε_i, are assumed to be distributed Gaussian with mean 0 and variance $\sigma^2 \mathbf{\Lambda}$. In the case of independent observations it follows that the correlation matrix will equal the identity matrix, $\mathbf{\Lambda} \equiv \mathbf{I}$. Where observations are not independent, a correlation structure may be assumed for $\mathbf{\Lambda}$ and any additional parameters required are estimated alongside the other model parameters. The degree of smoothness (or wiggliness) of the f_j is controlled through the use of penalized regression and, in the implementation used here, is determined automatically using a generalised cross-validation (GCV) routine or estimated directly using ML or REML (Wood 2006).

For regularly observed time series, autoregressive (AR), moving average (MA), or a combination of the two (ARMA) models can be used to parametrise $\mathbf{\Lambda}$. The order 1 autoregressive model, denoted AR(1), is the simplest and often the most useful autoregressive model (Pinheiro and Bates 2000) for such situations. These correlation structures are not appropriate for the irregular time series most often encountered in ecological studies. The AR(1) structure can be generalised to continuous time to allow for varying temporal differences between analysed samples, and is known as the continuous time AR(1), or CAR(1), structure. It can be shown (Pinheiro and Bates 2000) that the CAR(1) is equivalent to the exponential spatial correlation structure for a one dimensional position vector. Other spatial correlation structures may also be employed to parametrise $\mathbf{\Lambda}$, such as the Gaussian, Spherical, or Rational Quadratic structures, though these all have a superficially similar form and the end result is often the same regardless which structure is used.

Here we use the CAR(1) correlation structure for its simplicity and because it directly relates to the more common AR(1) structure in its definition. In the CAR(1), the correlation function, $h()$, between two observations is

$$h(s, \phi) = \phi^s, \quad s \geq 0, \quad \phi \geq 0 \tag{2.2}$$

where s is the temporal distance between observations. The single parameter, ϕ, is estimated as part of the model fitting.

The computational approach used here uses a formulation of Eq. 2.1 that is embedded in a linear mixed effects framework (Ruppert et al. 2003; Wood 2006). A mixed effects model is one that contains both fixed and random effects. The additive mixed model (AMM) version of Eq. 2.1 may take the following form

$$y_i = \mathbf{X}_i\boldsymbol{\beta} + \sum_{j=1}^{k} f_j(x_{ji}) + \mathbf{Z}_i\mathbf{b} + \varepsilon_i \tag{2.3}$$

where y_i is the univariate response, $\boldsymbol{\beta}$ is a vector of fixed parameters, $\mathbf{X}_i$ is the ith row of the model matrix of fixed effects which includes $\alpha = \beta_0$, the f_j are smooth functions of the covariates as before, $\mathbf{Z}_i$ is the ith row of the model matrix of random effects, $\mathbf{b}$ is a vector of random effects coefficients, which are assumed to be normally distributed with mean zero and unknown covariance matrix $\boldsymbol{\psi}_\theta$ with parameter $\boldsymbol{\theta}$, and $\varepsilon \sim N(\mathbf{0}, \sigma^2\mathbf{\Lambda})$ the model residuals (Wood 2006).

Equation 2.3, unlike the simple additive models above, does not require the concept of penalized regression for model fitting. Instead, it is possible to formulate the penalized smoothers of the additive model as components of the mixed model formulation (Eq. 2.3) (Ruppert et al. 2003; Wood 2006). Each smooth (f_j) is separated into an unpenalized component (the fixed effect), which is included in $\mathbf{X}_i\boldsymbol{\beta}$, and a penalised component (the random effect), which is included in $\mathbf{Z}_i\mathbf{b}$. The random effects component is assumed to be normally distributed, with mean 0 and one or more unknown variances to be estimated. Full details of the AMM formulation used here are given in Wood (2006, §6.6). Durbán et al. (2005) provide additional, practical advice on implementing models of this type.

In this AMM formulation, the model is actually a linear mixed model, albeit one that allows for smooth functions of the covariates, and therefore the usual methods of statistical inference for linear mixed models apply. As such, likelihood ratio tests and AIC (or BIC) can be used for model comparison in the same manner as that described above (Pinheiro and Bates 2000; Ferguson et al. 2008).

The additive model approach described here is similar to the non-parametric regression-based approach used by Ferguson et al. (2008) to model changes and detect trends in several limnological parameters in Loch Leven, Scotland. In the approach described in this study, we use CAR(1) correlation structures to cope with irregularly sampled data and smoothers based on regression splines not locally-linear smooths (Ferguson et al. 2008).

2.2.2 Specific details of model fitting and evaluation

Cubic regression splines were used for the trend component of the fitted model. For the seasonal component, a cyclic cubic regression spline was used, with end point knots fixed at day 1 and day 366 and remaining knots distributed evenly over the interval. A cyclic cubic regression spline has zero first and second derivatives at the end points, which are constrained to be equal. Hence this spline allows for a smooth transition from December to January.

The trend in the data was described by a *time* variable constructed from the sampled data as the number of days since sampling began at the location plus one (so that the first day is day 1 not day 0). The seasonal component was fitted to the day of the year (1,...,366) upon which sampling took place. The fitted models do not allow for evolution of the seasonal component through time. As such the same seasonal effect is modelled throughout each observed time series.

To ensure that the trend in each time series modelled contributes equally to the aggregated results, we use the fitted models to predict the expected daily water temperature for the period 1st January 1990 through 31st December 2006. We decompose the predicted daily temperatures, using the simple additive nature of the model, into the model intercept (mean temperature), the seasonal effect, and the trend effect, and use the latter to infer how temperatures have changed over the period of interest. Because the seasonal effect is ignored, we can simply compute the difference in the trends at the start and the end of the records as our measure of change.

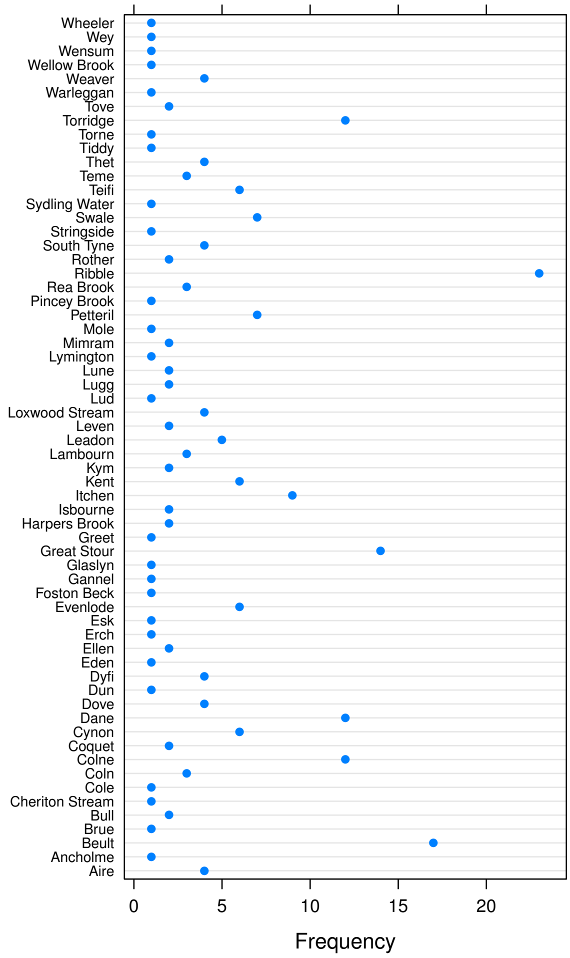

Figure 2.1: Dotplot showing the number of sampling stations within each Benchmark Catchments

2.3 Results

2.3.1 Benchmark catchments and water temperature archive sites

Figure 1.1 shows the locations of the 231 sampling stations that are located within Benchmark catchments. There is reasonable spatial coverage across England and Wales, though there is significant clumping of sites for which modelled trends were available, particularly in the north west and the south east, with rather sparse coverage in the Midlands and to the east. The sampling locations are found within a total of 62 Benchmark catchment. The number of sampling locations within each Benchmark catchment is shown in Figure 2.1. The majority of Benchmark catchments contain only a single Water Temperature Archive location (Figure 2.2), whilst 14 of the catchments contain five or more Water Temperature Archive locations.

2.3.2 Observed temperatures in benchmark catchments

Figure 2.3 shows the observed time series of water temperature data at each of the 231 sampling locations within a Benchmark Catchment. The fitted line in these plots is a Loess smoother (span = 0.2). Temperature variations within years (seasonal) is the dominant signal in these time series and no site shows a strong trend in water temperature. The temperature time series for these sites are mostly complete for the period of interest; in a number of cases there are periods of missing data but these missing periods are generally of the order of one year. There is no indication of any problems

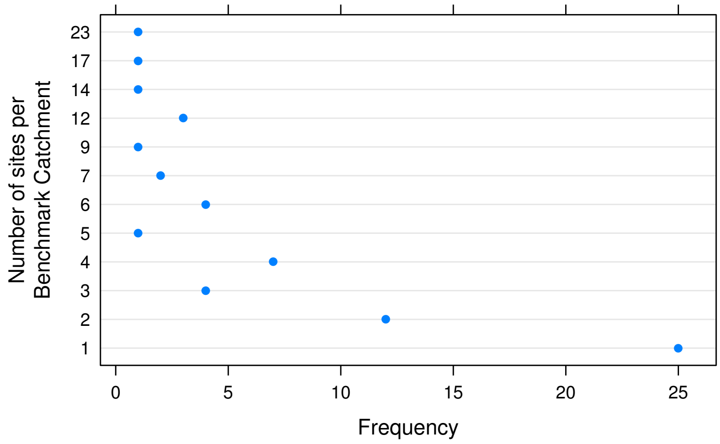

Figure 2.2: Dotplot showing the distribution of the number of Water Temperature Archive sites within Benchmark Catchments.

n	Min.	Q1	Mean	Median	Q3	Max.
231	-0.96	0.14	0.46	0.49	0.79	1.69

Table 2.1: Summary statistics of modelled trends in water temperature (℃) at sampling locations within Benchmark Catchments. Q1 and Q3 are the upper and lower quartiles respectively.

which might invalidate the fitted models.

Figure 2.4 shows the time series aggregated by Benchmark Catchment. In many cases (25) there is only a single site within a particular Benchmark Catchment. Where multiple sampling stations are located within a single Benchmark Catchment, the data within a catchment show a high degree of coherency, as we would expect.

2.3.3 Temperature change in benchmark catchments

Across all catchments 19% of sampling locations had experienced no change or a decrease in temperature over the period of interest. The observed range of temperature change is -0.96 to 1.69℃ (Table 2.1). A change in temperature of approximately 0.5℃ was observed at half the sampling locations, whilst 25% of locations had experienced a change of approximately 0.8℃ (Table 2.1). The River Tiddy experienced the largest temperature change of 1.69℃. Table 2.2 shows summary statistics for the distribution of temperature change at sites within each Benchmark Catchment. Figure 2.6 shows the distributions of temperature changes within each of the Benchmark Catchments.

Figure 2.7 displays the spatial pattern of modelled temperature change at sites within Benchmark Catchments. There are no clear spatial patterns in the modelled temperature change, although there is a considerable amount of spatial clustering. The degree to which this clustering is an artefact of restricting the analysis to the Benchmark Catchments deserves further analysis, though a similar analysis of the full Water Temperature Archive data set also demonstrated strong spatial clustering in the modelled temperature changes.

To investigate spatial patterns in the modelled temperature changes we plot the change against British National Grid easting and northing as well as altitude. As there is significant spatial clustering in the raw data, that is likely to remain unmodelled if we fitted a model to the data shown in Figure 2.8a–c, we do not pursue models of these simple relationships. However, a spatial additive model was fitted to the modelled temperature change. In this model, we fit a tensor product smooth of the easting and northing to capture the spatial structure in the temperature change. The tensor

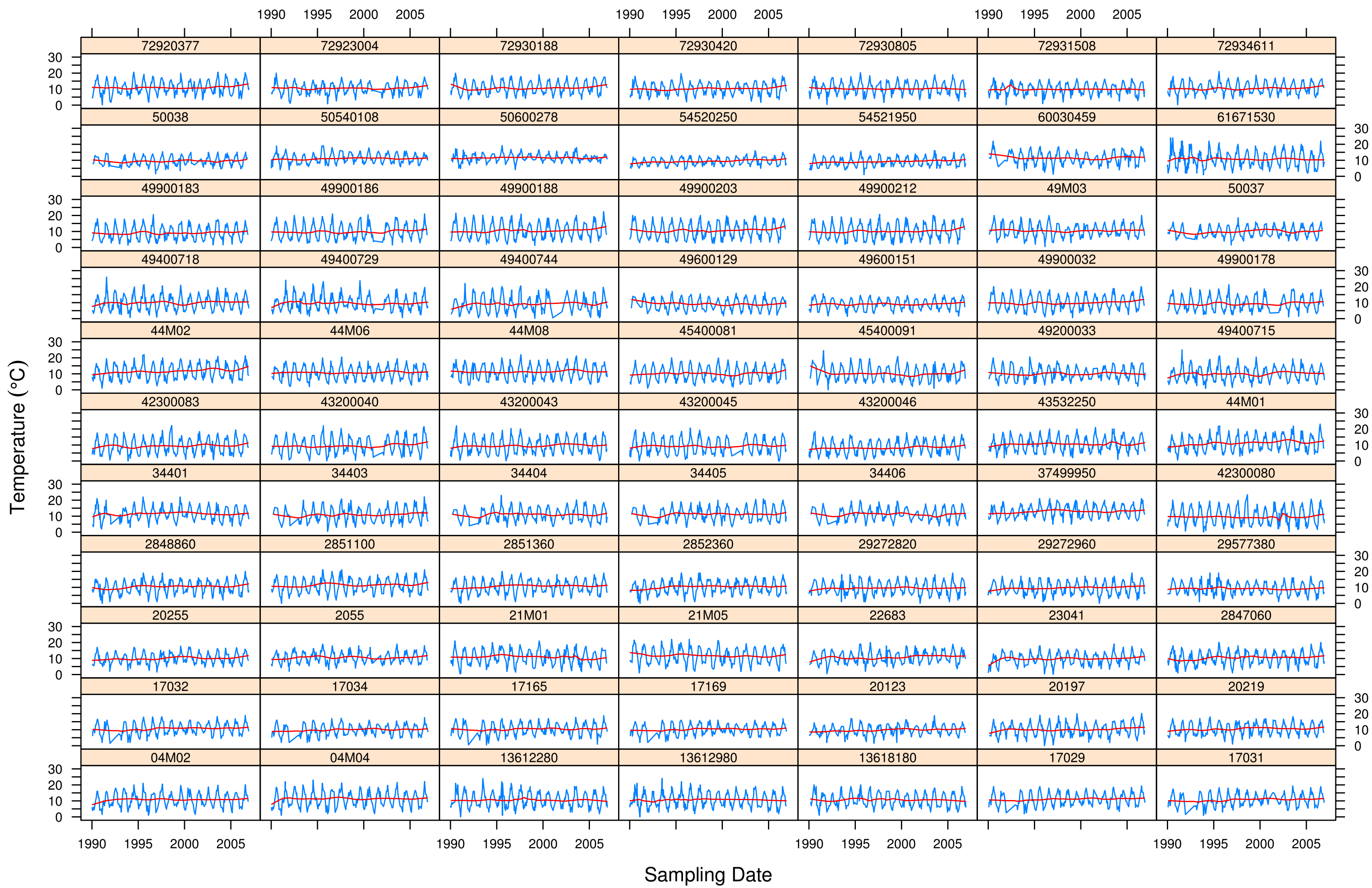

Figure 2.3: Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments. The fitted line is a extscLoess smoother within span 0.2.

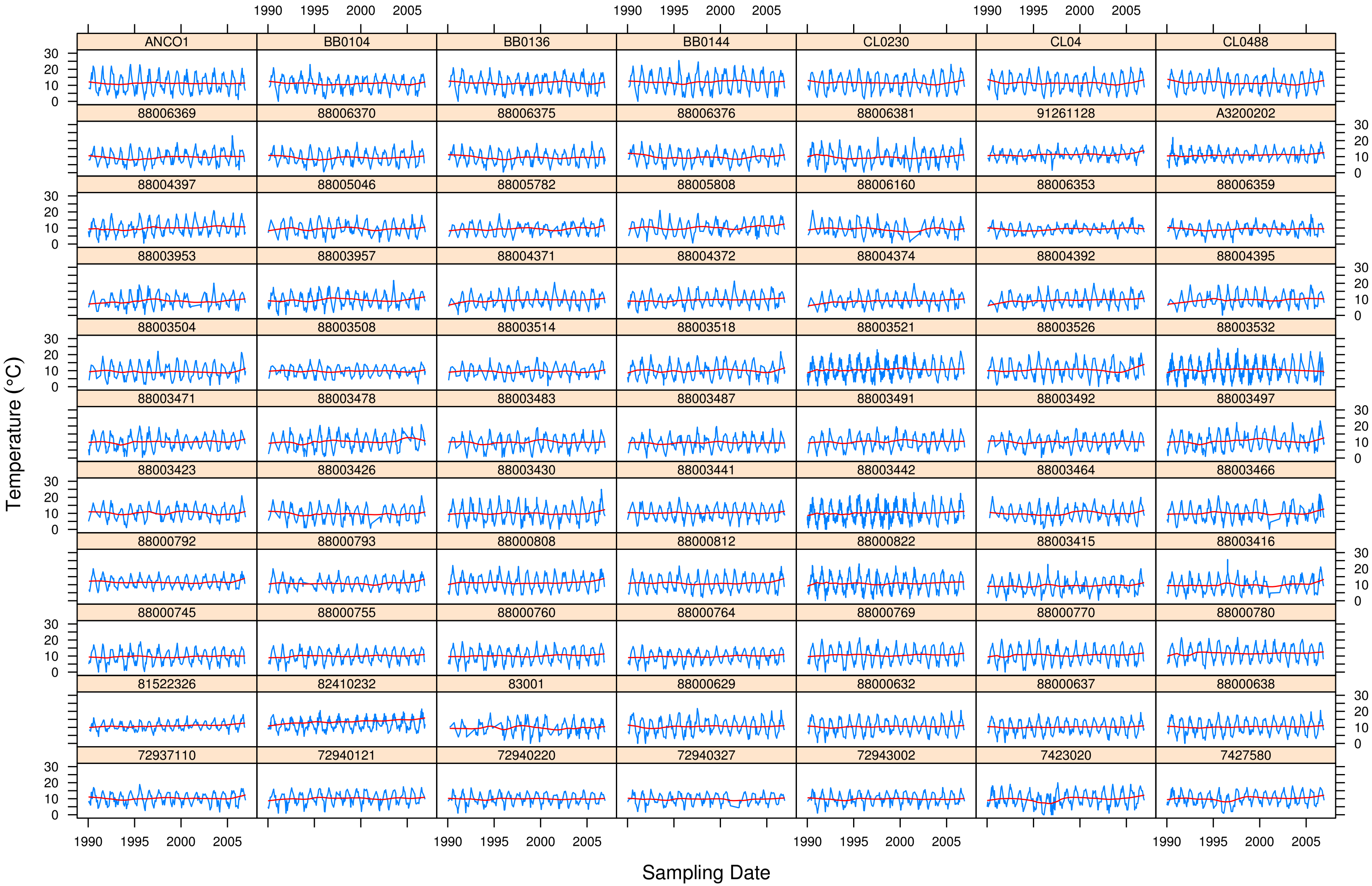

Figure 2.3: (Continued) Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments. The fitted line is a extscLoess smoother within span 0.2.

