Surface Water Temperature Archive for UK freshwater and estuarine sites

Draft Science Report – SC070035

August 2008

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

It’s our job to make sure that air, land and water are looked after by everyone in today’s society, so that tomorrow’s generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry’s impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned and funded by the Environment Agency’s Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive,
Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: XXXXXXXXXX

Further copies of this report are available from:
The Environment Agency’s National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
XX in alphabetical order

Dissemination Status:
Released to all regions
Publicly available / Restricted

Keywords:
Maximum of 10

Research Contractor:
Contractors name and address with tel. no.

Environment Agency’s Project Manager:
Project Manager’s name, Science Department

Collaborator(s):
In alphabetical order (refer to guidance document)

Science Project Number:
Insert project reference number

Product Code:
XXXXXXXXXXXX-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

The work of the Environment Agency's Science Department is a key ingredient in the partnership between research, policy and operations that enables the Environment Agency to protect and restore our environment.

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Head of Science

Contents

List of tables and figures

1 Introduction

Surface Water Temperatures can provide indicators of climate change and associated ecological responses. These are needed to inform regulation and the design and delivery of ecosystem management conservation and restoration targets prescribed by the Water Framework and Habitats Directives among others.

Ecological responses to temperature change are known to vary with water body type and geographic location, but studies of the impacts of climate change on aquatic ecosystems in England and Wales have been relatively few, possibly because of an absence of widely available temperature data. This Temperature Archive project aims to generate a database and a methodology able to support a wider assessment of ecological responses to climate change and to encourage studies of possible impacts of future warming.

1.1 Project background and aims

The Water Temperature Archive Project (Phase 2), is jointly commissioned by the Environment Agency and the Countryside Council for Wales. It builds on a Scoping Study (Phase 1; Hammond and Pryce, 2007), which compiled river water temperature data and analysed temporal trends at selected sites in each of eight Environment Agency regions in England and Wales.

However, the Archive put together during Phase 1 was considered inadequate for the purposes of Phase 2 as (i) it was not structured as a relational database; (ii) it had retained very few sites; and (iii) it contained no data for estuaries or lakes. Accordingly a new database has been developed. In addition, the statistical analyses used for the detection of trends in Phase 1 have been replaced here by more powerful, comprehensive and appropriate statistical models.

The main objectives of Phase 2 are to source, collate, organise and analyse the surface water temperature data held by the Agency and document and analyse data from other providers as available, particularly for Lakes and Estuaries.

Specifically, this phase of the Water Temperature Archive project presented here has four components:

- The Water Temperature Data Archive
- Statistical trend analyses and summary statistics by region, with an in-depth study of the effect of altitude and geology
- Methodology for simulating missing water temperature data from air temperatures
- Two case studies of how changes in temperature might affect fish (Salmon) and aquatic invertebrates (Dragonflies), and
- Recommendations for a future surface-water temperature monitoring network.

1.2 Report Structure

Methods and results specific to each project component are presented and discussed separately, in the next four report chapters. Chapter 6 brings the main points together for final Discussion and Recommendations.

Each chapter is structured into three parts - Methods, Results, Discussion. The more technical or detailed aspects of the research can be found in Appendices at the end of the report.

2 Data Archive

2.1 Introduction

The project's four components, archive, statistical analyses, case studies and monitoring network advice, have common and specific data requirements. The Data collated in the Archive aim to:

- provide a resource for the assessment of past water temperature records and changes for the Environment Agency and Countryside Council for Wales;
- describe and organise historical data from various sources within the EA, and provide an analysis of data quantity and quality issues; and
- describe important and potentially complementary data sources for lakes and estuaries.

2.2 Data Sources

The Archive's data holdings mostly originate from within the EA. Of the 30,580 sites currently in the Archive, the few exceptions concern:

- a marine site (Port Erin data collected by the Isle of Man Department of Local Government and the Environment (DLGE) and classified as Coastal in the Wales region for convenience);
- long-term time series from the Freshwater Biological Association (FBA) and Centre for Ecology and Hydrology (CEH) for surface temperatures of seven lakes sites in the Cumbrian Lake District; and
- four lake sites from the UK Acid Waters Monitoring Network (AWMN) provided by UCL-ENSIS (see Table 1).

Only the metadata for non-EA records will be kept in the Archive, with the primary data obtainable directly from the data owners under licence.

The great majority of EA surface-water temperature data have been collected incidentally with hydrographic or water quality monitoring projects, rather than for their own sake. The data therefore have had little or no analysis or quality assurance until now. The quality of the data collated in the Archive will ultimately depend on the extent of further quality control and assurance measures of the various EA data holdings documented here.

Within the EA, the data are held at central, regional and sometimes local levels. The largest repositories, WIMS, WISKI and regionally held TIMS and Cumbrian lakes databases are detailed below.

Table 1 Archive data holdings - Sites by region and source

EA_REGION	DLGE	EA TIMS	EA WIMS	EA WISKI	EA CUMBRIA	FBA-CEH	AWMN	Totals
AN		3	3,810	16				3,829
MD			3,977	38				4,015
NE			3,763	84				3,847
NW			3,586	3	10	7	2	3,608
SO		3	1,669	8				1,680
SW		3	5,972	19				5,994
TH		117	2,248	5				2,370
WA	1		5,192	42			2	5,237
Total Sites	1	126	30,217	215	10	7	4	30,580

2.2.1 EA centrally held databases

Water Information Management System (WIMS)

The largest of all centrally held water temperature data holdings in terms of number of sites and spatial coverage is the Water Information Management System or **WIMS**, maintained by the EA National Data Unit.

WIMS holds mostly spot measurements for 30,217 sites in the January 2008 copy provided to us. The vast majority are river sites (92% in Table 2 below) with a few lake/ponds/reservoir and canal sites and recently added transitional and coastal waters sites monitored under the Water Framework Directive.

Table 2 WIMS data holdings – number of sites by region and water body type

EA_REGION	CANAL	COASTAL	DRAIN	LAKE	RIVER	TRANS.	Totals
AN	45	16	5	269	3398	77	3,810
MD	275			61	3625	16	3,977
NE	86	21	17	70	3501	68	3,763
NW	195	81	1	123	3152	34	3,586
SO	11	61		26	1531	40	1,669
SW	63	31	4	139	5667	68	5,972
TH	45			117	2078	8	2,248
WA	63	58	30	151	4789	101	5,192
Total Sites	783	268	57	956	27,741	412	30,217

The geographical distribution of sites for which temperature is held in WIMS reflects approximately that of water body types in each of the eight regions, apart from the Thames region, which holds data in its own system (Table 2).