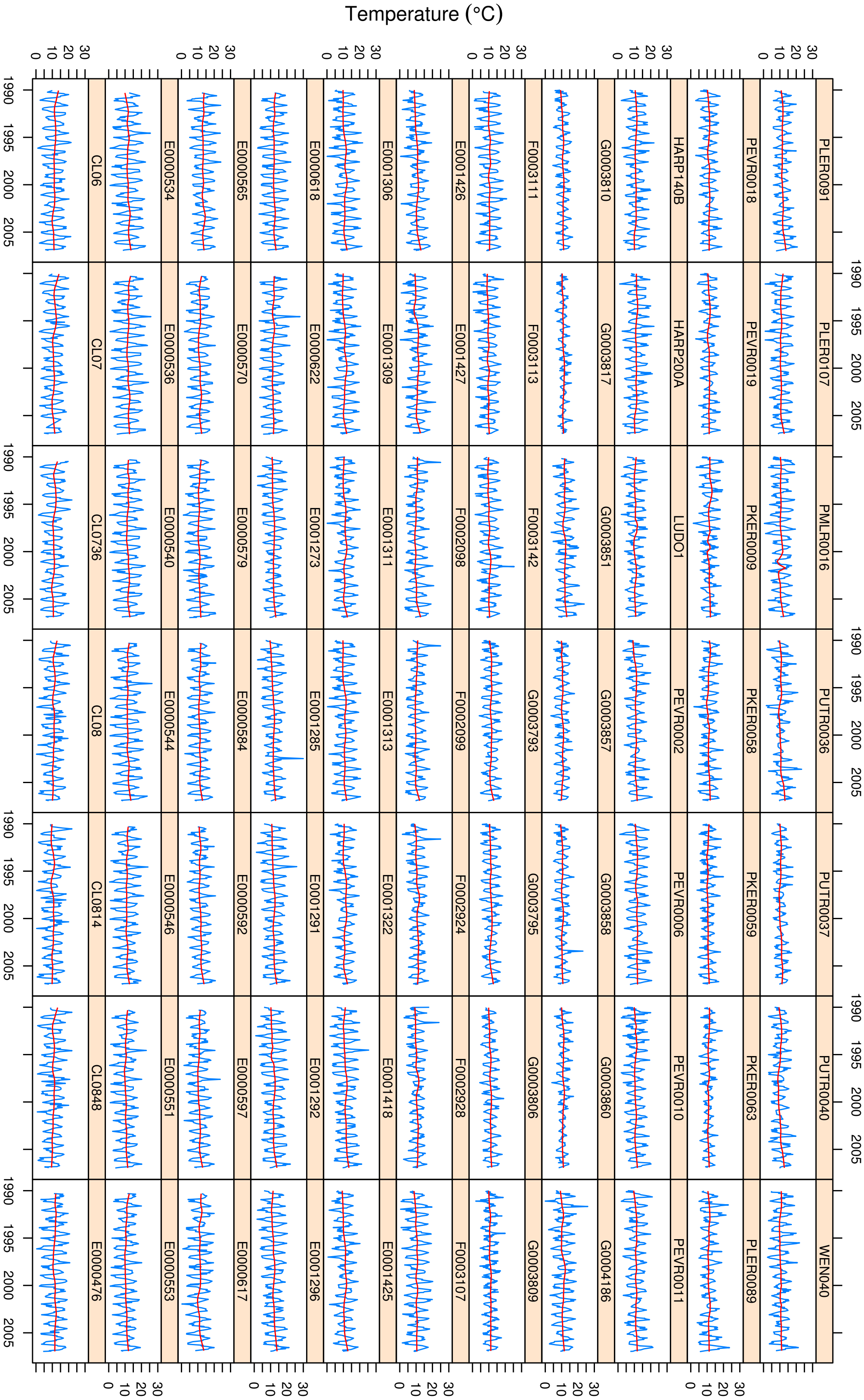

Figure 2.3: (Continued) Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments. The fitted line is a extscLoess smoother within span 0.2.

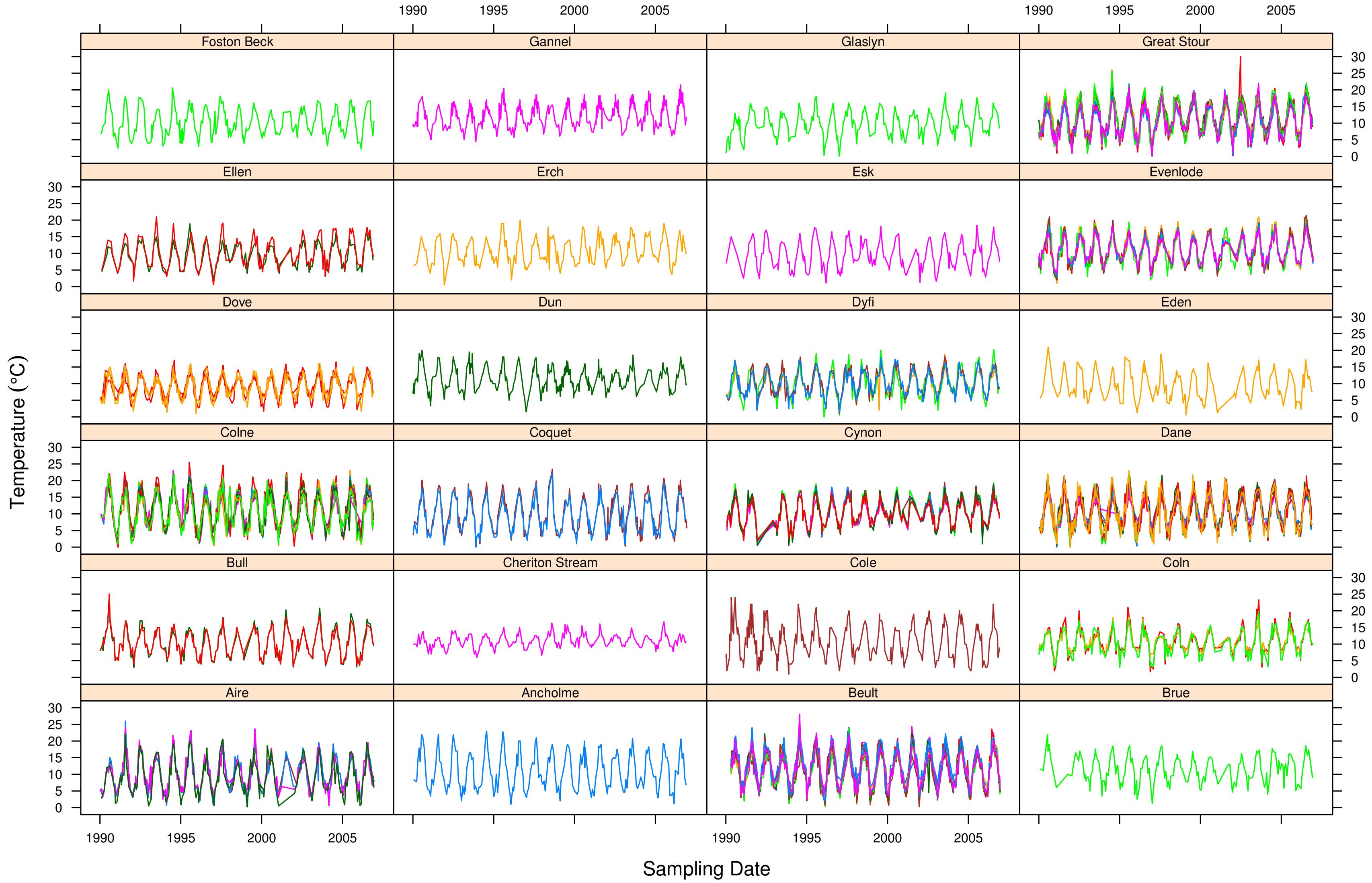

Figure 2.4: Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments, aggregated by catchment. The fitted line is a extscLoess smoother within span 0.2.

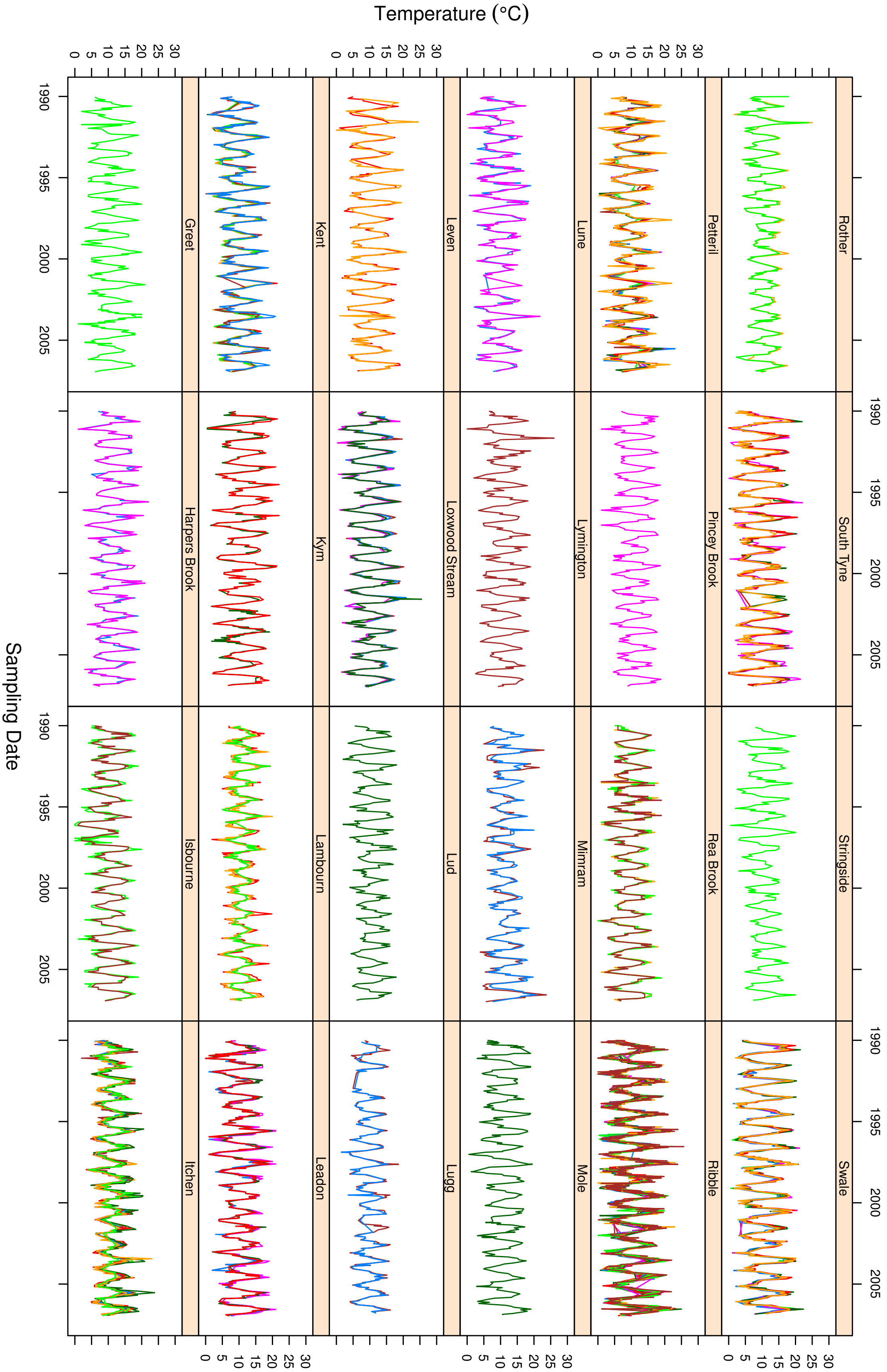

Figure 2.4: (Continued) Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments, aggregated by catchment. The fitted line is a extscLoess smoother within span 0.2.

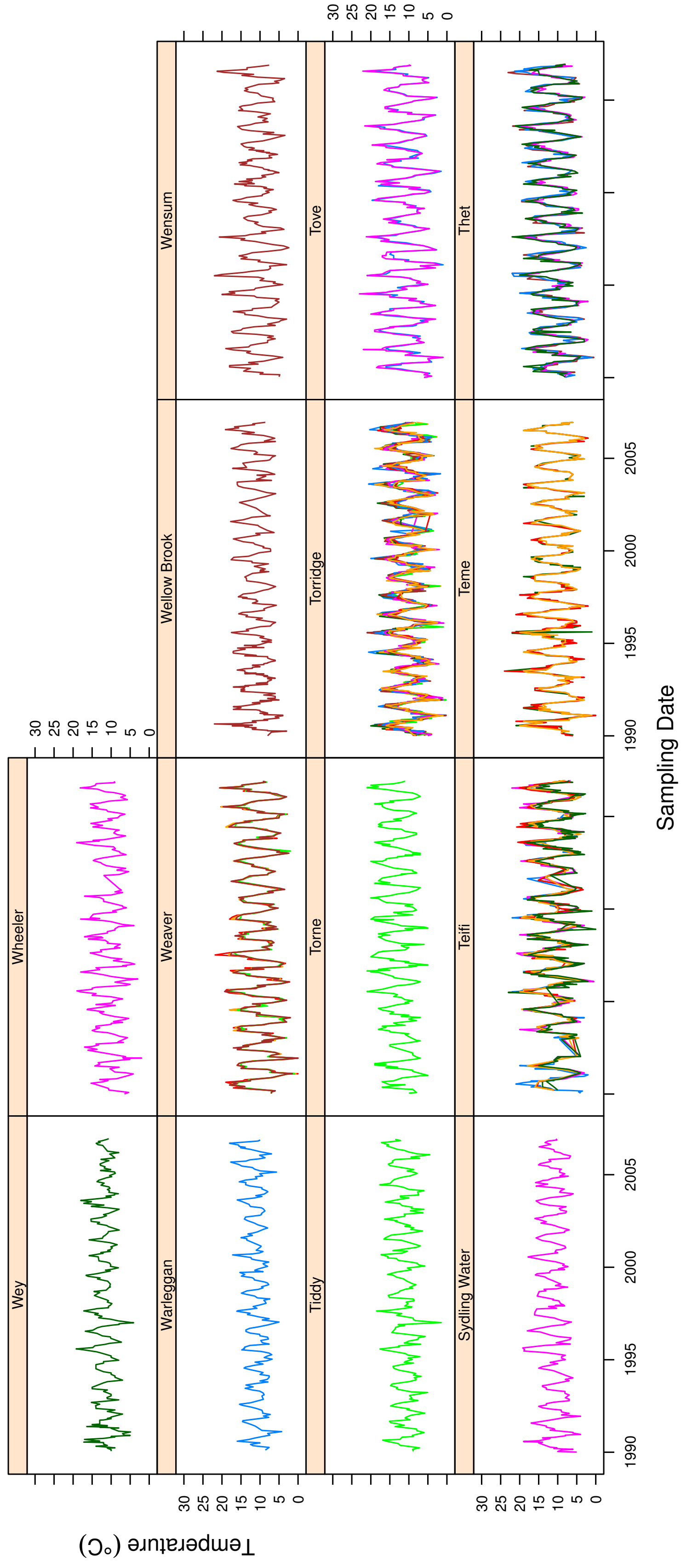

Figure 2.4: (Continued) Observed temperatures for the period 1 January 1990 – 31st December 2006 at sites within Benchmark catchments, aggregated by catchment. The fitted line is a extscLoess smoother within span 0.2.

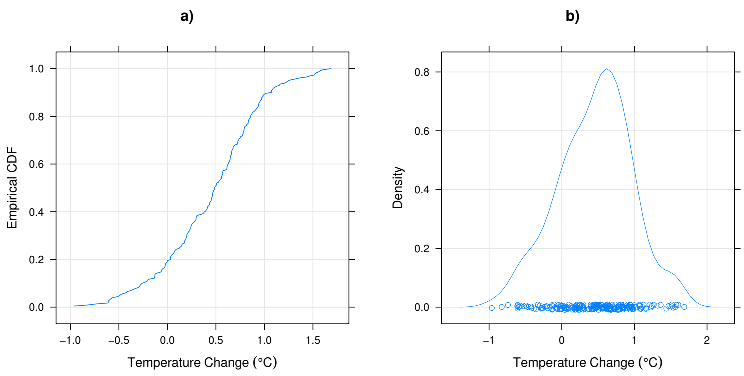

Figure 2.5: Change (trend) in temperature estimated via additive mixed models at sampling locations within Benchmark Catchments. a) Empirical cumulative distributions function plot showing the proportion of sampling locations that have observed a given change in temperature or lower; b) kernel density function of the distribution of observed changes in temperature.