The 30,217 WIMS sites in the Archive correspond to some 3.2 million records (see Table 3), approximately an average of 100 records per site. Some sites were only monitored over a short-time period. Others, such as coastal sites that have only been monitored by the National Maritime Team since 1991, have only been added recently. Typically, monitoring frequencies range from weekly to bi-monthly.

.

Table 3 WIMS data holdings – number of records by region and water body type

EA_REGION	CANAL	COASTAL	DRAIN	LAKE	RIVER	TRANS.	Totals
AN	7,503	927	93	18,426	329,933	8,336	365,218
MD	35,128			3,795	437,614	2,775	479,312
NE	12,149	619	531	1,711	343,575	9,882	368,467
NW	22,774	3,421	2	47,763	340,888	5,161	420,009
SO	2,192	6,793		525	234,219	7,755	251,484
SW	4,988	772	72	4,278	644,889	12,292	667,291
TH	4,711			2,160	279,572	4,846	291,289
WA	6,254	3,648	1,225	5,449	354,695	23,538	394,809
Total Records	95,699	16,180	1,923	84,107	2,965,385	74,585	3,237,879

However, there are several thousand sites that hold an average of 250 records. The sites retained for statistical trend analyses are described in section 5.2.

WIMS coverage is complemented by a number of other monitoring systems, including a network of Automatic Water Quality Monitoring Stations (**AWMS**) at central and regional level.

Water Information Management System Kisters (WISKI)

The WISKI database is held centrally by the EA Hydrometry Process Team. The data are collected by automated stations at 15 minute or hourly intervals. WISKI is designed to support river basin management with an emphasis on hydrology, and therefore temperature data are not quality assured. The original 58 WISKI sites identified by the Phase 1 Scoping Study were increased to 215 (Table 4) once it became apparent that water temperature in the WISKI database had been entered under two separate determinands TR or T6. WISKI sites are mostly on rivers, and are most numerous in the Northeast region (NE) although the Midlands region has the most data.

The 215 WISKI sites correspond to nearly 30 million records (Table 5), an average of more than 138,000 records per site, even though most data series only start after 1989.

Table 4 Archive WISKI data holdings – number of sites by region and water body type

EA_REGION	CANAL	RIVER	TRANS.	Sites
AN		14	2	16
MD		38		38
NE	3	63	18	84
NW		3		3
SO		8		8
SW		19		19
TH		5		5
WA	1	41		42
Total Sites	4	191	20	215

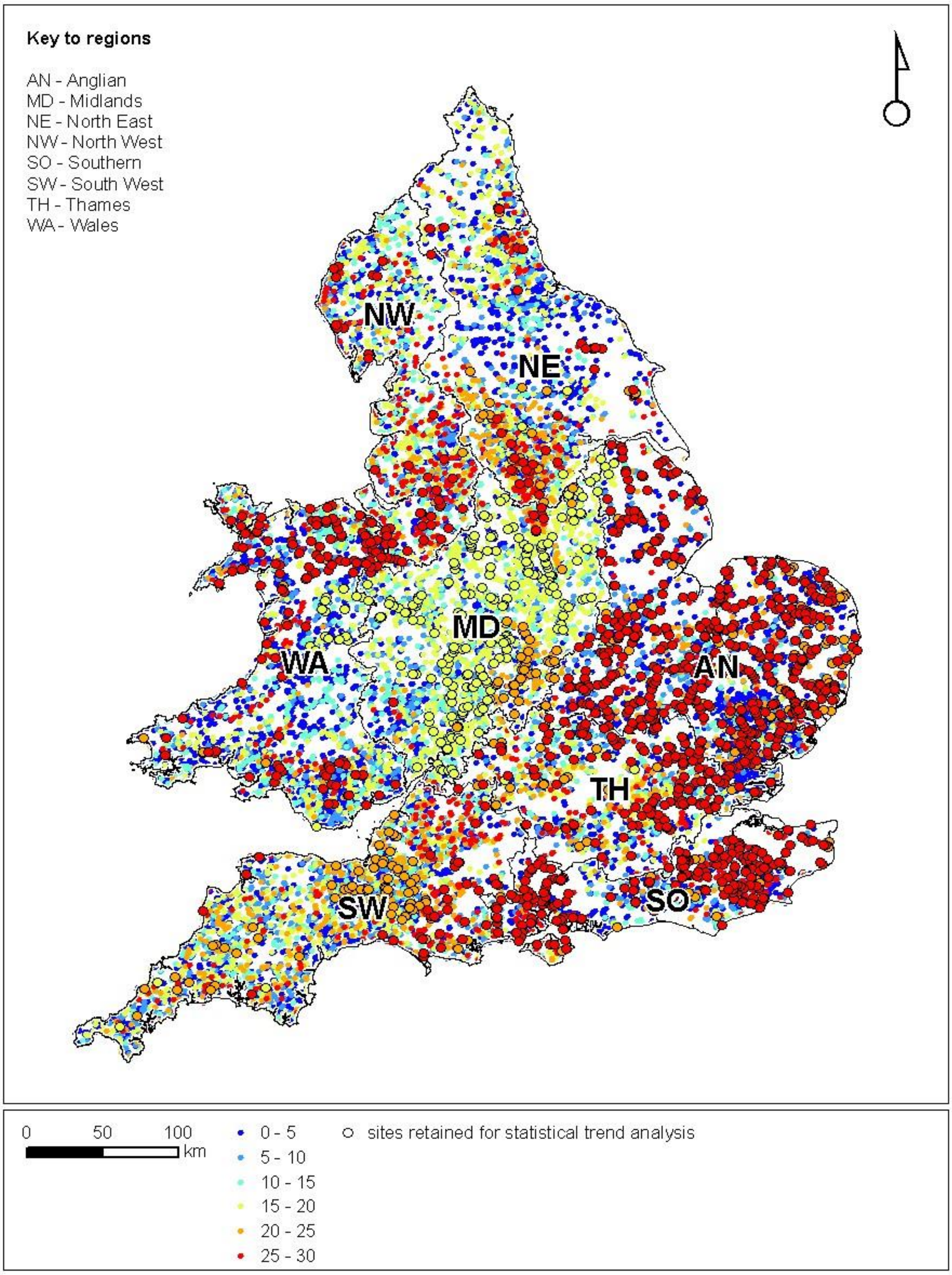

Figure 1 Archive WIMS river sites location, classified according to length of record in years

Table 5 Archive WISKI data holdings – number of records by region and water body type

EA_REGION	CANAL	RIVER	TRANS.	Records
AN		801,101	81,439	882,540
MD		11,510,883		11,510,883
NE	92,414	4,516,409	1,805,027	6,413,850
NW		608,373		608,373
SO		390,393		390,393
SW		1,059,343		1,059,343
TH		122,014		122,014
WA	33,559	8,769,218		8,802,777
Total Records	125,973	27,777,734	1,886,466	29,790,173

In addition to the centrally held WISKI, some regions have their own high frequency temperature information database, such as the Tideway Information Management System (TIMS, see below) of the Thames region.