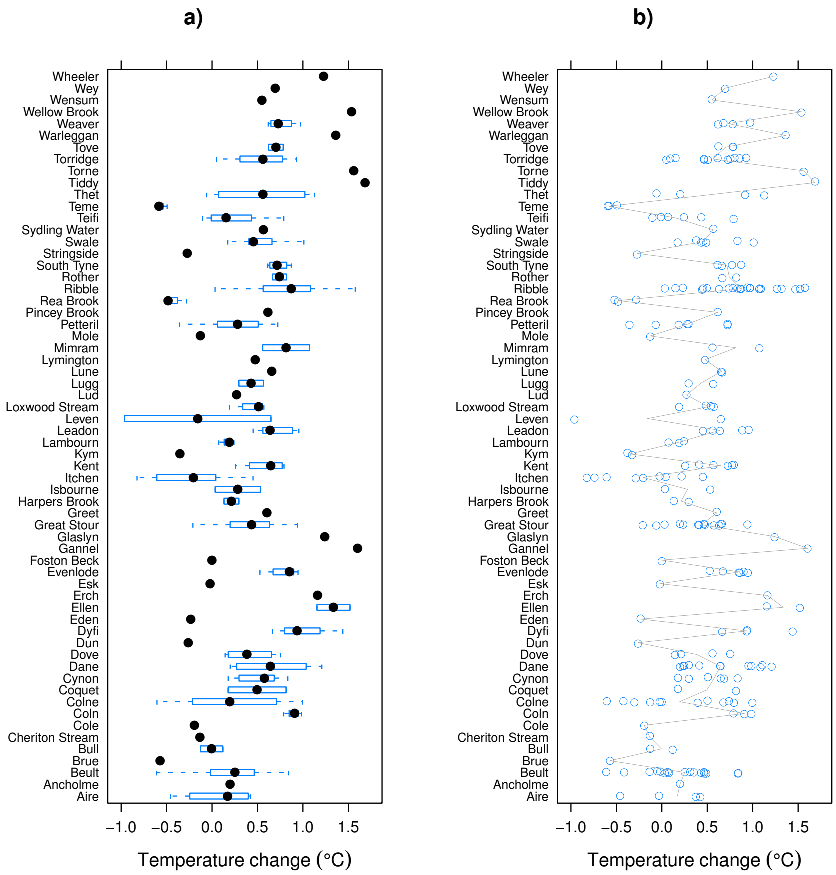

Figure 2.6: Boxplots (a) and strip plots (b) showing the distribution of modelled temperature changes within each Benchmark Catchment. The grey line in panel b joins the catchment medians.

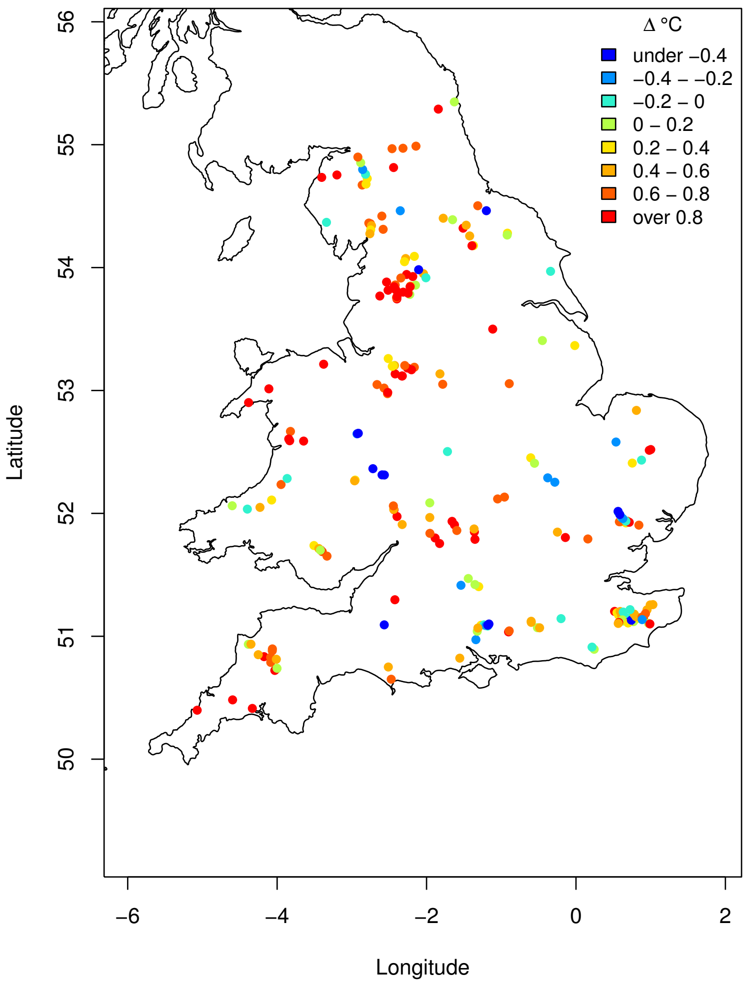

Figure 2.7: Map showing the Water Temperature Archive sampling locations within Benchmark Catchments with model-derived temperature change over the period 1st January 1990 – 31st December 2006.

product smooth allows for anisotropy in the predictor variables such that the degree of temperature change in the x or y direction is allowed to vary. The fitted tensor product smooth is illustrated as a contour plot in Figure 2.8d.

The spatial analysis indicates a degree of spatial pattern to the modelled temperature changes. The degree of temperature change increases, in general, from east to west across England and Wales, and from south to north, although there is a large amount of scatter in these relationships (Figure 2.8a–b). There appears to be no simple relationship between the altitude of the sampling location and the degree of temperature change (Figure 2.8c). Figure 2.8d–e shows the fitted tensor product smooth in the spatial additive model. Modelled temperature changes are lowest and even negative (temperature decrease) in the south east and increase most strongly to the north west and south west.

The spatial additive model fit is highly significant ($p =$ 4e-06) indicating a strong spatial structure to the temperature changes, however, additional analysis is required to confirm this result as the model currently does not account for small scale spatial autocorrelation, which, due to the clustering of sites within catchments, is likely to be quite high.

The final set of results presented here is a summary table of the trend components in the additive mixed models fitted to the water temperature data from sampling locations in the Benchmark Catchments (Table 2.3). The majority of the fitted trend components are linear or monotonic (Trend DF in Table 2.3 is, or is close to, 1), though a few of the fitted trends are highly non-linear (e.g. site 7427580). Of the 231 sites in Benchmark Catchments, 132 have significant fitted trends, which is 57%.

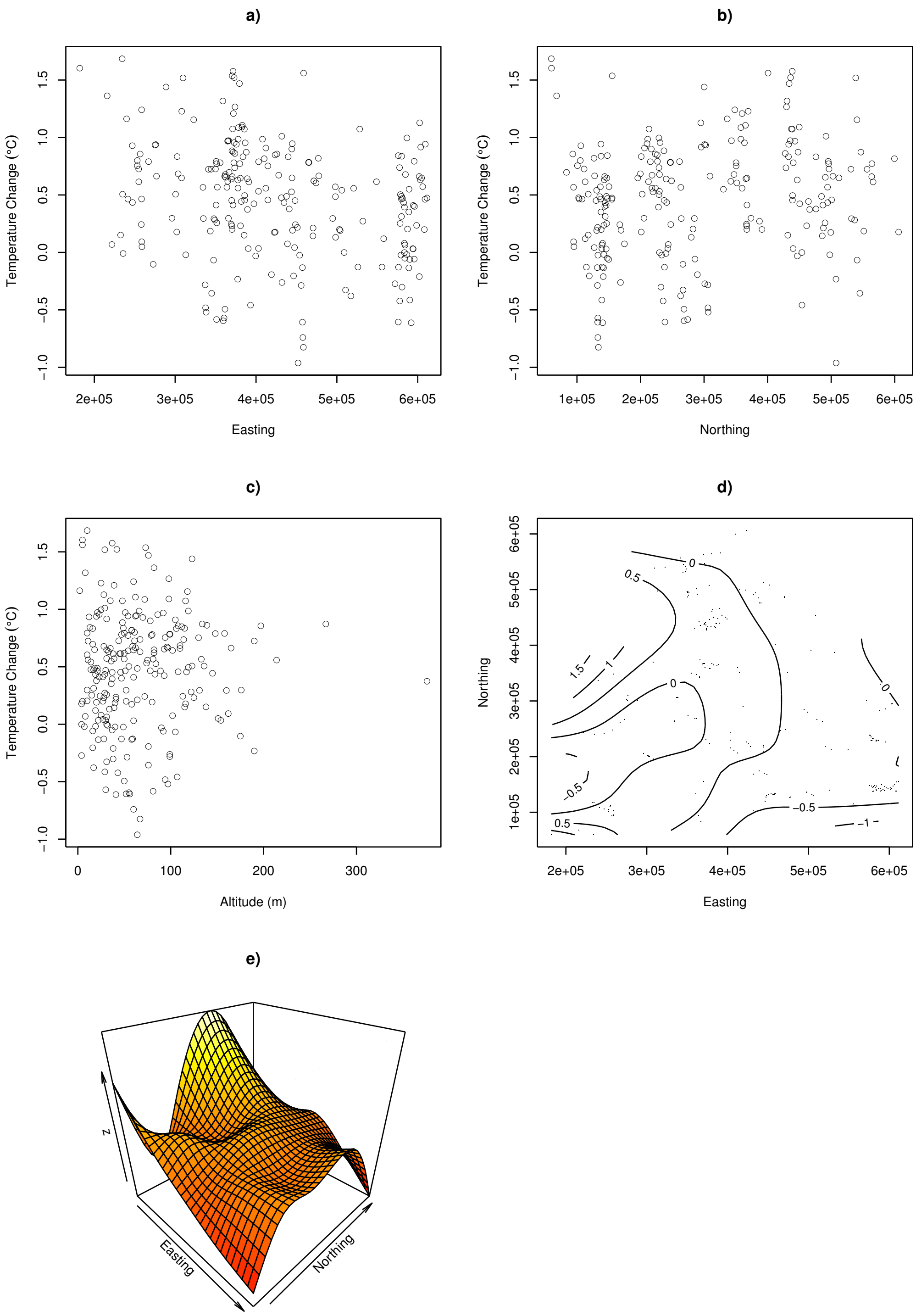

Figure 2.8: Analysis of spatial patterns in the modelled temperature changes; a) British National Grid easting, b) British National Grid northing, c) site altitude, d) and e) fitted tensor product smooth surface.

Table 2.2: Summary statistics by Benchmark Catchment of modelled trends in water temperature (℃) at sampling locations within Benchmark Catchments. Q1 and Q3 are the upper and lower quartiles respectively.

	n	Min.	Q1	Mean	Median	Q3	Max.
Aire	4	-0.46	-0.14	0.08	0.17	0.39	0.42
Ancholme	1	0.20	0.20	0.20	0.20	0.20	0.20
Beult	17	-0.61	-0.02	0.20	0.25	0.46	0.84
Brue	1	-0.57	-0.57	-0.57	-0.57	-0.57	-0.57
Bull	2	-0.13	-0.07	-0.00	-0.00	0.06	0.12
Cheriton Stream	1	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13
Cole	1	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19
Coln	3	0.79	0.85	0.89	0.91	0.95	0.99
Colne	12	-0.61	-0.17	0.22	0.20	0.69	1.00
Coquet	2	0.18	0.34	0.50	0.50	0.66	0.82
Cynon	6	0.18	0.35	0.52	0.58	0.68	0.83
Dane	12	0.20	0.28	0.67	0.64	1.01	1.21
Dove	4	0.14	0.20	0.42	0.39	0.61	0.75
Dun	1	-0.26	-0.26	-0.26	-0.26	-0.26	-0.26
Dyfi	4	0.66	0.87	0.99	0.94	1.06	1.44
Eden	1	-0.23	-0.23	-0.23	-0.23	-0.23	-0.23
Ellen	2	1.15	1.25	1.34	1.34	1.43	1.52
Erch	1	1.16	1.16	1.16	1.16	1.16	1.16
Esk	1	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Evenlode	6	0.53	0.72	0.79	0.85	0.89	0.95
Foston Beck	1	-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
Gannel	1	1.60	1.60	1.60	1.60	1.60	1.60
Glaslyn	1	1.24	1.24	1.24	1.24	1.24	1.24
Great Stour	14	-0.21	0.21	0.39	0.44	0.62	0.94
Greet	1	0.60	0.60	0.60	0.60	0.60	0.60
Harpers Brook	2	0.13	0.17	0.21	0.21	0.25	0.30
Isbourne	2	0.03	0.16	0.28	0.28	0.41	0.53
Itchen	9	-0.83	-0.61	-0.22	-0.20	0.04	0.45
Kent	6	0.26	0.45	0.59	0.65	0.76	0.79
Kym	2	-0.38	-0.37	-0.35	-0.35	-0.34	-0.33
Lambourn	3	0.07	0.13	0.17	0.19	0.22	0.24
Leadon	5	0.45	0.56	0.70	0.64	0.88	0.96
Leven	2	-0.96	-0.56	-0.16	-0.16	0.25	0.65
Loxwood Stream	4	0.19	0.41	0.45	0.51	0.55	0.57
Lud	1	0.27	0.27	0.27	0.27	0.27	0.27
Lugg	2	0.29	0.36	0.43	0.43	0.50	0.57
Lune	2	0.65	0.66	0.66	0.66	0.66	0.66
Lymington	1	0.48	0.48	0.48	0.48	0.48	0.48
Mimram	2	0.56	0.69	0.82	0.82	0.94	1.07
Mole	1	-0.13	-0.13	-0.13	-0.13	-0.13	-0.13
Petteril	7	-0.36	0.06	0.25	0.28	0.51	0.72
Pincey Brook	1	0.61	0.61	0.61	0.61	0.61	0.61
Rea Brook	3	-0.52	-0.50	-0.43	-0.48	-0.38	-0.28
Ribble	23	0.03	0.56	0.86	0.87	1.08	1.58
Rother	2	0.67	0.70	0.74	0.74	0.78	0.82
South Tyne	4	0.61	0.65	0.73	0.72	0.80	0.87
Stringside	1	-0.27	-0.27	-0.27	-0.27	-0.27	-0.27
Swale	7	0.17	0.41	0.54	0.46	0.66	1.01
Sydling Water	1	0.57	0.57	0.57	0.57	0.57	0.57
Teifi	6	-0.10	0.01	0.24	0.16	0.39	0.79
Teme	3	-0.60	-0.59	-0.56	-0.58	-0.54	-0.49
Thet	4	-0.06	0.14	0.55	0.56	0.97	1.13
Tiddy	1	1.69	1.69	1.69	1.69	1.69	1.69
Torne	1	1.56	1.56	1.56	1.56	1.56	1.56
Torridge	12	0.05	0.39	0.53	0.56	0.77	0.93
Tove	2	0.62	0.66	0.70	0.70	0.74	0.78
Warleggan	1	1.36	1.36	1.36	1.36	1.36	1.36
Weaver	4	0.62	0.66	0.76	0.73	0.83	0.97
Wellow Brook	1	1.54	1.54	1.54	1.54	1.54	1.54
Wensum	1	0.55	0.55	0.55	0.55	0.55	0.55
Wey	1	0.70	0.70	0.70	0.70	0.70	0.70
Wheeler	1	1.23	1.23	1.23	1.23	1.23	1.23

Table 2.3: Output from the additive mixed models fitted to the time series data from the Water Temperature Archive sampling locations in Benchmark Catchments. Trend DF is the complexity of the fitted trend component of the model (1 = linear trend), F and p are the F statistic and it's p-value for the trend smooth, and Sig. is an indicator of whether the trend component is significant at the $alpha = 0.05$ (95%) level.

Site ID	Trend DF	F	p	Sig. ($\alpha = 0.05$)
04M02	3.06	7.60	0.00	Yes
04M04	1.00	4.93	0.03	Yes
13612280	1.00	1.16	0.28	No
13612980	1.60	0.92	0.38	No
13618180	1.00	2.38	0.12	No
17029	3.25	2.24	0.08	No
17031	2.61	3.97	0.01	Yes
17032	2.18	3.24	0.04	Yes
17034	1.61	0.90	0.39	No
17165	1.98	1.96	0.14	No
17169	1.00	0.48	0.49	No
20123	3.23	3.93	0.01	Yes
20197	1.00	19.24	0.00	Yes
20219	3.54	5.93	0.00	Yes
20255	3.52	5.78	0.00	Yes
2055	1.00	36.97	0.00	Yes
21M01	2.06	2.24	0.11	No
21M05	2.07	2.99	0.05	No
22683	1.00	20.06	0.00	Yes
23041	1.00	24.03	0.00	Yes
2847060	1.00	2.35	0.13	No
2848860	1.00	6.71	0.01	Yes
2851100	1.00	4.99	0.03	Yes
2851360	1.00	1.24	0.27	No
2852360	1.00	3.21	0.07	No
29272820	2.16	4.66	0.01	Yes
29272960	2.56	6.46	0.00	Yes
29577380	1.00	1.24	0.27	No
34401	1.72	7.79	0.00	Yes
34403	1.00	11.37	0.00	Yes
34404	1.00	1.13	0.29	No
34405	1.00	3.82	0.05	No
34406	1.00	0.00	0.97	No
37499950	2.93	9.73	0.00	Yes
42300080	2.88	5.31	0.00	Yes
42300083	1.00	7.05	0.01	Yes
43200040	1.00	3.22	0.07	No
43200043	1.00	2.09	0.15	No
43200045	1.00	2.65	0.10	No
43200046	1.00	4.92	0.03	Yes
43532250	1.00	2.19	0.14	No
44M01	1.00	5.99	0.02	Yes
44M02	1.00	14.37	0.00	Yes
44M06	1.00	0.04	0.84	No
44M08	1.00	0.73	0.39	No

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Table 2.3: (Continued)