2.2.2 EA regionally held databases

The Phase 1 Scoping Study established a list of data held in regional databases, for which updated versions have been obtained. We found that the distinction between nationally and regionally held data is not always clear.

Tideway Information Management System (TIMS)

TIMS is similar to WISKI to the extent that it holds records from Automatic Water Quality Monitoring Stations (AWMS) collecting sub-daily information. TIMS has temperature data for 126 sites and is managed by the Thames Region. It covers the entire Thames River Basin District and includes three sites in each of the Anglian, Southern and Southwest Regions, and 117 in the Thames EA Region (Table 6), for a total of nearly 8.5 million records between 1986 and 2007.

Table 6 TIMS data holdings – number of sites and records by region and water body type

EA_REGION	CANAL	RIVER	TRANS.	Sites
AN		1	2	3
SO		2	1	3
SW		3		3
TH	2	93	22	117
Total Sites	2	99	25	126
EA_REGION	CANAL	RIVER	TRANS.	Records
AN		29,957	347,862	377,819
SO		23,201	24,729	47,930
SW		107,850		107,850
TH	30,931	5,157,596	2,685,330	7,873,857
Total Records	30,931	5,318,604	3,057,921	8,407,456

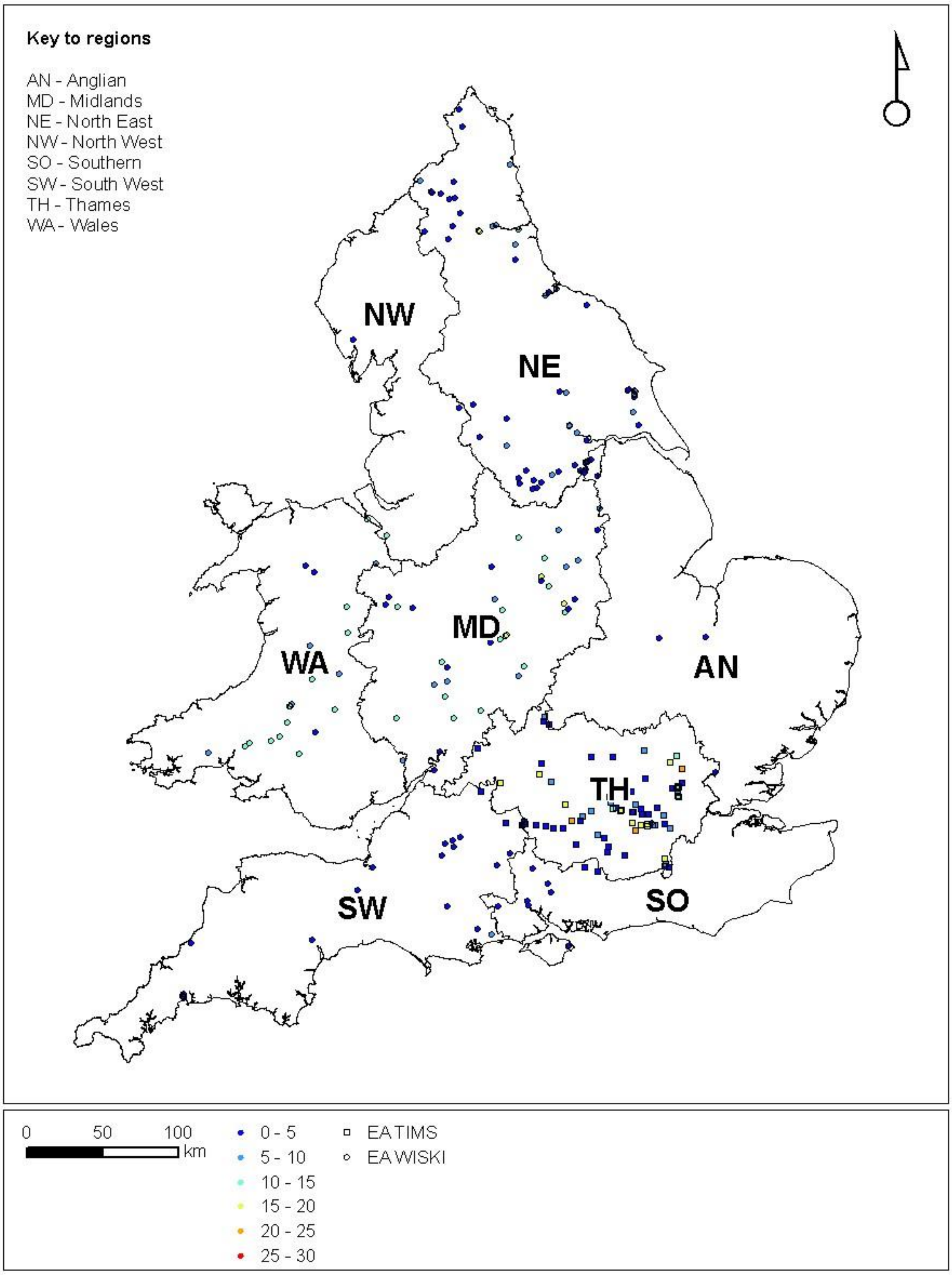

Figure 2 WIMS river sites in the Archive, classified according to length of record in years

Figure 2 gives the location of WISKI and TIMS river sites, with an indication of the length (in years) of the time-series record at each site.

Northwest and Wales regions Lake Data

Data for the 956 Lake sites held in WIMS (Table 2) are complemented by seven sites from the FBA-CEH database, four lake sites from the AWMN (two in NW and two in Wales), and ten Cumbrian sites (nine lakes) monitored by the Northwest Region.