Site ID	Trend DF	F	p	Sig. ($\alpha = 0.05$)
45400081	1.00	1.70	0.19	No
45400091	1.00	2.20	0.14	No
49200033	1.00	0.00	1.00	No
49400715	1.00	5.83	0.02	Yes
49400718	1.00	0.04	0.85	No
49400729	2.44	3.51	0.02	Yes
49400744	1.00	1.52	0.22	No
49600129	1.94	2.31	0.10	No
49600151	1.00	0.94	0.33	No
49900032	1.00	4.24	0.04	Yes
49900178	1.00	0.77	0.38	No
49900183	1.00	6.15	0.01	Yes
49900186	2.79	6.35	0.00	Yes
49900188	1.00	10.95	0.00	Yes
49900203	1.00	6.60	0.01	Yes
49900212	1.00	5.24	0.02	Yes
49M03	1.00	0.85	0.36	No
50037	4.80	4.47	0.00	Yes
50038	4.20	4.03	0.00	Yes
50540108	1.00	7.48	0.01	Yes
50600278	4.34	8.99	0.00	Yes
54520250	1.00	6.26	0.01	Yes
54521950	1.00	3.68	0.06	No
60030459	4.85	4.44	0.00	Yes
61671530	1.00	0.19	0.66	No
72920377	1.91	2.64	0.08	No
72923004	1.00	7.32	0.01	Yes
72930188	2.23	4.22	0.01	Yes
72930420	1.00	0.54	0.47	No
72930805	3.84	6.83	0.00	Yes
72931508	1.00	6.63	0.01	Yes
72934611	1.00	4.79	0.03	Yes
72937110	1.00	3.94	0.05	Yes
72940121	1.00	4.81	0.03	Yes
72940220	1.00	0.22	0.64	No
72940327	1.00	9.67	0.00	Yes
72943002	1.00	0.05	0.82	No
7423020	5.86	6.25	0.00	Yes
7427580	10.41	7.79	0.00	Yes
81522326	2.88	11.84	0.00	Yes
82410232	1.00	45.21	0.00	Yes
83001	1.97	2.78	0.06	No
88000629	1.00	7.33	0.01	Yes
88000632	1.00	8.39	0.00	Yes
88000637	1.00	7.44	0.01	Yes
88000638	1.00	23.40	0.00	Yes
88000745	1.00	10.38	0.00	Yes
88000755	1.00	24.58	0.00	Yes
88000760	1.00	28.55	0.00	Yes
88000764	1.00	9.11	0.00	Yes

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Table 2.3: (Continued)

Site ID	Trend DF	F	p	Sig. ($\alpha = 0.05$)
88000769	1.00	1.72	0.19	No
88000770	1.00	0.99	0.32	No
88000780	5.10	4.81	0.00	Yes
88000792	2.45	25.21	0.00	Yes
88000793	1.00	37.67	0.00	Yes
88000808	1.00	34.86	0.00	Yes
88000812	1.00	1.31	0.25	No
88000822	1.00	3.14	0.08	No
88003415	2.09	2.17	0.11	No
88003416	1.00	1.95	0.16	No
88003423	1.56	5.01	0.01	Yes
88003426	2.47	4.60	0.01	Yes
88003430	1.75	1.12	0.32	No
88003441	1.00	8.44	0.00	Yes
88003442	4.11	15.96	0.00	Yes
88003464	2.09	3.96	0.02	Yes
88003466	1.93	3.44	0.03	Yes
88003471	1.00	0.59	0.44	No
88003478	2.41	4.32	0.01	Yes
88003483	1.83	1.65	0.20	No
88003487	1.00	0.02	0.88	No
88003491	1.46	1.91	0.16	No
88003492	1.00	16.51	0.00	Yes
88003497	2.70	9.02	0.00	Yes
88003504	2.13	3.44	0.03	Yes
88003508	4.43	5.45	0.00	Yes
88003514	3.53	6.86	0.00	Yes
88003518	3.24	5.20	0.00	Yes
88003521	4.80	16.97	0.00	Yes
88003526	1.87	2.78	0.07	No
88003532	9.68	11.24	0.00	Yes
88003953	1.00	8.96	0.00	Yes
88003957	1.00	8.31	0.00	Yes
88004371	1.87	3.60	0.03	Yes
88004372	2.60	5.54	0.00	Yes
88004374	1.99	3.25	0.04	Yes
88004392	1.00	6.00	0.01	Yes
88004395	1.00	1.20	0.27	No
88004397	1.00	4.98	0.03	Yes
88005046	1.00	0.01	0.92	No
88005782	1.54	16.72	0.00	Yes
88005808	1.96	8.78	0.00	Yes
88006160	1.00	1.36	0.24	No
88006353	1.00	16.27	0.00	Yes
88006359	1.00	2.55	0.11	No
88006369	1.00	1.47	0.23	No
88006370	1.00	0.09	0.77	No
88006375	1.00	2.89	0.09	No
88006376	3.62	3.63	0.01	Yes
88006381	6.07	4.28	0.00	Yes

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Table 2.3: (Continued)

Site ID	Trend DF	F	p	Sig. ($\alpha = 0.05$)
91261128	3.00	9.49	0.00	Yes
A3200202	2.49	16.87	0.00	Yes
ANCO1	1.00	0.53	0.47	No
BB0104	1.00	1.26	0.26	No
BB0136	1.00	1.65	0.20	No
BB0144	1.00	3.71	0.06	No
CL0230	1.00	6.31	0.01	Yes
CL0488	1.00	9.24	0.00	Yes
CL04	1.00	23.44	0.00	Yes
CL06	1.81	3.67	0.03	Yes
CL0736	2.19	1.77	0.17	No
CL07	4.72	4.58	0.00	Yes
CL0814	1.00	0.09	0.77	No
CL0848	1.80	1.80	0.17	No
CL08	2.07	2.99	0.05	Yes
E0000476	1.00	2.02	0.16	No
E0000534	1.00	13.69	0.00	Yes
E0000536	1.00	0.82	0.37	No
E0000540	1.00	1.28	0.26	No
E0000544	1.00	2.17	0.14	No
E0000546	1.00	0.00	0.95	No
E0000551	1.00	0.27	0.61	No
E0000553	1.00	0.02	0.90	No
E0000565	1.00	3.05	0.08	No
E0000570	1.00	0.03	0.87	No
E0000579	1.00	0.08	0.78	No
E0000584	1.00	0.07	0.80	No
E0000592	1.00	12.64	0.00	Yes
E0000597	1.00	3.19	0.07	No
E0000617	1.00	1.91	0.17	No
E0000618	1.00	1.77	0.18	No
E0000622	1.00	5.20	0.02	Yes
E0001273	1.00	7.25	0.01	Yes
E0001285	1.00	7.65	0.01	Yes
E0001291	1.00	4.79	0.03	Yes
E0001292	1.00	13.80	0.00	Yes
E0001296	1.00	11.46	0.00	Yes
E0001306	1.00	0.58	0.45	No
E0001309	1.00	5.47	0.02	Yes
E0001311	6.07	3.56	0.00	Yes
E0001313	1.00	2.01	0.16	No
E0001322	1.00	0.05	0.83	No
E0001418	1.00	10.51	0.00	Yes
E0001425	1.00	0.46	0.50	No
E0001426	3.95	1.77	0.13	No
E0001427	1.00	0.36	0.55	No
F0002098	1.00	0.34	0.56	No
F0002099	1.00	0.31	0.58	No
F0002924	1.00	23.22	0.00	Yes
F0002928	1.00	10.55	0.00	Yes

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Table 2.3: (Continued)

Site ID	Trend DF	F	p	Sig. ($\alpha = 0.05$)
F0003107	1.00	0.72	0.40	No
F0003111	1.00	4.71	0.03	Yes
F0003113	1.00	4.85	0.03	Yes
F0003142	1.00	6.82	0.01	Yes
G0003793	4.19	4.42	0.00	Yes
G0003795	1.00	0.05	0.82	No
G0003806	1.70	0.83	0.42	No
G0003809	1.00	0.02	0.89	No
G0003810	1.00	3.08	0.08	No
G0003817	5.79	6.00	0.00	Yes
G0003851	1.00	2.61	0.11	No
G0003857	5.82	5.31	0.00	Yes
G0003858	1.00	7.95	0.01	Yes
G0003860	1.00	6.56	0.01	Yes
G0004186	1.00	4.93	0.03	Yes
HARP140B	1.00	0.96	0.33	No
HARP200A	1.00	0.25	0.62	No
LUDO1	1.00	1.30	0.25	No
PEVR0002	1.00	22.93	0.00	Yes
PEVR0006	1.00	36.35	0.00	Yes
PEVR0010	1.00	25.57	0.00	Yes
PEVR0011	1.00	11.87	0.00	Yes
PEVR0018	1.00	34.21	0.00	Yes
PEVR0019	1.00	6.01	0.01	Yes
PKER0009	2.06	1.83	0.16	No
PKER0058	1.00	0.97	0.32	No
PKER0059	1.00	2.46	0.12	No
PKER0063	1.00	0.30	0.58	No
PLER0089	1.00	6.85	0.01	Yes
PLER0091	1.00	30.58	0.00	Yes
PLER0107	1.00	5.10	0.02	Yes
PMLR0016	3.53	2.97	0.02	Yes
PUTR0036	1.00	10.70	0.00	Yes
PUTR0037	3.40	6.60	0.00	Yes
PUTR0040	1.00	6.52	0.01	Yes
WEN040	1.00	6.21	0.01	Yes

Chapter 3

Seasonal trends and patterns in water temperatures

3.1 Introduction

The models fitted in the first phase of the Water Temperature Archive Project were formulated to model trends in the long-term underlying level or mean temperature throughout each time series. These models did not allow for changes in the seasonal pattern of temperatures through time. Here we present the results of two analyses that use models formulated to allow changes in the seasonal patterns of temperatures. The seasonal patterns we address with these models are, i) different trends in each of the four seasons, and ii) change in the seasonal smoother as a function of time. The former model allows the fitted trend to be stronger or have a different non-linear form in each of the four seasons representing a hypothesis that water temperatures have changed more quickly at different times of the year. The latter model allows the seasonal cycle of temperatures to vary through time. This model is complex and is able to capture a range of variations in the seasonal pattern of temperatures.

3.2 Methods

The work programme for the seasonal analysis required fitting additive models with additional flexibility to model trends seasonally and to investigate patterns of change in the seasonal component of the water temperature time series through time. Two modelling approaches were used, each formulated to investigate a different change in the seasonal component of the water temperature time series; varying coefficient additive models, and additive models incorporating a two-dimensional smooth fitted to the combination of the *trend* and *seasonal* components. Each of these models is briefly described below.

3.2.1 Varying Coefficient Models

In a varying coefficient model, smoothers are fitted to subsets of the original data conditional upon the value of an additional covariate. The additional covariate, usually a factor or indicator variable, indicates the subset of the data to which an individual trend smoother is fitted. Here we used the **season** (Spring, Summer, Autumn, Winter) as our covariate, such that a separate smoother was fitted to the data within each season, resulting in four separate trends being estimated from each time series. **season** was also included in the model as a factorial covariate so that the seasonal smoothers were centred about the seasonal mean temperature. An example of the fitted smooths is show in Figure 3.1 for the site 04M02.

3.2.2 Multivariate Smoother Models

As well as a difference in the shape of the trend, other changes in the seasonal component of the water temperature data may also be of interest. The models fitted in earlier phases of the project employed a seasonal smoother that was fixed to remain the same throughout the time series. Changes

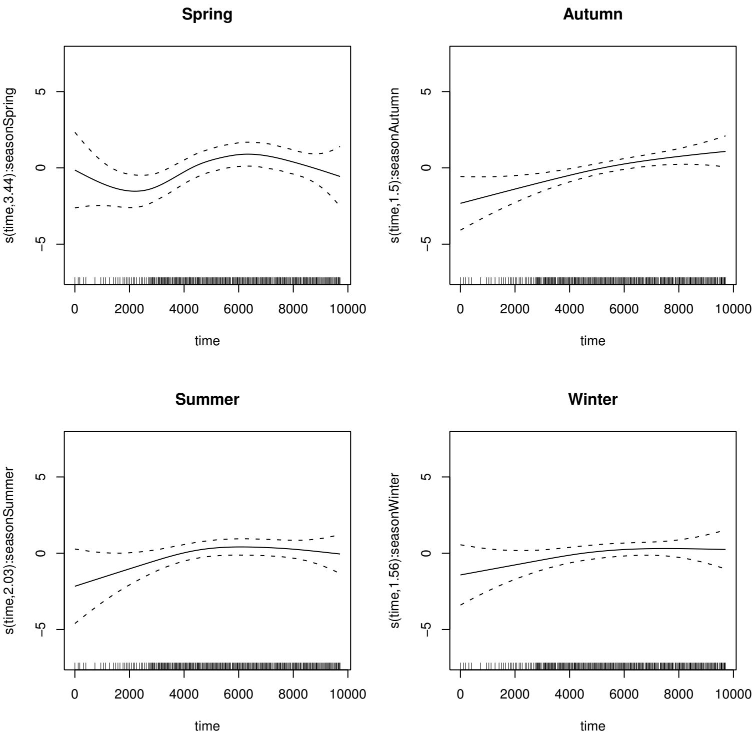

Figure 3.1: Illustration of the varying coefficient model fitted to the temperature data for site 04M02, showing the four smoothers fitted the data within each season.

in temperatures may act to alter the shape of the seasonal cycle of rising and falling temperatures, altering the timing within the year when temperatures begin to change or extending the length of time where warmer temperatures are observed (e.g. increasing the length of the "summer" period. Such shifts are not modelled in either the simple, annual trend models or the varying coefficient models described above.

To model such shifts we employed an additive model that incorporated a two-dimensional smoother fitted to both *season* **and** *time*. A tensor product smooth was used to generate the two-dimensional smoother, with a cyclic cubic regression spline used as the basis for the seasonal part and a cubic regression spline for the trend part of the tensor product smooth. One way to think of this model is a piece of A4 paper, curved along the shorter dimension so that the paper forms a tunnel along the longer dimension of the piece of paper. The tunnel represents the passage of time. The two-dimensional smoother allows us to warp the tunnel such that it can get wider or narrow along its length as well as raising or lowering the base of the tunnel. An example of the fitted smooths is show in Figure 3.2 for the site 04M02.

In order to assess whether any shifts in the seasonal pattern were detected using the multivariate smooth models, we fitted a simpler model using tensor product smooths of the trend and seasonal components independently of one another. We were careful to insure that the bases for the smoothers used in this model were the same as the bases that were used to produce the multivariate smoother in the more complex model. This simpler model is therefore fully nested within the more complex model and we can compute a likelihood ratio test or use information statistics to investigate whether the multivariate smooth is supported over the simpler model; i.e. whether the model that allows for changes in the seasonal component over time fits the data better than the model that does not allow the seasonal component to change.

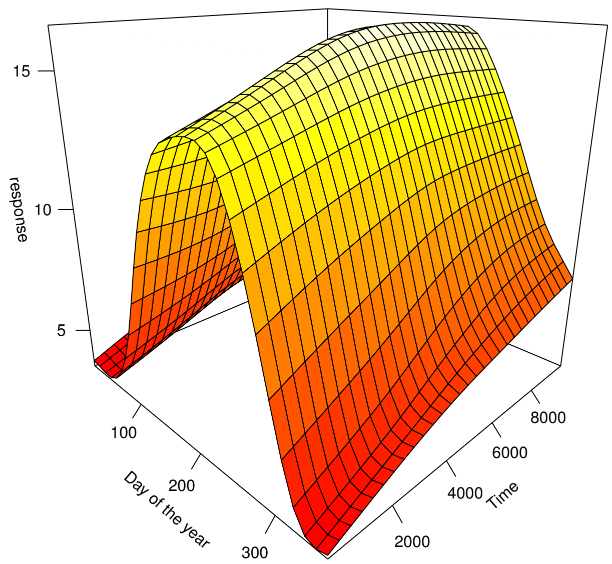

Figure 3.2: Illustration of the multivariate smooth model fitted to the temperature data for site 04M02, showing the response surface fitted to the temperature data.

3.3 Results

3.3.1 Seasonal Trends

The distribution of changes in the trend components for the four seasons over the period 1 January 1990 to 31 December 2006 as derived from the varying coefficient models, for all Benchmark sites, is shown in Figure 3.3. The left hand panel shows the empirical cumulative distribution functions (ECDF) of the distribution of change statistics for the four seasons, whilst the right panel shows a kernel density estimate of the same distribution.

In general, fewer sites showed an increase in summer temperatures than for the other seasons, with Winter and Autumn seeing the greatest proportion of sites showing an increase in temperatures over the period of interest. 40% and 30% of sites respectively had an increase of more than 1℃ in Winter and Autumn. Only 10% of sites did not show an increase in Autumn temperatures.

Figure 3.4 shows the spatial distribution of seasonal trends for the sites in benchmark catchments. These maps emphasise the main results described above. Winter and autumn temperature changes over the period under study show predominantly increases in temperature, with an emphasis towards a greater number of sites showing increased temperatures in winter compared to autumn. Trends in Summer temperatures show a greater predominance of temperature decreases over the period of study, with spring temperature changes somewhat intermediate between the summer and the autumn and winter changes.

3.3.2 Multivariate smooths

Results from the multivariate smoother models and comparisons with simpler models, that do not allow for evolution of the seasonal component, are shown in Table 3.1. The temperature data at 53 sites (23%) were better fitted with the multivariate smoother model than the fixed season model when assessed by AIC (ΔAIC > 2, the difference in AIC between the two models), and 45 sites (19%) when

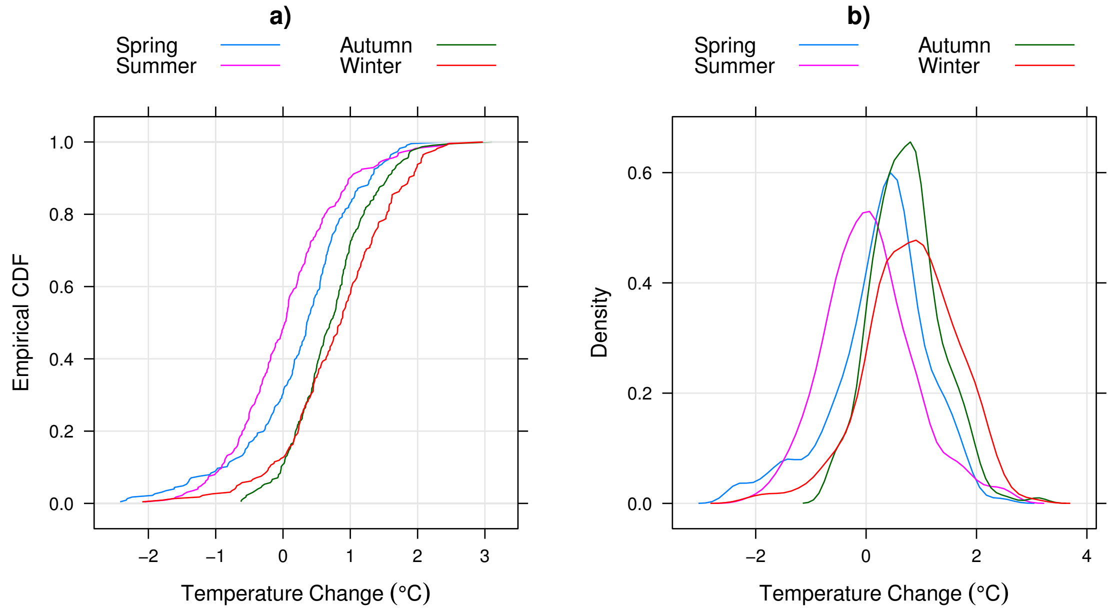

Figure 3.3: Empirical cumulative distribution function (a) and kernel density estimates (b) of the distribution of the change in the trend component of the varying coefficient models fitted to the Benchmark Sites.

assessed using a likelihood ratio test evaluated at the $\alpha = 0.01$ level. The results suggest that at a significant proportion of sites, change in the seasonal pattern of temperatures has been observed and is detectable from the spot sampling data.

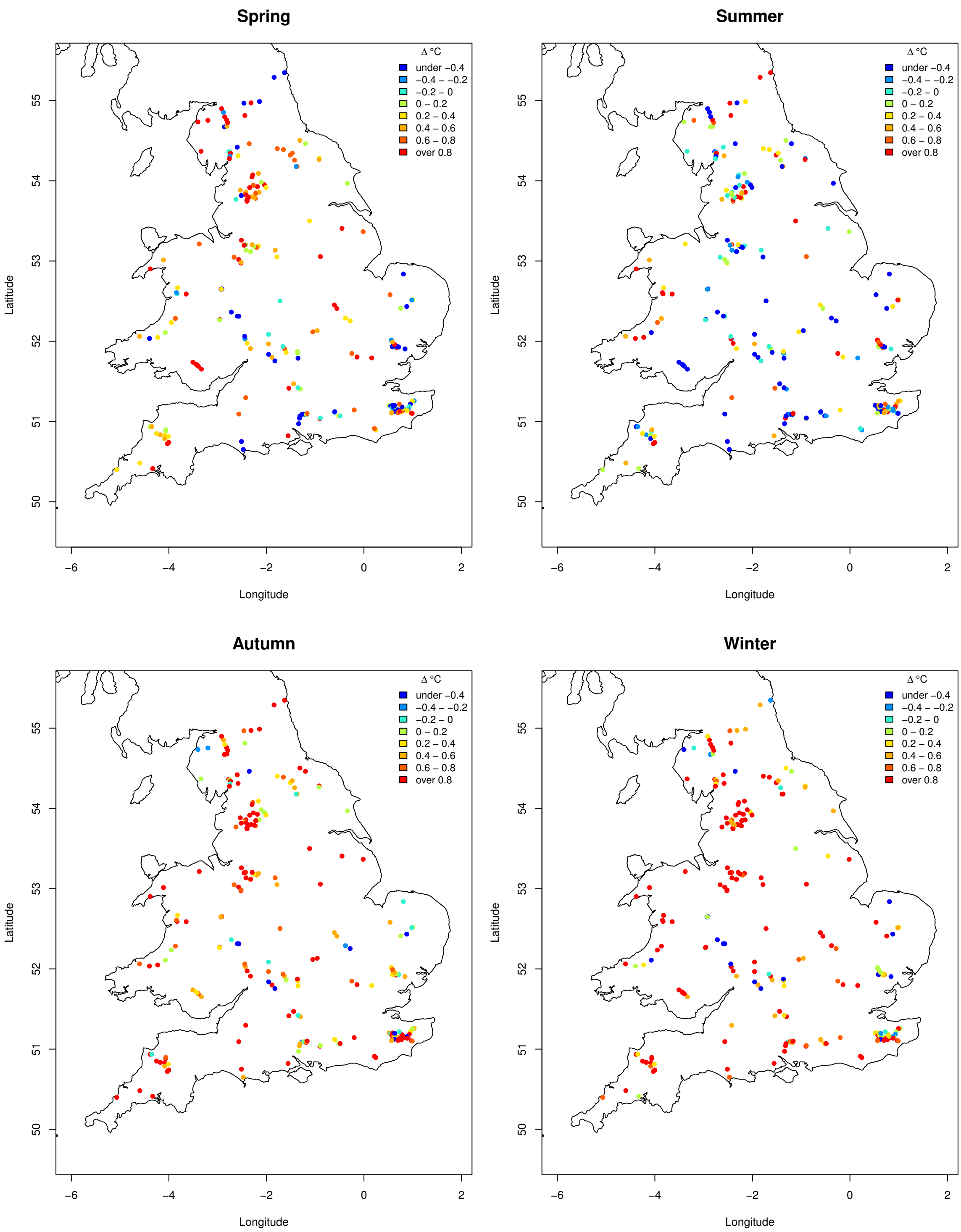

Figure 3.4: Maps showing the Water Temperature Archive sampling locations within Benchmark Catchments with model-derived seasonal temperature change over the period 1st January 1990 – 31st December 2006.

Table 3.1: Summary statistics by Benchmark Catchment of modelled trends in water temperature (℃) at sampling locations within Benchmark Catchments, based on multivariate smoother models. AIC and AIC_{mvr} are the AIC statistics for the univariate and multivariate smooth models respectively, ΔAIC is the difference in AIC between the two models, Deviance is the difference in deviance of the two models and *p*-value is the probability of achieving a difference in deviance as large or larger than the observed if the Null hypothesis were true.

Site ID	AIC	AIC_{mvr}	ΔAIC	Deviance	*p*-value
04M02	1132.83	1143.33	-10.50	16.21	0.84
04M04	1466.70	1474.50	-7.81	-13.83	
13612280	1217.47	1222.15	-4.68	55.92	0.21
13612980	1536.96	1542.70	-5.74	60.12	0.19
13618180	1000.03	1005.32	-5.29	26.70	0.34
17029	2476.17	2501.96	-25.79	-56.34	
17031	1346.71	1352.78	-6.07	37.96	0.25
17032	1489.86	1498.67	-8.81	21.69	0.56
17034	1296.35	1295.82	0.53	53.34	0.03
17165	1145.45	1155.35	-9.90	9.87	0.87
17169	1074.90	1070.97	3.93	42.26	0.02
20123	1184.49	1195.42	-10.93	4.22	0.97
20197	1100.09	1105.34	-5.25	13.44	0.58
20219	1244.95	1259.64	-14.69	-13.05	
20255	1352.75	1369.99	-17.24	-46.94	
2055	1658.62	1666.93	-8.31	19.81	0.60
21M01	1272.84	1278.13	-5.29	46.39	0.26
21M05	1392.75	1391.92	0.83	79.61	0.04
22683	1294.47	1293.32	1.16	34.74	0.06
23041	1391.30	1394.52	-3.22	22.18	0.28
2847060	1227.23	1239.80	-12.57	-44.61	
2848860	1105.08	1113.46	-8.38	-23.56	
2851100	1050.95	1050.75	0.20	35.56	0.08
2851360	1048.37	1046.57	1.80	40.02	0.04
2852360	1112.64	1118.93	-6.29	-8.67	
29272820	1320.60	1318.48	2.12	64.47	0.03
29272960	1263.61	1253.78	9.83	95.80	0.00
29577380	1108.41	1106.98	1.43	32.89	0.06
34401	1874.95	1882.15	-7.20	32.37	0.36
34403	1213.54	1215.41	-1.88	46.74	0.12
34404	1133.60	1132.13	1.46	59.60	0.03
34405	1141.21	1141.71	-0.50	57.47	0.05
34406	1053.08	1056.29	-3.20	28.16	0.19
37499950	1029.05	1030.90	-1.85	65.19	0.06
42300080	2451.67	2395.66	56.01	719.50	0.00
42300083	1997.02	1986.37	10.66	351.04	0.00
43200040	2009.78	1955.06	54.72	1148.10	0.00
43200043	1664.22	1579.60	84.62	1273.19	0.00
43200045	1641.47	1502.74	138.73	1574.87	0.00
43200046	1536.05	1457.81	78.24	1003.59	0.00
43532250	1176.74	1179.28	-2.54	58.44	0.11
44M01	1134.18	1138.81	-4.63	57.86	0.20
44M02	1128.47	1129.67	-1.21	70.56	0.05
44M06	1054.38	1050.23	4.15	57.34	0.01

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Table 3.1: (Continued)

Site ID	AIC	AIC_{mvr}	ΔAIC	Deviance	p-value
44M08	1282.14	1289.17	-7.02	11.20	0.69
45400081	1866.18	1708.50	157.68	2231.10	0.00
45400091	1410.71	1355.86	54.86	1168.72	0.00
49200033	1746.70	1754.64	-7.94	4.31	0.94
49400715	1982.21	1987.89	-5.68	20.01	0.47
49400718	3374.84	3365.50	9.34	92.60	0.00
49400729	2046.59	2058.15	-11.56	14.99	0.91
49400744	1282.04	1287.41	-5.37	39.27	0.41
49600129	928.93	935.77	-6.85	12.87	0.53
49600151	1500.24	1520.73	-20.50	-58.76	0.00
49900032	1580.02	1588.00	-7.98	-0.69	
49900178	1398.12	1406.31	-8.18	-1.00	
49900183	1555.94	1565.03	-9.09	0.36	1.00
49900186	1550.29	1560.18	-9.89	36.43	0.51
49900188	1364.27	1356.80	7.47	63.98	0.00
49900203	1694.46	1706.80	-12.34	24.36	0.79
49900212	1708.78	1713.89	-5.12	66.75	0.14
49M03	1210.80	1201.01	9.79	133.29	0.00
50037	1325.44	1330.72	-5.28	54.46	0.08
50038	1211.97	1217.81	-5.84	51.96	0.09
50540108	1419.40	1431.10	-11.69	-2.19	
50600278	1537.03	1523.32	13.71	91.71	0.00
54520250	820.25	829.07	-8.81	9.69	0.60
54521950	996.28	996.90	-0.63	10.97	0.17
60030459	1110.45	1117.20	-6.75	108.15	0.09
61671530	1445.95	1450.18	-4.23	32.37	0.39
72920377	1534.82	1536.49	-1.67	63.41	0.10
72923004	1183.33	1186.13	-2.80	20.06	0.27
72930188	1303.27	1296.02	7.25	99.89	0.00
72930420	1243.02	1247.24	-4.21	10.21	0.50
72930805	1390.67	1401.01	-10.34	69.51	0.27
72931508	1525.34	1528.64	-3.30	22.31	0.27
72934611	1221.55	1220.17	1.38	55.21	0.03
72937110	1051.18	1050.07	1.11	29.64	0.06
72940121	1350.68	1352.19	-1.50	43.13	0.10
72940220	1349.66	1346.83	2.83	35.41	0.03
72940327	963.55	962.57	0.98	28.52	0.05
72943002	1412.26	1414.29	-2.03	26.91	0.19
7423020	1203.11	1231.67	-28.56	-55.01	
7427580	961.39	1008.57	-47.18	-73.10	
81522326	1272.07	1261.75	10.32	68.98	0.00
82410232	1954.98	2002.55	-47.57	-164.04	0.00
83001	1235.63	1241.91	-6.27	40.83	0.29
88000629	1282.81	1286.84	-4.03	22.63	0.36
88000632	1306.13	1309.28	-3.16	22.49	0.26
88000637	1283.52	1283.61	-0.09	30.92	0.09
88000638	1534.95	1532.59	2.36	49.08	0.03
88000745	1541.29	1540.40	0.89	39.80	0.06
88000755	1464.55	1458.47	6.08	51.63	0.01
88000760	1632.33	1632.37	-0.04	37.16	0.08

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Table 3.1: (Continued)

Site ID	AIC	AIC_{mvr}	ΔAIC	Deviance	p-value
88000764	1228.88	1225.80	3.08	50.34	0.02
88000769	1173.03	1174.51	-1.48	64.66	0.06
88000770	1924.99	1922.61	2.39	55.19	0.03
88000780	1571.52	1580.11	-8.58	44.59	0.32
88000792	1077.93	1061.93	16.00	79.85	0.00
88000793	1134.58	1133.65	0.93	42.55	0.04
88000808	1291.98	1291.35	0.63	70.91	0.03
88000812	1335.54	1338.31	-2.77	47.07	0.13
88000822	3157.95	3157.43	0.52	51.97	0.05
88003415	1797.65	1781.84	15.81	189.51	0.00
88003416	2101.98	2104.70	-2.72	28.40	0.27
88003423	1072.03	1072.79	-0.75	22.64	0.15
88003426	1674.58	1667.05	7.53	119.83	0.00
88003430	1960.14	1963.56	-3.42	62.83	0.17
88003441	1063.82	1063.85	-0.04	33.85	0.08
88003442	7174.37	7110.32	64.05	1048.74	0.00
88003464	1221.76	1223.92	-2.16	63.63	0.08
88003466	1713.14	1692.86	20.29	225.81	0.00
88003471	1705.60	1703.16	2.43	90.48	0.02
88003478	1727.75	1728.48	-0.73	101.76	0.03
88003483	1275.53	1282.91	-7.38	33.63	0.41
88003487	1266.36	1268.38	-2.02	64.40	0.07
88003491	1337.87	1340.09	-2.21	49.62	0.11
88003492	1010.23	1016.16	-5.93	9.86	0.62
88003497	2269.50	2275.73	-6.23	83.67	0.13
88003504	1490.99	1496.82	-5.84	53.72	0.23
88003508	1173.08	1170.81	2.27	73.61	0.01
88003514	1105.18	1114.47	-9.28	35.76	0.39
88003518	2901.79	2922.42	-20.63	-5.94	
88003521	6738.88	6697.99	40.89	692.62	0.00
88003526	1773.41	1775.45	-2.04	60.15	0.11
88003532	7328.43	7248.27	80.16	1064.12	0.00
88003953	1202.36	1201.88	0.48	39.45	0.07
88003957	1518.79	1524.75	-5.95	15.21	0.61
88004371	1135.35	1134.36	0.99	73.69	0.02
88004372	1726.70	1717.65	9.05	130.02	0.00
88004374	1080.33	1080.07	0.25	77.01	0.03
88004392	1097.58	1094.09	3.49	84.50	0.01
88004395	1175.76	1176.22	-0.47	64.62	0.05
88004397	2273.37	2298.17	-24.80	-58.12	
88005046	2100.37	2064.53	35.84	308.66	0.00
88005782	1043.77	1046.53	-2.77	29.05	0.16
88005808	1094.94	1096.35	-1.41	63.52	0.06
88006160	1271.24	1284.55	-13.31	-50.32	
88006353	1148.66	1155.42	-6.76	-14.25	0.00
88006359	1217.19	1227.04	-9.85	-27.60	0.00
88006369	1352.78	1353.31	-0.54	31.95	0.11
88006370	1336.46	1333.20	3.27	55.59	0.02
88006375	1334.19	1333.09	1.10	48.31	0.04
88006376	1317.87	1331.52	-13.65	8.34	0.97

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Table 3.1: (Continued)

Site ID	AIC	AIC_{mvr}	ΔAIC	Deviance	p-value
88006381	2342.27	2365.17	-22.90	-48.73	
91261128	1064.30	1074.43	-10.13	19.01	0.60
A3200202	2625.55	2629.14	-3.59	83.09	0.07
ANCO1	1518.56	1515.37	3.20	85.99	0.02
BB0104	1203.73	1214.16	-10.43	-35.10	
BB0136	1166.82	1166.42	0.39	43.49	0.08
BB0144	1129.26	1131.15	-1.89	51.50	0.13
CL0230	1094.25	1102.64	-8.39	13.98	0.74
CL0488	1695.77	1699.98	-4.21	37.42	0.21
CL04	2127.12	2130.03	-2.91	34.93	0.20
CL06	1547.14	1556.25	-9.11	30.25	0.50
CL0736	1169.51	1171.97	-2.45	65.04	0.06
CL07	1682.92	1683.84	-0.92	142.90	0.01
CL0814	1168.37	1172.05	-3.69	72.41	0.15
CL0848	1176.09	1176.05	0.04	104.32	0.04
CL08	1685.27	1681.65	3.62	139.84	0.01
E0000476	1140.30	1145.76	-5.46	20.95	0.47
E0000534	1443.25	1444.30	-1.06	48.61	0.09
E0000536	1322.85	1329.93	-7.08	27.33	0.49
E0000540	1281.51	1288.19	-6.68	15.14	0.65
E0000544	1338.88	1345.19	-6.31	14.74	0.67
E0000546	1314.06	1319.47	-5.41	19.85	0.49
E0000551	1247.96	1255.33	-7.38	9.41	0.78
E0000553	1269.65	1277.97	-8.32	21.65	0.59
E0000565	1165.92	1169.62	-3.70	21.64	0.28
E0000570	1038.64	1042.20	-3.55	19.35	0.31
E0000579	1361.23	1366.67	-5.44	32.54	0.35
E0000584	1229.88	1229.61	0.27	55.82	0.04
E0000592	1179.36	1181.48	-2.13	36.09	0.11
E0000597	1260.26	1263.87	-3.62	36.66	0.19
E0000617	1250.93	1256.52	-5.59	24.14	0.46
E0000618	1102.70	1111.27	-8.57	9.87	0.81
E0000622	1261.27	1265.99	-4.72	41.62	0.21
E0001273	1671.23	1669.54	1.70	76.42	0.02
E0001285	2017.46	2019.67	-2.22	71.99	0.05
E0001291	1322.48	1315.08	7.40	126.71	0.00
E0001292	2250.07	2253.84	-3.76	54.66	0.14
E0001296	2222.24	2220.30	1.94	113.16	0.01
E0001306	1293.30	1303.90	-10.60	-35.05	
E0001309	2136.47	2146.45	-9.98	-19.01	
E0001311	1300.23	1310.03	-9.80	65.71	0.28
E0001313	1334.74	1333.18	1.56	85.56	0.02
E0001322	1253.56	1252.34	1.21	73.01	0.03
E0001418	1911.73	1911.57	0.16	104.89	0.02
E0001425	1348.91	1363.37	-14.45	-60.53	
E0001426	1371.60	1389.78	-18.18	-60.49	
E0001427	1279.66	1289.72	-10.06	9.46	0.92
F0002098	1429.81	1434.37	-4.56	83.11	0.07
F0002099	1283.16	1286.27	-3.11	61.83	0.08
F0002924	1827.27	1824.95	2.31	79.10	0.01