For the Northwest Region (NW) sites, two instruments (Automatic Water Quality Monitoring Stations, AWQMS), one at the surface and one about 1 m from the bottom, are deployed at each site to record water temperature every 15 minutes averaged to hourly.

Table 7 presents a summary of the data holdings for 21 Lake sites held in systems other than WIMS. Lake monitoring by the EA in Cumbria started in the mid-1990s, while 4 FBA-CEH sites go back to 1947. Two lakes, Bassenthwaite and Grasmere, currently monitored by the EA are also monitored less frequently by the FBA-CEH. The 4 Acid Waters Water Monitoring Network (AWMN) sites are the only lakes higher than 200m in the Archive.

Table 7 Archive non-WIMS lake sites details

siteName	sourceCode	startDate	endDate	siteZ	Records
BASSENTHWAITE	EA CUMBRIA	01-Jan-95	31-Dec-07	68	67720
BROTHERSWATER	EA CUMBRIA	30-Jul-02	16-Oct-07	156	24112
BUTTERMERE	EA CUMBRIA	20-Jan-97	19-Nov-02	98	36283
CONISTON	EA CUMBRIA	01-Aug-02	22-Dec-07	42	25266
ELTERWATER	EA CUMBRIA	06-Dec-95	22-Dec-07	54	63504
ENNERDALE	EA CUMBRIA	20-Feb-97	31-Dec-07	110	57070
GRASMERE	EA CUMBRIA	28-Mar-94	31-Dec-07	60	76598
LOWESWATER	EA CUMBRIA	18-Jul-96	31-Dec-97	120	10445
ULLSWATER NORTH	EA CUMBRIA	28-Oct-97	31-Dec-07	142	54766
ULLSWATER SOUTH	EA CUMBRIA	02-Jul-97	31-Dec-07	142	63553
BASSENTHWAITE	FBA-CEH	10-Jan-90	13-Dec-07	68	426
BLELHAM	FBA-CEH	28-Jan-47	11-Dec-07	40	2456
DERWENT	FBA-CEH	10-Jan-90	13-Dec-07	74	437
ESTHWAITE	FBA-CEH	22-Jan-47	06-Dec-07	64	2526
GRASMERE	FBA-CEH	04-Jan-69	11-Dec-07	60	994
WINDERMERE - NORTH BASIN	FBA-CEH	04-Jan-47	06-Dec-07	38	2591
WINDERMERE - SOUTH BASIN	FBA-CEH	05-Jan-47	06-Dec-07	38	2550
BURNMOOR TARN	UKAWMN	27-Jul-99	10-Aug-07	253	35228
LLYN CWM MYNACH	UKAWMN	25-Jul-99	21-Jun-07	278	30178
LLYN LLAGI	UKAWMN	26-Jul-99	08-Aug-07	374	35216
SCOAT TARN	UKAWMN	28-Jul-99	09-Aug-07	595	35203

2.2.3 Non-River sites

Although far fewer than River sites, the Archive holds a large number of non-river sites. Their location is given in Figure 3, which shows that the lack of estuarine data noted in Phase 1 has been remedied through the inclusion of Transitional Waters' sites from WIMS (412, Table 2), WISKI (20, Table 4) and TIMS (25, Table 6).

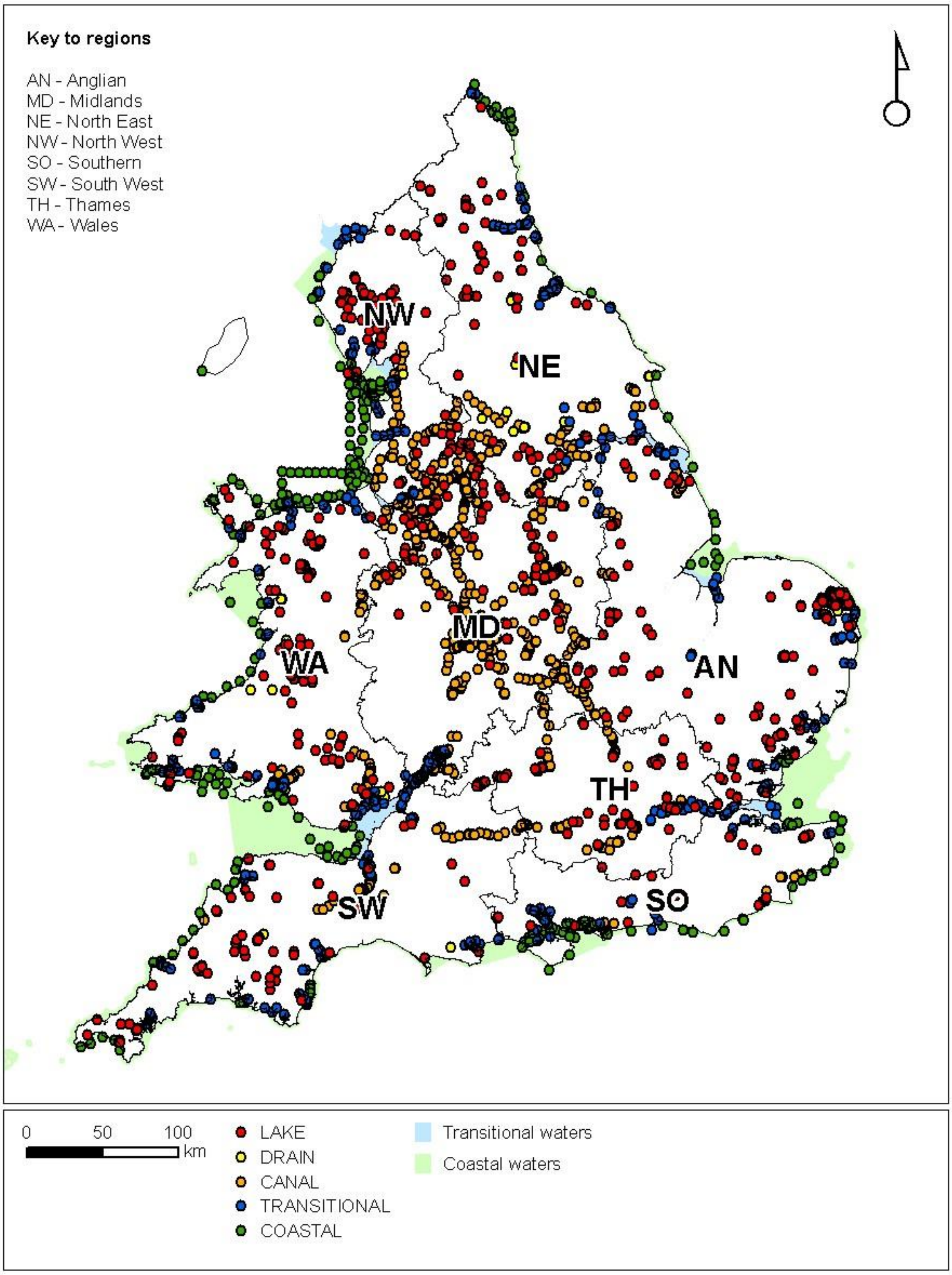

Figure 3 Non-River sites in the Archive classified according to type

2.3 GIS Layers

The EA provided a number of GIS layers for the purpose of this project. The layers are used to obtain additional metadata for the sites but also for visualisation, illustration and analysis of information held in the Archive.

River network

The river network provided by the EA is derived from Ordnance Survey data at a scale of 1:250,000. This small scale is unsuitable for matching locations of sites in the database as mostly these are located to 100m or better. Consequently sites do not fall on or near the river network in the majority of cases, limiting our analyses for the purposes of this project to the potential effects of site altitude, site proximity, WFD typology and base flow index (BFI) attributes. A more detailed river layer based on OS MasterMap data is due to be launched late in 2008.

The Salmon Action Plan (SAP) River Network (Figure 4, darker shade) obtained independently is used by the EA in its collaborative annual report to ICES on Atlantic Salmon (Cefas and EA, 2008).

Elevation

Elevation data obtained from the EA Geomatics Group under licence is derived from SAR (synthetic aperture radar) data and supplied in ESRI grid format at 50 m resolution (Figure 5).

Each site in the Archive has an altitude attributed through this GIS layer, which is stored in the site data table.