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Table 3.1: (Continued)

Site ID	AIC	AIC_{mvr}	ΔAIC	Deviance	p-value
F0002928	1801.51	1795.54	5.97	107.69	0.00
F0003107	1795.89	1792.56	3.32	112.00	0.01
F0003111	1170.47	1161.69	8.78	100.76	0.00
F0003113	1353.53	1344.92	8.61	112.66	0.00
F0003142	1378.21	1373.63	4.57	97.53	0.01
G0003793	1934.63	1949.57	-14.93	26.86	0.71
G0003795	1851.56	1840.27	11.29	188.65	0.00
G0003806	1285.77	1291.47	-5.71	38.51	0.23
G0003809	2042.55	2040.34	2.21	46.58	0.02
G0003810	1952.41	1964.30	-11.89	-29.48	
G0003817	1260.94	1247.44	13.50	109.47	0.00
G0003851	1078.59	1071.89	6.70	76.34	0.00
G0003857	1510.94	1511.70	-0.76	112.13	0.01
G0003858	1160.94	1164.89	-3.94	29.24	0.18
G0003860	1145.91	1112.34	33.57	144.47	0.00
G0004186	1915.41	1917.79	-2.38	67.54	0.07
HARP140B	1074.91	1075.30	-0.40	41.33	0.08
HARP200A	1217.84	1219.57	-1.73	33.39	0.14
LUDO1	1336.07	1339.81	-3.74	41.16	0.13
PEVR0002	1509.21	1513.19	-3.97	-10.96	
PEVR0006	1821.30	1831.57	-10.27	-7.73	
PEVR0010	1824.93	1826.21	-1.28	56.69	0.06
PEVR0011	1661.34	1659.44	1.91	28.76	0.05
PEVR0018	1608.20	1606.20	2.00	32.80	0.04
PEVR0019	1133.59	1136.16	-2.57	17.40	0.20
PKER0009	1473.66	1452.64	21.02	157.60	0.00
PKER0058	1246.99	1258.16	-11.17	-26.74	
PKER0059	1896.87	1905.86	-8.99	-8.12	
PKER0063	1213.35	1228.42	-15.07	-28.97	0.00
PLER0089	1430.90	1434.33	-3.42	62.28	0.10
PLER0091	1462.18	1460.88	1.30	39.45	0.05
PLER0107	1249.51	1246.72	2.79	32.53	0.04
PMLR0016	1274.73	1277.86	-3.13	34.48	0.19
PUTR0036	1281.02	1288.26	-7.24	9.27	0.82
PUTR0037	1490.41	1507.97	-17.56	-7.46	
PUTR0040	1135.26	1146.82	-11.56	-30.91	
WEN040	1560.85	1549.09	11.76	89.44	0.00

Chapter 4

River flow and temperature trends

4.1 Introduction

The aim of this section of the report is to examine trends in river flows in the benchmark network (Bradford and Marsh 2003) to allow comparison with water temperature trends. Here we focus on at-site trends and the spatial patterns which result from mapping these at a national scale. Previous work (Hannaford and Marsh 2006; 2008) assessed trends over much longer time periods (to the early 1960s and 1970s), so it was necessary to assess trends over an equivalent time period to the temperature data. The first part of this section focuses on river flow trends, whilst the second part considers relationships with water temperatures.

4.2 Methods

Annual and seasonal river flow datasets were derived for all benchmark catchments in England and Wales. As with Hannaford and Marsh (2006; 2008), the Mann-Kendall Trend test was employed. However, as the records are short, significance testing was not carried out; moreover, there are arguments in the literature for not using significance testing in hydro-climatic trend testing, due to the effects of multi-decadal variability (Chen and Grasby 2009) and long-term persistence (Cohn and Lins 2005), and their effects on significance tests. Instead, the magnitude of the trend was computed, using the Thiel-Sen (Theil 1950; Sen 1968) non-parametric estimator of slope. The slope was used to find the absolute change over the period in question, which was then expressed as a percentage of the long term average (LTA) (% LTA) to account for the widely varying magnitude of absolute run-off across England and Wales.

4.3 Results

The results of the trend tests for annual and seasonal river flows are presented in Figures 4.1 and 4.2.

4.3.1 Annual flow trends

The annual trends are interesting in that they show some departures from the spatial patterns observed in annual run-off by Hannaford and Marsh (2006). This is clearly a factor of the different record used. In the previous study, positive trends were found in most northern and western regions. In the present study, some negative trends are found in these regions, and some of the strongest trends are observed towards the east. These short-term trends are undoubtedly affected by starting in a very dry period (during the 1988–1992 drought), and also by finishing in 2006. Whilst 2003–2004 6 droughts occurred in this period, the trend lines are likely to be drawn up by the very wet period from 1998–2002. The reason for the pronounced upward trends in eastern areas may be due to the predominance of groundwater catchments; in these areas, the annual flows in the 1990s was low for several years, due to the persistence of the drought. This is shown in Figure 4.3, with two high-BFI (Base Flow Index) catchments in Anglian region.

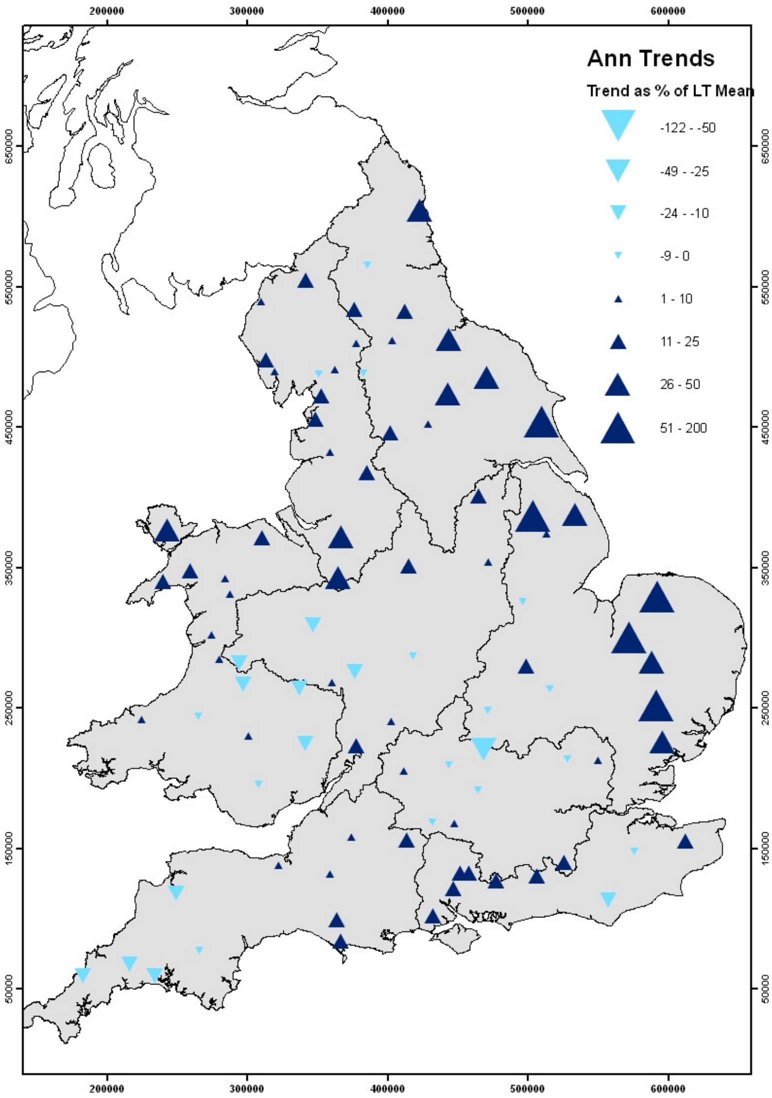

Figure 4.1: Annual average flow trends in the Benchmark Network, 1990–2006

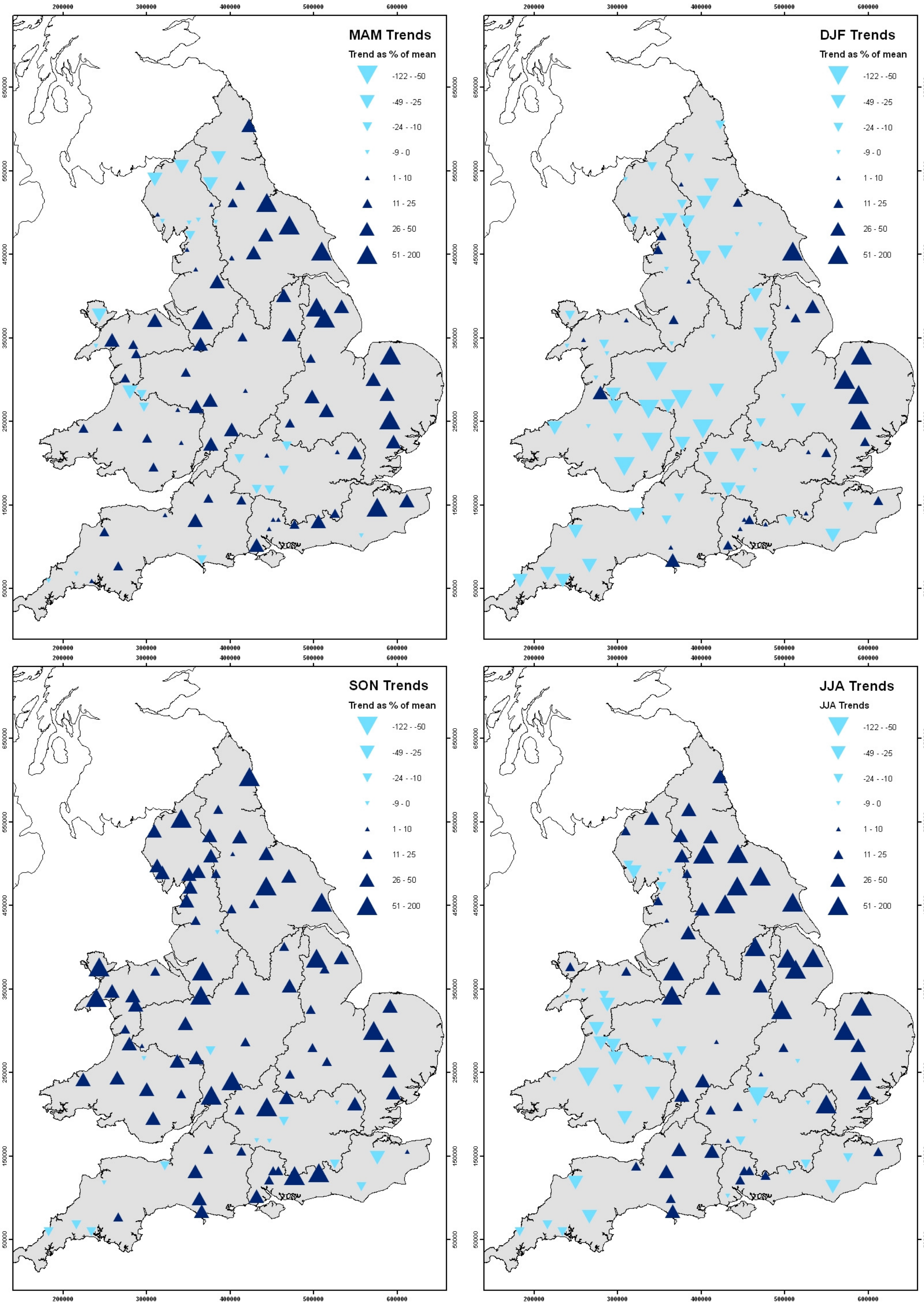

Figure 4.2: Seasonal river flow trends, 1990–2006

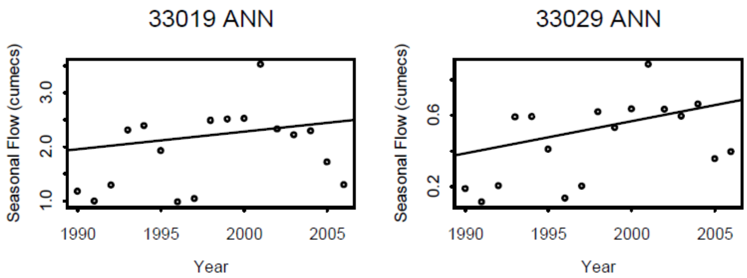

Figure 4.3: Annual trends for two Anglian catchments, 1990–2006

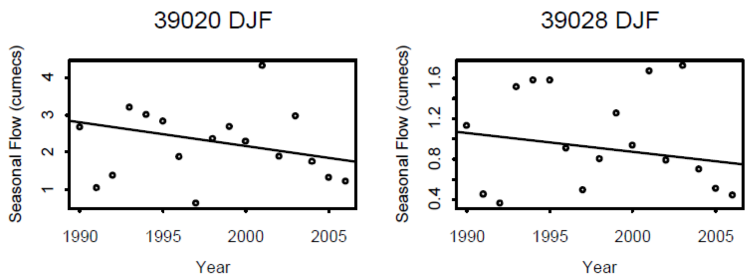

Figure 4.4: Winter trends for two Thames catchments, 1990–2006

In contrast, in western and some central areas, the early 1990s were not as dry, and in fact there were some notably wet years in the early to mid 1990s, which may account for the negative trends. In general however, the picture at the annual scale is of relative stability — whilst there are positive and negative trends, and some tendency towards increasing flows overall, most trends are fairly weak, except in the east of England and Wales.

4.3.2 Seasonal flow trends

As with the annual trends, these results show some departures from work carried out over a longer time frame. Whilst Hannaford and Marsh (2006; 2008) did not consider seasonal trends *per se*, the results observed were thought to be driven by increases in winter rainfall due to the North Atlantic Oscillation (NAO). A related study found winter trends in western areas to be strongly positive (Hannaford et al. 2007), and other work points to similar results over a long period (Dixon et al. 2006). The present results show that winter trends in many western areas (and much of central England) are negative; there are some positive trends in East Anglia, which may be driven by the dry winters in the early 1990s, associated with the early 1990s drought. The negative trends in most areas are driven by the fact there are some wetter years in the early to mid 1990s, whilst the end of the series was associated with several dry winters (associated with the 2004–2006 drought). This is illustrated by the trends in two Thames catchments shown in Figure 4.4.

In spring, positive trends are prevalent across much of the country (although they are generally weak in much of the west), with some pockets of decreasing flows (e.g. the far north west). Strongest trends were again observed in the east. Summer flows exhibit a west-east gradient, with strongly positive increases in the north and east, and negative increases in Wales and the south west, and also the south east. In some western areas, this may be because the early 1990s had comparatively wet summers, with drier summers later in the period (see Figure 4.5)

The autumn trends are positive across most of the country, strongly so in many cases. This is almost undoubtedly due to the effects of the dry autumn periods of the early 1990s. The autumn of 2000, a period associated with major flooding and resulting in the wettest autumn on record, also has some ‘leverage’; although is in the middle of the series, it is such an ‘outlier’ that it can increase the

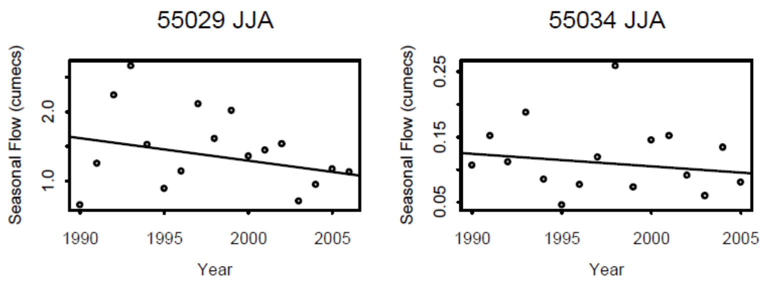

Figure 4.5: Summer trends for two Welsh catchments, 1990–2006

trend in some catchments.

The annual and seasonal trends reveal that patterns are quite different than those observed in the previous work, and this is principally due to the relatively short period used in this study, combined with the fact there are notably dry and/or wet periods at the start and ends of records, depending on which region and season is being tested. It is clear that the broad annual picture masks considerable variation between the seasonal patterns.

4.3.3 Catchment water temperature trends

The catchment average water temperature trends (See Chapter 5) were then plotted using a similar scheme to the flow trends — although note the class intervals are different, and the magnitude is reported differently (as degrees absolute change).

In the annual temperature data, positive trends were prevalent; all but a few catchments showed increasing trends, and these were strong in some cases. There was no obvious spatial pattern, although the highest increases are in western catchments. There is no obvious relationship with the river flow data. Whilst the river flow data also showed a general tendency towards increasing flows, there was more spatial variation and a higher proportion of decreasing flows. As with the flow data, the annual temperature trends mask considerable seasonal variation.

In winter, temperature trends showed the strongest increases (in terms of absolute change) of any season. Water temperatures have increased across all of England and Wales, except for a few isolated cases (including some strong downward trends in the Welsh borders). The predominance of positive trends contrasts with the winter flow data, where many catchments exhibit decreasing flows (with some strong downward trends).

In spring, the directionality of trends is more mixed. However, there were a higher number of positive trends, and they tended to be stronger, although the greatest decrease across the whole dataset was observed for the South Tyne, NE region, in spring. There is no obvious congruency with the patterns seen in the flow data.

Summer temperature trends were the weakest, in absolute terms, across the seasons. The changes were generally smaller, and there was no obvious spatial pattern; there is certainly no reflection of the NE–SW gradient of summer flows. Autumn temperature trends were positive in all but one catchment, and some relatively strong increases were observed. This appears to be consistent with the pattern seen for autumn flows, although caution must be exercised in making this comparison due to the short record, which may mean the prevalence of increasing autumn flows is a result of 'clustering' of dry and wet periods.

The general lack of consistent relationships between flow and temperature is underlined further by scatterplots of river flow trends against water temperature trends (Figure 4.8). Caution must be exercised in making these comparisons, as the two trend estimates are derived using different methods. However, the plots are usefully indicative; there is a high degree of scatter associated with the relationships for all seasons, which again suggests there is no obvious influence of river flow on recent water temperature trends.

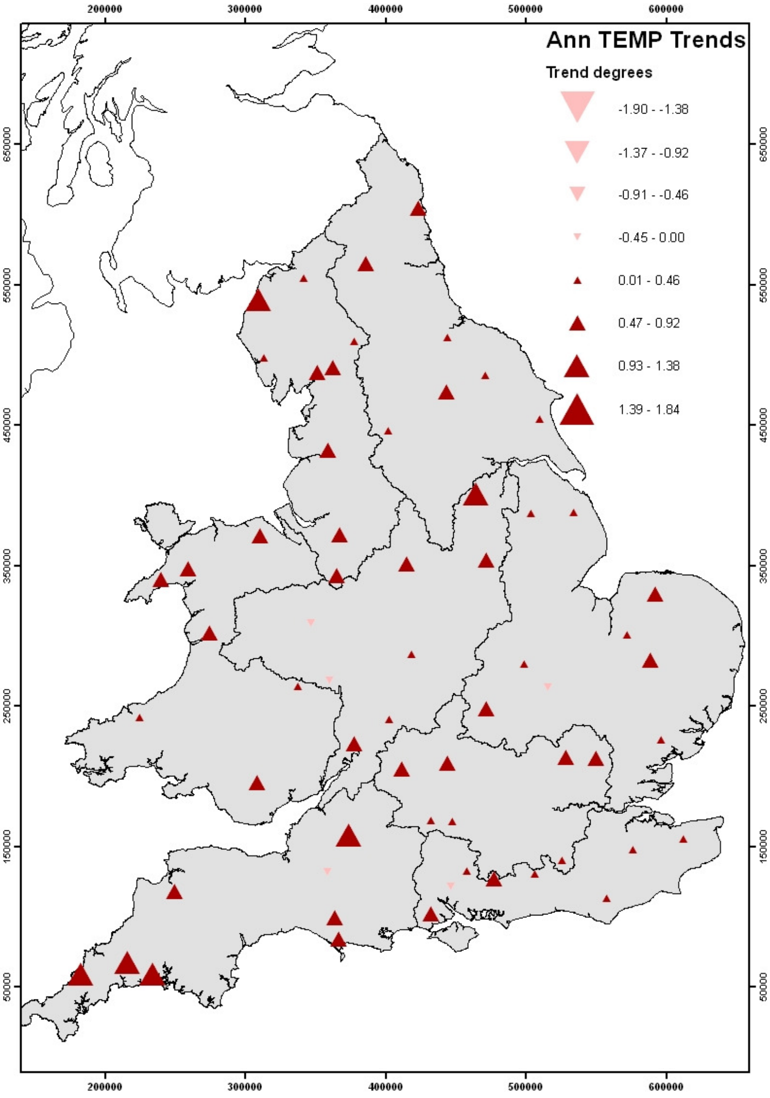

Figure 4.6: Annual average water temperature trends in the Benchmark Network, 1990–2006

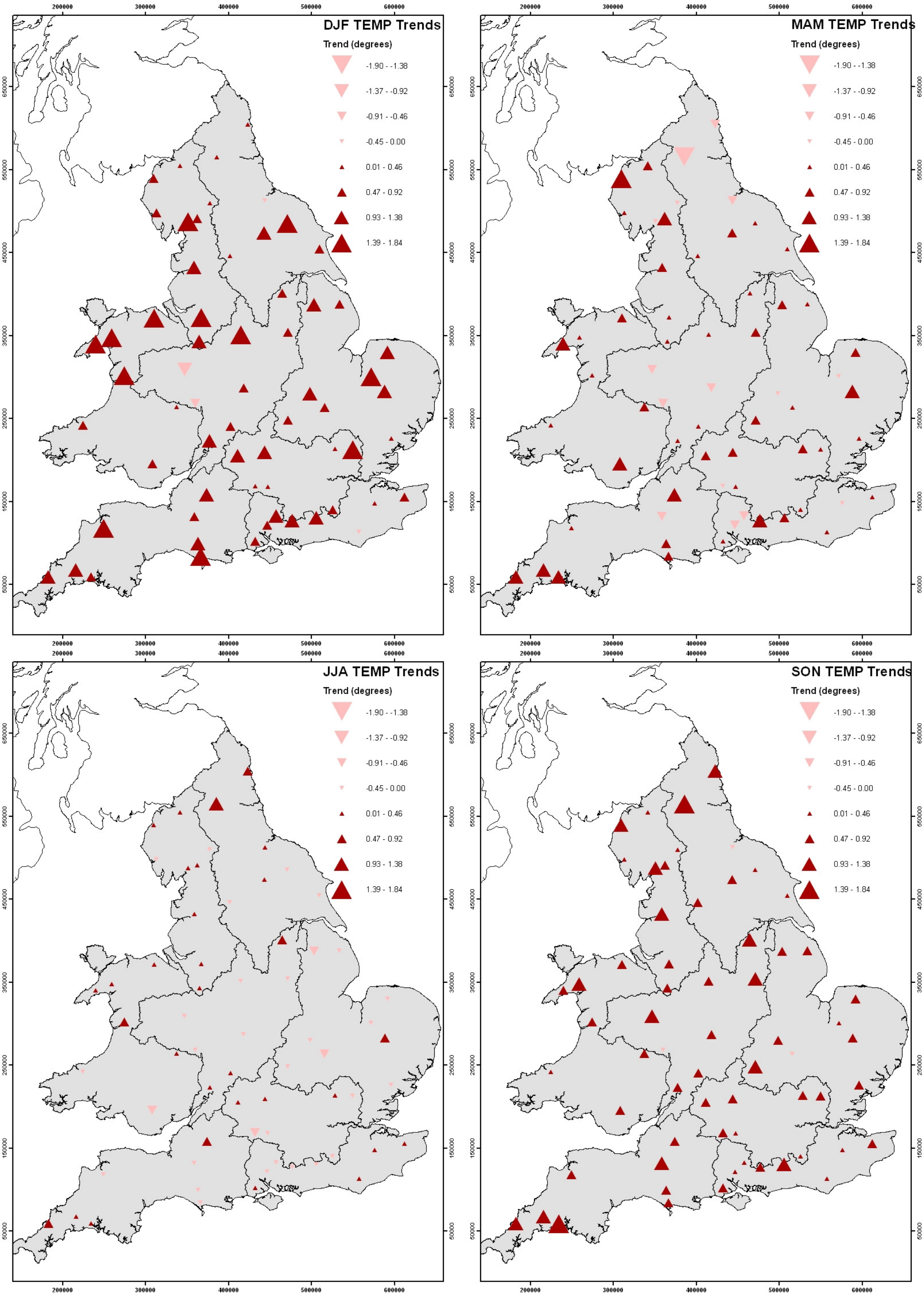

Figure 4.7: Seasonal average water temperature trends in the Benchmark Network, 1990–2006

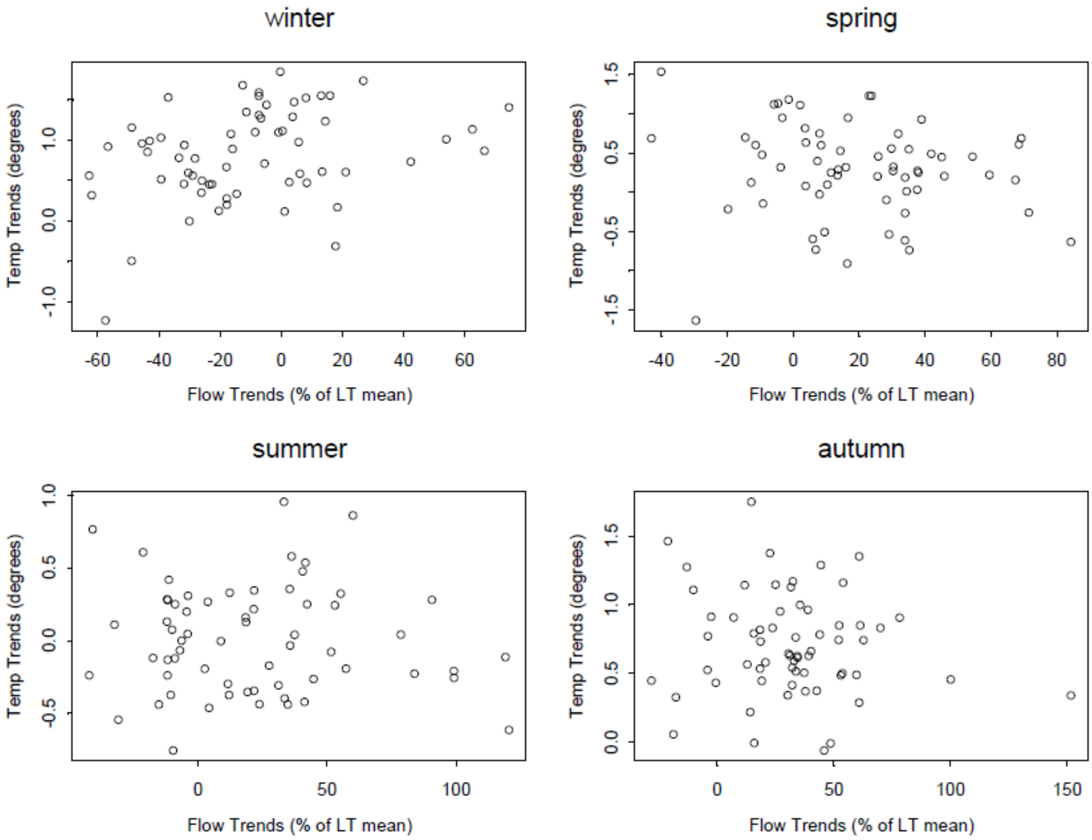

Figure 4.8: Scatterplots for each season, showing relationships between flow trends and water temperature trends

Chapter 5

Patterns in temperature trends within benchmark catchments

5.1 Introduction

The 231 temperature monitoring sites were linked to 63 of the benchmark catchments. 40% of the catchments had one monitoring site, and 20% had two, the remainder following quite a skewed distribution (Figure 5.1) with the maximum number being 23 temperature stations (catchment of site 71001, River Ribble)

The majority of the temperature stations were contained within the benchmark catchments, but 33 were located downstream, but on the same stretch of river (same stream order), the furthest downstream being 7.7km (South Tyne).

The temperature stations were matched to a series of catchment characteristics using the CEH Intelligent River Network. These include altitude, catchment area, stream order, total length of upstream river network. Further, using information from the river network and the Land Cover Map 2000, we derived measures of the proportion of riparian area[1] with land cover of deciduous and coniferous woodland.

A further set of characteristics had already been derived for the benchmark catchment gauging stations, including Flood Estimation Handbook Characteristics, such as Standard Period Annual Rainfall from 1961–1990, BFI, plus standard period (1961–1990) air temperature and MORECS potential evaporation.

Unfortunately we did not have these catchment characteristics for three of the benchmark stations (41029, 74007, 75017), these correspond to five temperature stations. Furthermore, we could not derive catchments for two of the temperature monitoring stations (within the catchments of gauges 25005 and 42010), and we had problems defining a riparian buffer for one temperature station. For the seasonal analysis, the GAM models used to derive the trends did not converge for five of the temperature stations.

The end result of these restrictions was that the seasonal analyses were undertaken on between 222 and 226 temperature stations rather than 231, however analyses involving proportion of riparian buffer with deciduous trees used only 210 sites from 52 catchments. Scatterplots of the key explanatory variables used in the subsequent analysis are shown in Figure 5.2.

5.2 Methods

We used linear mixed effects regression models to relate the characteristics of the temperature sites and the benchmark catchment gauges to the modelled temperature changes. Initial analysis focused on the annual temperature changes, but as subsequent analysis on the seasonal temperature changes indicated that there were strong differences in change between seasons, we only describe the results for the seasonal analyses here. We used mixed effects models to account for the fact that the temperature

[1] defined this as 50m either side of the river channel

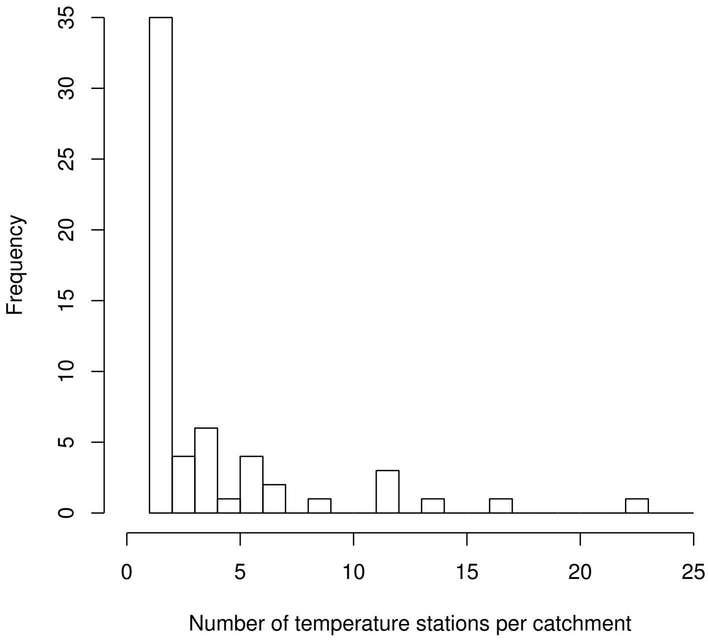

Figure 5.1: Histogram of number of temperature stations per benchmark catchment

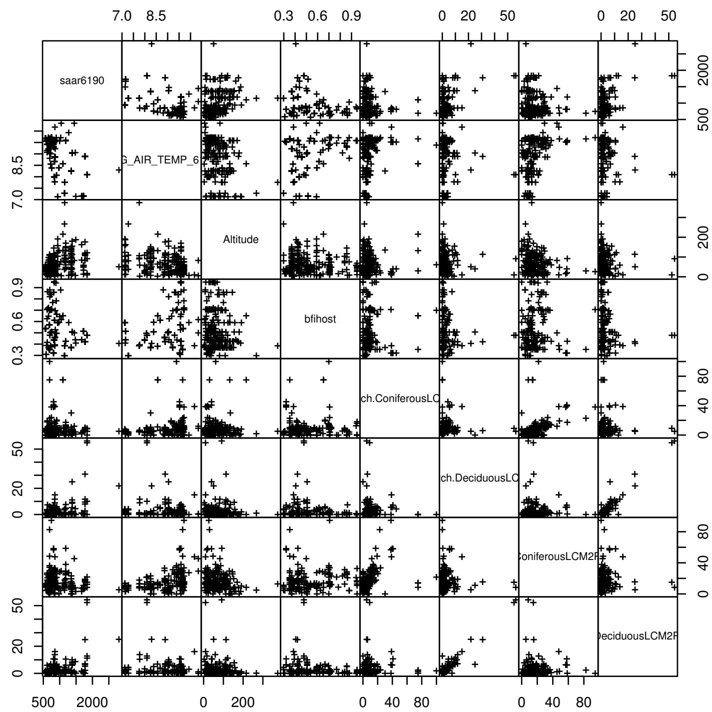

Figure 5.2: Scatterplot of key explanatory variables

Table 5.1: Summary of mixed model results for seasonal temperature changes

Season	Mean Temp. Change	SE	Expl. Variables
Spring	0.266	0.105	Mean rainfall (+), PE (+)
Summer	-0.022	0.085	Catchment Area (+)
Autumn	0.700	0.070	Mean Rainfall (+), Altitude (-)
Winter	0.855	0.010	Mean Rainfall (+), PE (+)

stations are clustered within the benchmark catchments. There are consequently two residual or error terms in the model, one associated with unexplained variation between sites within catchments, and one associated with unexplained variation between catchments. Some explanatory variables are only associated with the catchments, others with each individual temperature site.

We used likelihood ratio tests to compare nested models. We focused on a subset of the potential list of explanatory variables which we felt were most likely to be associated with temperature change.

5.3 Results

5.3.1 Annual trends

For the annual temperature changes, there was a highly significant mean temperature increase of 0.46℃(standard error: 0.063℃). Two catchment-level variables, SAAR61-90 and MORECS PE 61-90 were together associated with the temperature change. With both of these terms in the model, the relationship between both variables and the temperature changes was positive. That is, there were more positive temperature changes in catchments with higher average rainfall (with PE held constant) and more positive temperature changes in catchments with higher MORECS PE (with rainfall held constant). Both of these effects were highly significant, but there was still considerable unexplained residual variation, which was almost equally partitioned between the temperature station and catchment level.

5.3.2 Seasonal trends

A summary of the mixed model results for the seasonal trends is shown in Table 5.1. For the seasonal temperature changes, there were substantial difference between the seasons, with autumn and winter showing above average increases, spring showing a significant, but below average increase, and summer change is not significantly different from zero.

In two cases, spring and winter, the explanatory variables were the same as for the annual data, SAAR61-90 and MORECS PE 61-90. For autumn, the explanatory variables were SAAR61-90 (positive) and altitude (negative). For summer, although there was no significant overall pattern, temperature change was related to catchment area, which larger catchments showing a more positive change.

It is notable that at the site and catchment level, there seems to be a relatively low correlation between autumn temperature trend and winter temperature trend (Figures 5.3 and 5.4).

5.3.3 Riparian Woodland

Given that the greatest increases are occurring in autumn and winter, and the least increases are occurring in summer, we looked at the proportion of deciduous woodland in the riparian zone as a predictor. For the year-round data, the magnitude of the effect was in the logical direction, i.e. less positive trends for greater proportions of deciduous woodland. The effect was marginally significant. For the seasonal data, the results were non-significant but in the logical direction and of similar magnitude for spring and autumn, and highly non-significant for summer and winter. It should be

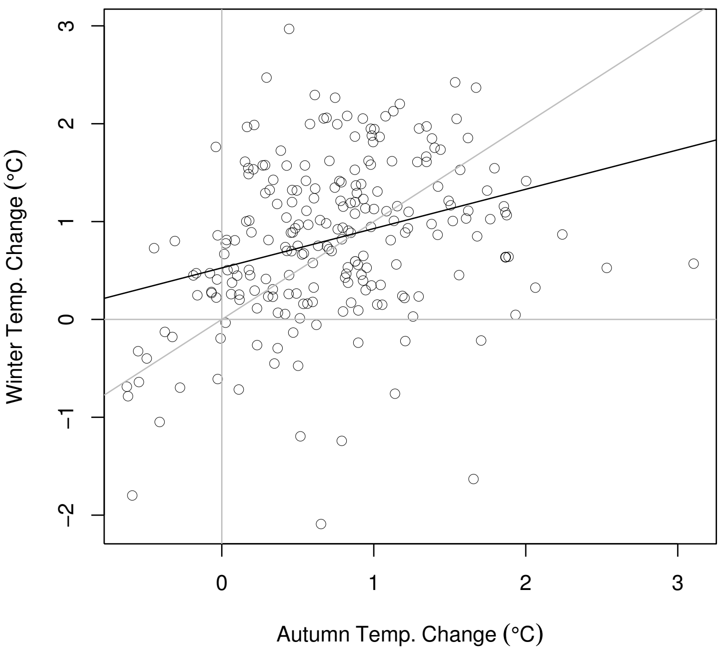

Figure 5.3: Site temperature trend from GAM models for autumn and winter. Grey lines show zero change and a 1:1 relationship. Black line is a simple regression through the data.