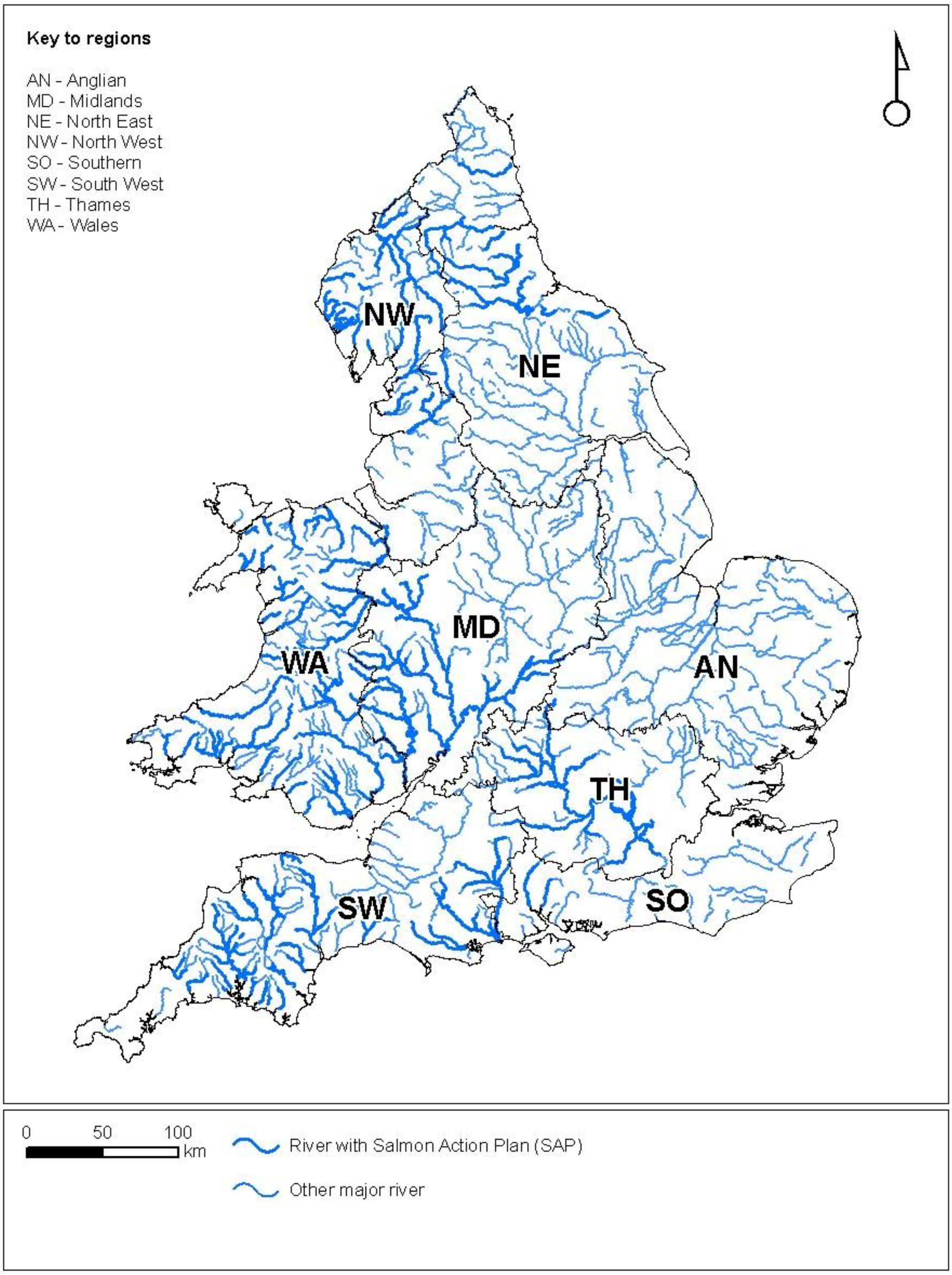

Figure 4 Major rivers and Salmon Action Plan (SAP) river network

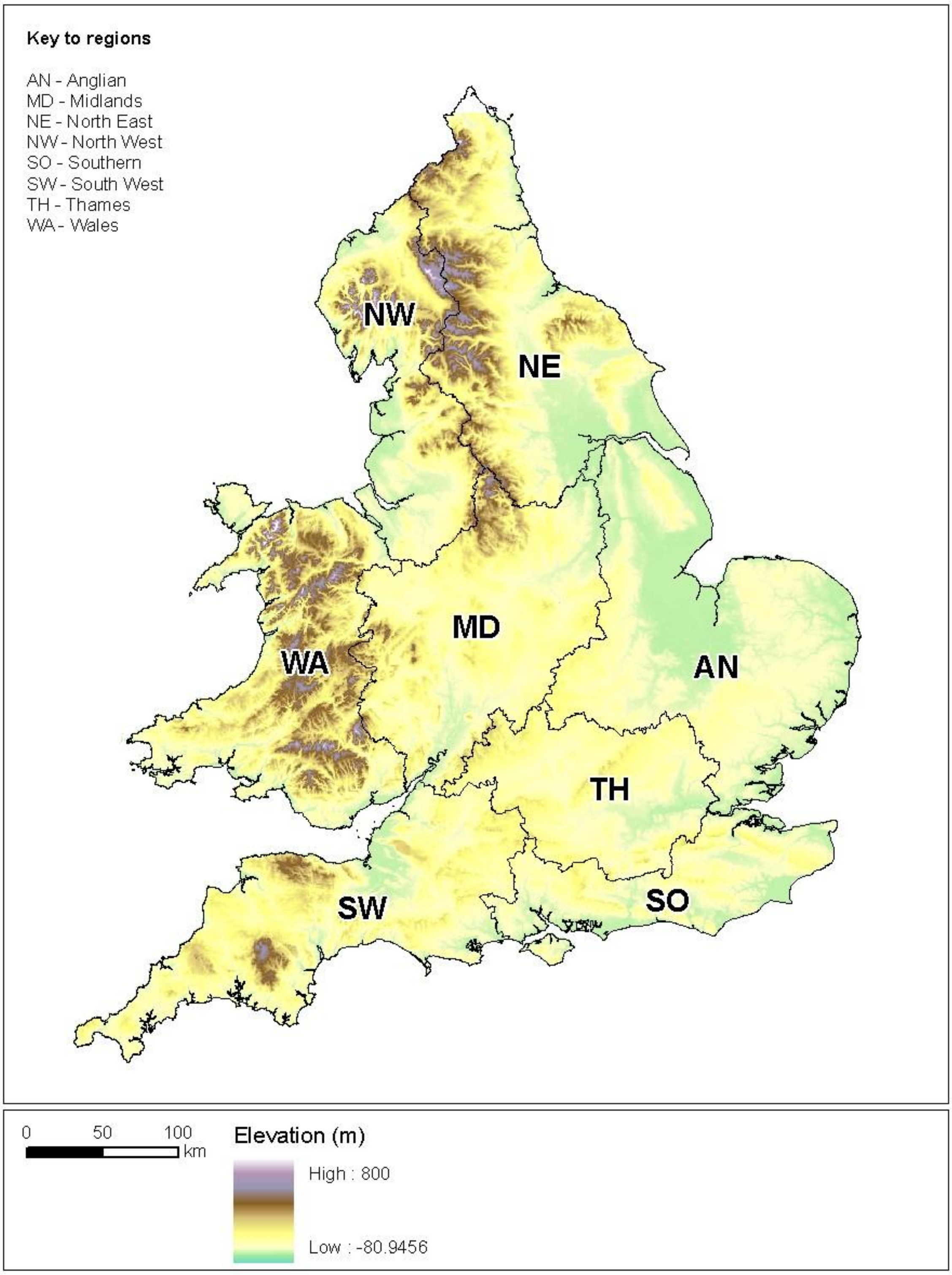

Figure 5 Elevation map with EA Regions boundaries

Water Framework Directive (WFD) Typology

The WFD Typology[1] uses three criteria – altitude, geology and catchment size – to classify European river catchments. Only some of the criteria combinations (Table 8) are represented in England and Wales, giving a total of 21 Types and a "zero" type for those that have not been classified yet.

Table 8 WFD River water bodies - typology

Altitude (mean catchment)	Dominant Geology	Catchment size (km2)
LOW: < 200 m	SI: Siliceous	XS: <10
MID: 200 – 800 m	CA: Calcareous	S: 10 -100
HIGH: > 800 m	OR: Organic	M: 100 - 1000
	SA: Salt	L: 1000 - 10,000

Not all possible types generated by the typology criteria in Table 8 are represented in England and Wales. In particular there are no sub-catchments of type 9 and 18 and non higher than 800m (types 19 to 27) while there are large numbers of very small (XS) (types 37 to 43) and relatively few Large (types 7, 8, 16 and 17) sub-catchments.

Table 9 gives the number of different sub-catchments or Water Bodies (WBs) per Region, with an indication of the Altitude, Geology and Catchment Size categories for each WFD Type. U indicates Un-typed categories.

Each EA Region has a unique mix of WFD Types (Figure 6), which can be expected to influence surface water temperature regimes and changes.

Apart from the zero category of non-typed Water Bodies (WBs), Type 2 catchments (Lowland Calcareous Small) are most prevalent in all Regions except for Wales, with 44% of the 6320 non-zero WBs. In Wales, Type 10 sub-catchments (Mid-altitude Siliceous Small) WBs, are most numerous, followed by types 2, 1 and 11. Sub-catchments with OR (Organic Geology, types 3, 6, 12, 15 and 43) are rare throughout.

River catchments that remain un-typed at this stage (U, 1412 or 18% of all sub-catchments, Table 9) are situated around transitional and coastal waters (left in white).

Base Flow Index (BFI)

Base flow is the component of stream flow that can be attributed to groundwater discharge into streams, and the BFI is defined as the ratio of base flow (the slower varying component of flow from groundwater) to total stream flow, expressed as a proportion (between 0 and 1). For rivers, the BFI may be more precise and meaningful than the WFD Groundwater Body Types as it relates directly to river surface water flow and integrates deep geology, surface geology/permeability and catchment slope.

The EA Water Resources Team provided two BFI information GIS layers, one for the total upstream catchment and another for the sub-catchment. We have used the sub-catchment data to match the spatial scale of the WFD typology. The data are illustrated in Figure 7 showing catchments with a high base flow % component (BFI close to 1) in red.

---

[1] Details of the typology and water body delineation method on the UK Technical Advisory Group website on http://www.wfduk.org/whats_new/TAG_Guidance/view

Each of the 30580 sites in the Archive has been attributed a BFI sub-catchment value through a GIS spatial join. Just as for the WFD sub-catchment typology a few sites (44) have fallen on the border of two (or even three: siteID 1188) BFI sub-catchments. Further complications arise from the fact that BFI and WFD sub-catchment boundaries do not all coincide and that some sub-catchments have not been WFD-typed.

Table 9 Numbers of WFD River Water Bodies in England and Wales by Region

TYPE	AN	MD	NE	NW	SO	SW	TH	WA	WBs	ALT	SIZE	GEOL	%WBs
0	266	13	92	72	229	376	14	350	1,412	U	U	U	
1	9	29	46	36	117	252	39	156	684	LOW	S	SI	11%
2	682	517	374	214	184	332	314	162	2,779	LOW	S	CA	44%
3	10			3					13	LOW	S	OR	0%
4		2	9	4	7	24	6	7	59	LOW	M	SI	1%
5	94	68	36	21	39	49	66	13	386	LOW	M	CA	6%
6	2								2	LOW	M	OR	0%
7		6				1			7	LOW	L	SI	0%
8	15	13	6	2	6	5	8		55	LOW	L	CA	1%
10		98	117	128		92		257	692	MID	S	SI	11%
11		47	166	116		7	14	133	483	MID	S	CA	8%
12		4	84	30		1		1	120	MID	S	OR	2%
13		15	8	19		17		41	100	MID	M	SI	2%
14		7	26	17				14	64	MID	M	CA	1%
15			1	2					3	MID	M	OR	0%
16				1				3	4	MID	L	SI	0%
17		2	4	3				11	20	MID	L	CA	0%
28				13					13	LOW	S	SA	0%
37	4		4	10	52	237	2	132	441	LOW	XS	SI	7%
38						10		16	26	MID	XS	SI	0%
40	52	11	58	44	50	70	4	79	368	LOW	XS	CA	6%
43				1					1	LOW	XS	OR	0%
Totals	1,134	832	1,031	736	684	1,473	467	1,375	7,732				
%WBs	15%	11%	13%	10%	9%	19%	6%	18%	100%				

* Excluding the sub-catchments in Scotland, seven water bodies are miscoded for either Type or categories in the GIS layer river_catch_typology_1_6.

2.4 Archive Holdings

The Archive can be split into separate data and metadata components. The metadata component links sites to geographical information provided during the project (EA Typologies, BFI, elevation) and contains a summary of the data available including date range, number of records and data sources. The database structure is described in Annex X