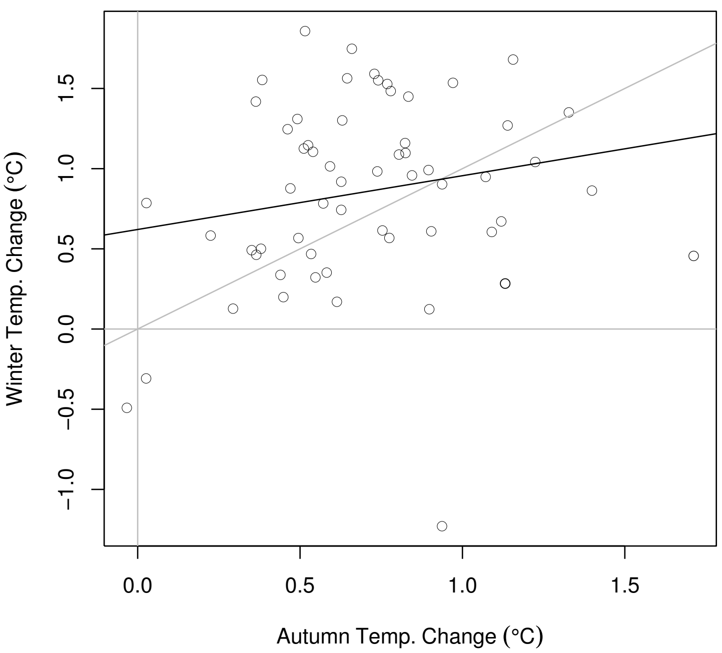

Figure 5.4: Catchment temperature trend from GAM models for autumn and winter. Grey lines show zero change and a 1:1 relationship. Black line is a simple regression through the data.

noted that the distributions of the proportions of riparian woodland are highly skewed, with many values close to zero, however transformation (arcsine-square root) did not improve the relationship.

5.3.4 Relation with flow trends

Given that the greatest increases are occurring in autumn and winter, and the least increases are occurring in summer, we looked at the proportion of deciduous woodland in the riparian zone as a predictor. The magnitude of the effect was in the logical direction, i.e. less positive trends for greater proportions of deciduous woodland. The effect was marginally significant. It should be noted that the distributions of the proportions of riparian woodland are highly skewed, with many values close to zero, however transformation (arcsine-square root) did not improve the relationship.

Chapter 6

Relationship between air and water temperatures

6.1 Introduction

To investigate the changes in air temperature at the benchmark sites and compare these to the changes in water temperatures, we fitted simple additive models to daily air temperature data records for each site, computed the change in the trend component over time and compared this with the change statistic derived from the Stage I modelling.

6.2 Methods

Daily mean temperature data on a 5x5km grid over the entire UK land area were downloaded from the UKCP09 website for the period 1990-2006. The mean daily temperature for each day during this period over the entire UK area is represented by a grid of temperature data. Each daily grid was read into R and processed in such a way as the locations of the benchmark catchments could be overlaid on to the the temperature grid. This overlay was used to extract each day's temperature for each site for the period of interest. The resulting data were combined into a time series of daily air temperature data for each Benchmark site, to which an additive model was fitted. Change statistics in the fitted air temperature trends were computed for each site in the same manner as the change statistics for the original models described in the earlier Stage I report. The two sets of change statistics were compared using a linear regression.

6.3 Results

Figure 6.1 shows the results of the comparison of changes in trend components of additive models fitted to air and water temperatures at the Benchmark Sites. The results are shown for the full set of 231 sites (Figure 6.1a) and for the subset of Benchmark sites where the fitted trend in water temperature is greater than 0 (i.e. all those sites at which an increase in temperature was modelled).

The rationale for comparing the relationship between change in air and water temperatures at only those sites with a modelled increase in water temperature is that if air temperature is the main driver of change in water temperatures (or is a surrogate or proxy for the main driver) then we would expect all sites to show an increase in water temperature as the UKCP09 data show no temperature decreases over the period of interest. hence if there is a relationships between air and water temperature change, we are most likely to see it in the subset of site showing water temperature increases. There is, however, no relationship between the change in air and water temperature trends at the Benchmark sites, either for the full data set ($F_{1,229} = 1.917$, $p = 0.168$), or the subset of sites with a positive modelled increase in water temperature ($F_{1,184} = 0.069$, $p = 0.793$).

The solid line in both panels of Figure 6.1 is the 1:1 line. Where points lie above this line, the change in water temperature is greater than the observed change in air temperature. There are FALSE

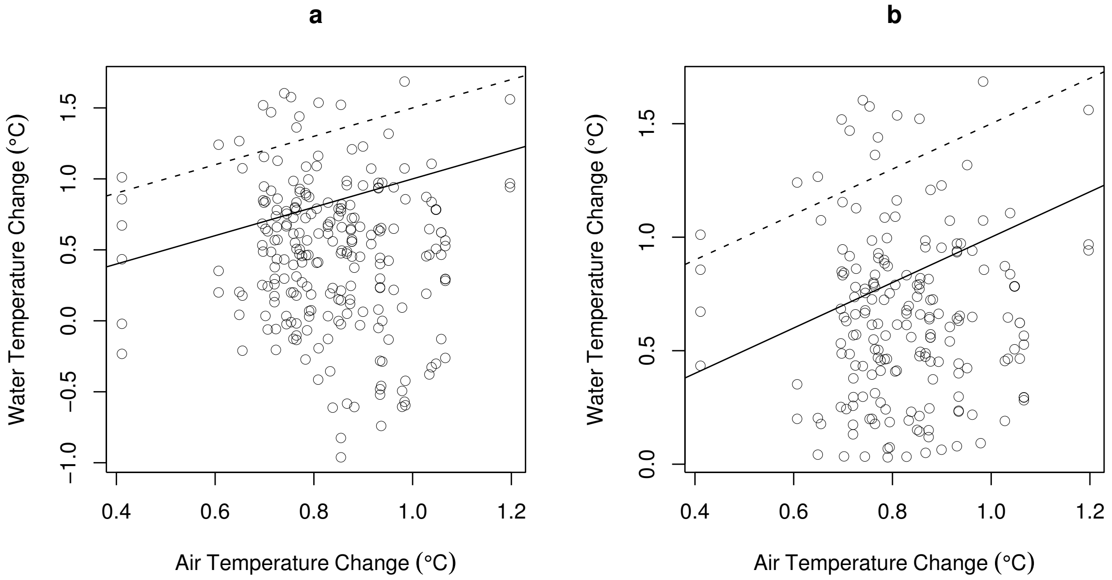

Figure 6.1: Comparison of changes in the trend components of additive models fitted to water temperature and air temperature records for Benchmark Sites; (a) comparison for all Benchmark Sites, (b) comparison for Benchmark Sites where the modelled change in the trend is positive. The solid line is the 1:1 line. The dashed line indicates the boundary where water temperatures are 0.5℃ above the *expected* air temperature increase.

sites where water temperature change is greater than the modelled air temperature change over the same period. Of these sites, 12 have changed by more than 0.5℃.

Chapter 7

Accounting for the effect of spot sampling

7.1 Introduction

All of the water temperature data for the Benchmark sites are based on spot sampled taken at varying times of the day over the entire time series and at varying intervals. To investigate the how well trends fitted to the spot sample data related to trends in mean daily water temperature, we used high resolution data from site W6007 to simulate the effect of spot sampling. The data from site W6007 cover the period 29 July 1989 to 1 August 2007, sampled on an hourly to 15 minute basis. A period of samples in 2006 had negative temperature values, perhaps indicating a period of equipment malfunction. As such, these values were discarded prior to analysis.

7.2 Methods

The average daily water temperatures were computed for the entire period, and an additive model with smoothers for the seasonal and trend components was then fitted to this entire time series. This fitted model represents the trend in average daily water temperatures where we have all the observations for the period of interest. Owing to the number of data points in this series, we were unable to compute the auto-correlation function for the model residuals on the whole model, and instead nested the autocorrelation within sampling years.

We then sub-sampled a time series from the raw data that was representative of the way in which spot sampling is performed. We selected from samples taken, on the hour, between 10am and 2pm, and selected 2 samples per month separated by 14 days to reflect fortnightly sampling. This simulated time series can be thought of representing an idealised sampling programme where no samples were missed and the samples taken were equally spaced. We allow a level of variability only in the timing of the sample collection. An additive model was then fitted to the sub-sampled series of exactly the same form as the one fitted to the full daily data set. As such we nested the auto-correlation structure within sampling years even though we could estimate it for the entire series. The change in the trend over the period 1 Jan 1990 to 31 December 2006 was computed from the fitted trend and the value of the trend was computed for 100 equally spaced observations throughout the period of interest.

This process was repeated a total of 100 times to produce 100 simulated spot sample time series. We compared the fitted trends and change statistics for the set of simulations with the same values computed for the full, daily time series to investigate how the degree to which spot sampling is representative of mean daily water temperature patterns.

7.3 Results

Figure 7.1 shows the fitted trend in average daily temperature at site W6007 for the period 1 January 1990 to 31 December 2006. Superimposed upon this plot are the fitted trends from 100 randomly

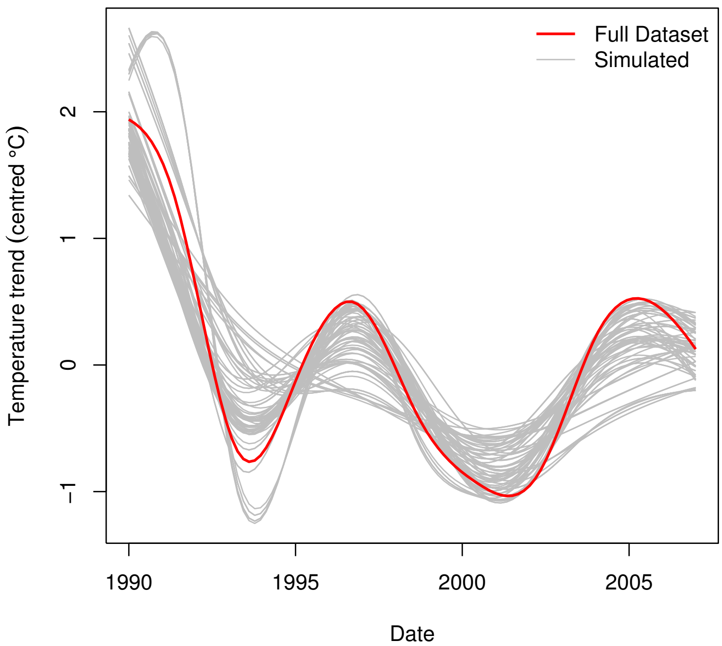

Figure 7.1: Fitted trend in average daily temperatures at site W6007 for the period 1 January 1990 to 31 December 2006 (thick line) and trends fitted to 100 random time series from the same site, chosen in such a way as to simulate the effect of spot sampling on the detectable trend component.

simulated time series, constructed so as to replicate the effect of spot sampling. The trend fitted to the full data set shows more extreme behaviour than the trends fitted to the 100 simulated time series from 1993 onwards, travelling to the extremes of the distribution of simulated trends. As such, the spot sampling at fortnightly interval has the effect of reducing the complexity of the fitted trend in the majority of the simulated time series and suggesting less variation in time in the trend component compared to the trend fitted to the full data set.

Despite the apparent reduction in variance of the trends fitted to simulated data, the simulated spot sampling has less of an effect on the change statistic. The observed change in the fitted trend for the full data set is -1.81, compared to the median change in the trends of the 100 simulated time series of -1.66. The 95% coverage interval of the change in the trend for the simulated series is -2.86 – -1.27.

Chapter 8

Conclusions

8.1 Trends and seasonal patterns in water temperatures

The majority (c. 80%) of sites in the benchmark network exhibit an increase in water temperature over the period 1990 to 2006. This number of sites is in broad agreement with the proportion of sites showing an increase in the full suite of Water Temperature Archive sites. The spatial pattern of temperature change is also consistent with the larger set of sites, with greater change in general from east to west across England and Wales. The general conclusion is that river water temperatures are increasing, in many cases rapidly, since 1990 and that this is a pattern reflected throughout England and Wales.

Superimposed upon this general pattern of increasing water temperatures are marked differences in temperature changes seasonally. The seasonal trend analysis indicates that many sites are showing positive changes in water temperature in autumn and winter, and to a lesser extent in spring. Summer temperatures have, on average across the benchmark network, remained stable over the period 1990–2006, although the magnitude of the range in temperature change exhibited is comparable across the four seasons. The spatial distribution of temperature change is similar to the annual change in spring only; warming predominantly in the north and west of England and Wales. Warming is observed throughout the region in autumn and winter, whilst cooling is observed across most of England and Wales in summer, with the exception of the western coast of Wales.

Complex changes in the seasonal pattern of temperature changes, beyond simple seasonal trends, are in evidence at c. 20% of sites in the benchmark network as shown by the results of the multivariate additive models. Further work is required to explore the results of these complex models to understand the nature of the change in the seasonal smooth component through time.

8.2 Relationship between flow and temperature

It is apparent that there is no obvious relationship between the trends observed in water temperatures and the patterns seen in river flows. Whilst there is an overall tendency towards increasing temperatures over this period, and a similar tendency towards increasing flows, the underlying regional and seasonal patterns are far more complex.

The generally positive signal for water temperatures is fairly resilient across seasons, although the strength varies between seasons, and there are no obvious spatial patterns. In contrast, river flow trends exhibit geographical tendencies, and these vary from season to season; in particular, winter flows appear to decrease overall, in contrast with water temperature, which has strongly increased in winter. This may be of interest, and may merit further, more detailed investigation. In general, these findings suggest that at the catchment scale, and pooling data from across the entire benchmark network, changes in river flows have not exhibited a strong control on temperature over the period studied.

However, it must be emphasised that this study has only compared the overall trends seen from 1990–2006, on a site by site basis, and has then examined spatial patterns in these results, and correlations between the trend estimates from two different datasets. Whilst this is suitable for a broad, qualitative assessment of the relationship between the two variables, the approach used cannot positively identify, and therefore, cannot rule out, a causal relationship between flow and temperature. This is principally because of the strong inter-annual variation that exists in these datasets (particularly for flows), which means that the overall trend may be similar, but the actual relationship over time may be very different. Furthermore, the different mechanisms used to test for trend in the two variables, and the different ways they are presented, means there is no direct way to compare the magnitude of trends. Finally, it is very important to consider that the period of study is relatively short, which implies any observed trends may be part of a longer-term process occurring at an inter-decadal time scale.

Whilst these caveats must be borne in mind, the overall message is that the results support a general conclusion that river flow changes over the period of study are not likely to have strongly influenced the observed positive temperature trends.

8.3 Relationship between water temperature and other factors

This study has demonstrated a general increase in river water temperatures from daytime spot samples in benchmark catchments. The positive annual trend is mainly driven by increases in autumn and winter temperatures. Furthermore, there are spatial patterns, and some seasonal variation in spatial pattern.

There was a positive relationship between the magnitude of the trend and mean rainfall in three out of four seasons, and a positive relationship with mean potential evaporation in two out of four seasons. In one season, winter, there was a positive relationship between the trend in mean flow and the trend in temperature. Relationships between autumn and winter temperature trend indicate some concordance – there is a lack of stations with trends of opposite sign — but there is still wide scatter. The simplistic models linking seasonal temperature change to riparian tree cover illustrate no strong obvious effects, but show some interesting patterns which are in the logical direction (lower increases for more tree cover).

The fact that increases in spot river water temperature outstrip increases in air temperature in some instances is notable and needs further investigation. This highlights that the observed increases may driven by a range of climatic factors, and not simply direct heat transfer from air to water.

8.4 Relationships between air and water temperature changes

Two key findings arise from the comparison of changes in air and water temperatures at the benchmark sites. Firstly, there is no statistical relationship between annual water and air temperature changes across the benchmark network. Secondly, at many sites, water temperature have changed more rapidly than air temperatures over the study period, with 12 sites increasing by more than 0.5℃ over the observed air temperature change. Additional work should attempt to address these findings to investigate whether there is a relationship between air and water temperatures in autumn and winter where water temperatures have predominantly increased.

8.5 The effect of spot sampling on trend estimation

The data analyses presented in this report derive from data collected via spot temperature measurements collected by Agency and other staff over periods of many years. These data, therefore, reflect are particular sampling distribution of the underlying water temperature process at each site. It is important to ask what effect this imposed sampling distribution might have on i) the ability to detect trends, and ii) the form of any trends thus identified.

The key result from this part of the work programme is that the trends fitted when simulating a spot sampling regime are similar in many regards to the fitted trend using the full daily range of data, which affords a good degree of confidence that the patterns in water temperatures described above are real features of the changes in water temperatures in England and Wales. Owing to the lower number of observations in each of the simulated spot-sampled temperature series, the trends fitted to these series often show less variation or flexibility when compared with the trend fitted to the full time series. In this regard, the ability to detect a similar degree of change in temperatures at a multi-annual scale is diminished compared to high resolution monitoring with automated sampling. The change in temperature between 1990 and 2006 at the study site is robust to the effect of spot sampling. This suggests that whilst the shape of the fitted trends may not have been fully captured from the spot sampling at sites across England and Wales, the water temperature change statistics are a more faithfully represented, again affording a good degree of confidence in the results presented earlier.

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