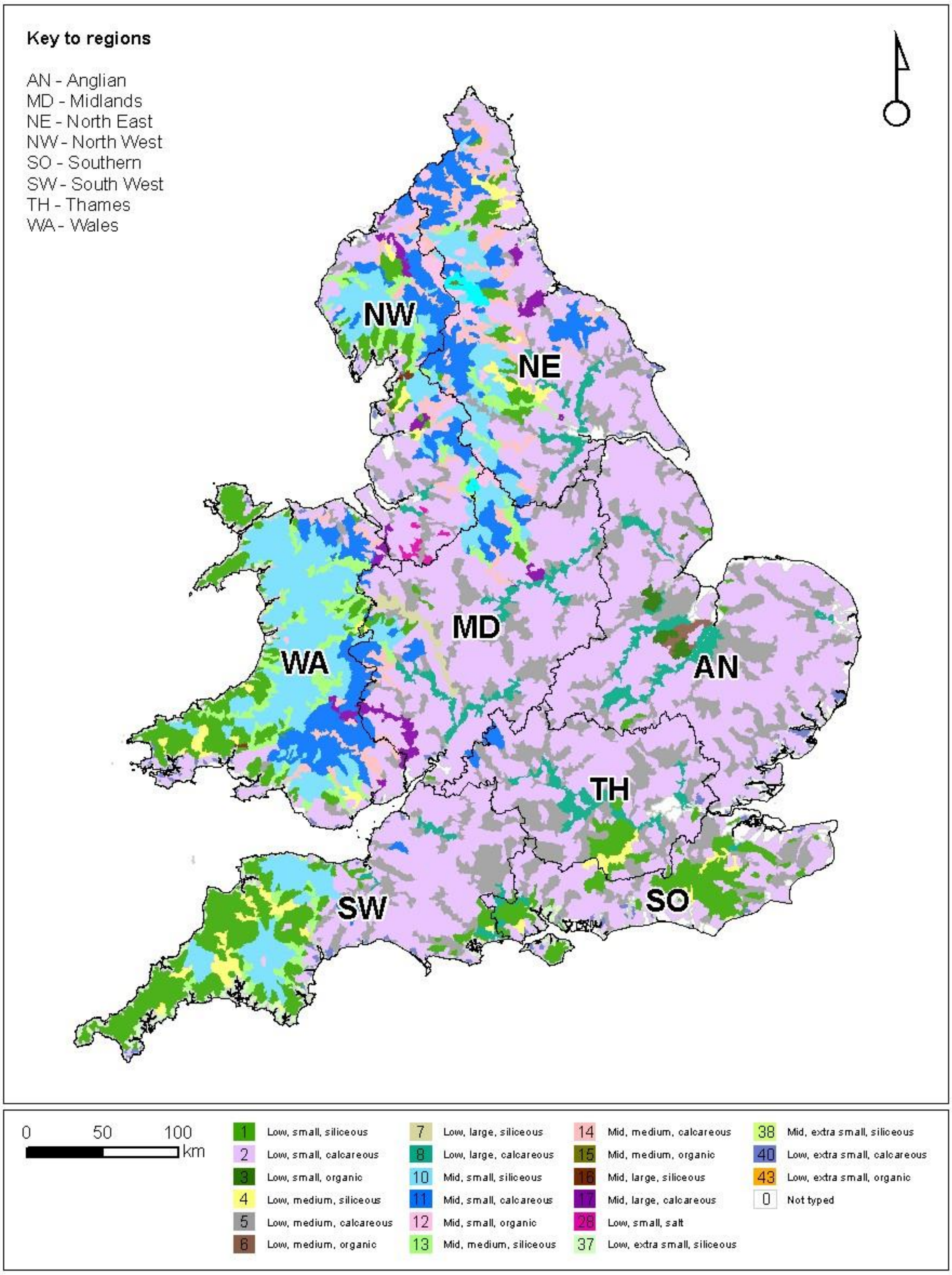

Figure 6 WFD River Catchments and Types

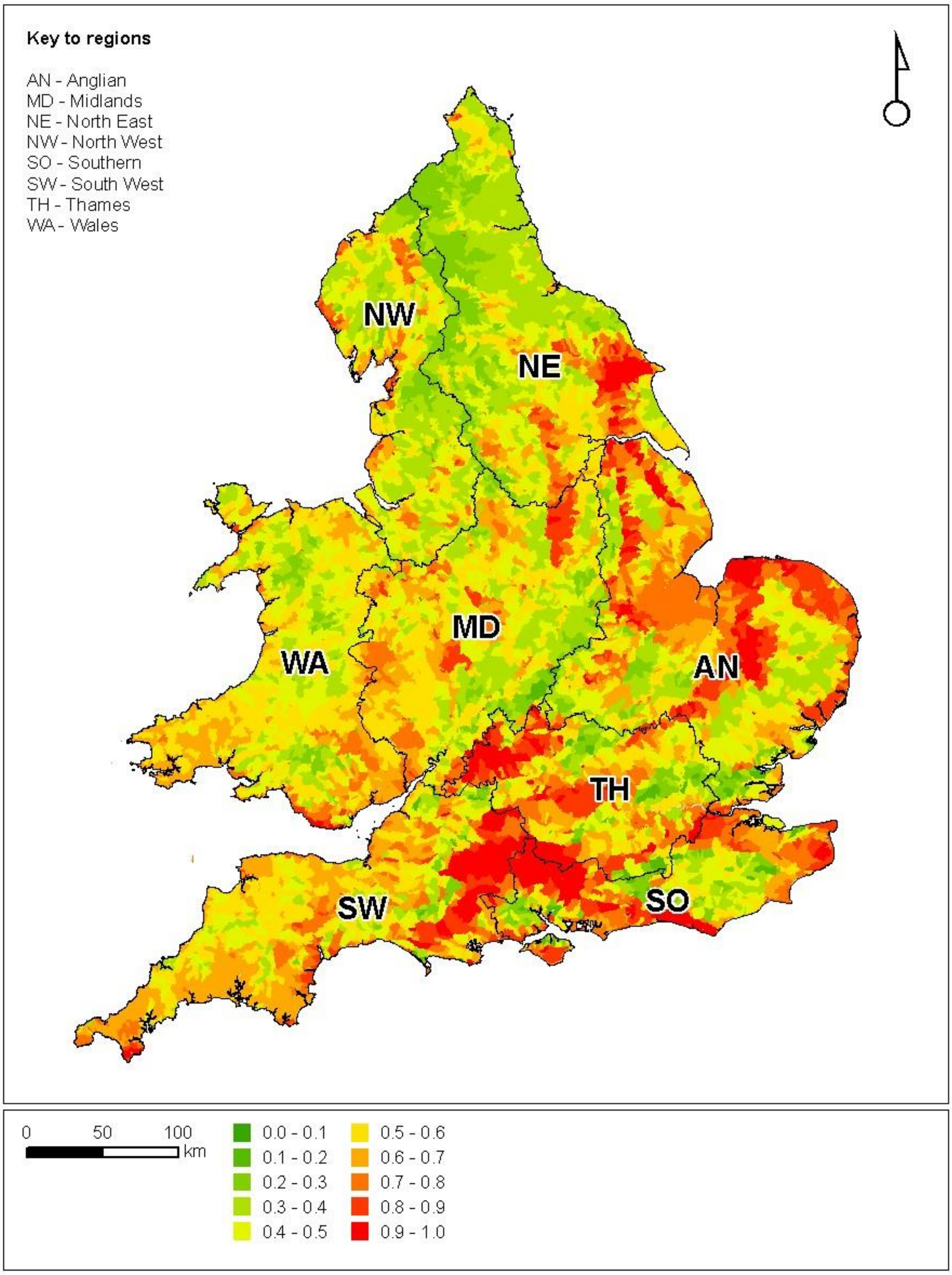

Figure 7 Sub-catchment BFI values for England and Wales

2.4.1 Temperature Records

The water temperature data collated by this project are structured by EA Administrative region (although sites can also be located in EA Water Management regions). Due to size constraints in Microsoft Access software the database is provided by region, so the NW Region database only contains NW region data.

The data structure for temperature records has been designed to best accommodate the various sources of data used in the Archive. It contains separate fields for site code, sample code, date, time, determinand, temperature value, comments.

Table 10 Record duration of Archive data by region and source

sourceCode	EA Region	Sites	Average Records #	Earliest Yr_Start	Avg. Yr_start	Avg. Yr_end	Avg. duration Yrs
DLGE	WA	1	37905	1904	1904	2008	104
EA TIMS	AN	3	125940	1986	1998	2007	8
EA TIMS	SO	3	15977	1997	2002	2004	1
EA TIMS	SW	3	35950	1997	2001	2005	4
EA TIMS	TH	117	67298	1986	1998	2005	7
EA WIMS	AN	3810	96	1972	1985	1995	10
EA WIMS	MD	3977	121	1962	1990	2001	12
EA WIMS	NE	3763	98	1965	1988	1998	10
EA WIMS	NW	3586	117	1952	1985	1997	13
EA WIMS	SO	1669	151	1965	1985	1999	14
EA WIMS	SW	5972	112	1965	1986	1997	11
EA WIMS	TH	2248	130	1969	1984	1997	13
EA WIMS	WA	5192	76	1962	1987	1995	8
EA WISKI	AN	16	55159	1991	1996	2000	3
EA WISKI	MD	38	302918	1989	1995	2004	9
EA WISKI	NE	84	76355	1992	1998	2003	5
EA WISKI	NW	3	202791	1995	2001	2006	5
EA WISKI	SO	8	48799	2004	2005	2007	1
EA WISKI	SW	19	55755	2000	2006	2008	2
EA WISKI	TH	5	24403	1997	1999	2000	1
EA WISKI	WA	42	209590	1989	1997	2004	7
EA CUMBRIA	NW	10	47932	1994	1997	2006	9
FBA-CEH	NW	7	1711	1947	1962	2007	46
UKAWMN	NW	2	35216	1999	1999	2007	8
UKAWMN	WA	2	32697	1999	1999	2007	8

2.4.2 Holdings by EA Administrative Regions and Water Body Types

The Archive holds temperature records for two to six thousand sites in each of the eight EA Administrative regions (Table 11). This corresponds to a total in excess of 30,000 sites and more than 42 million records.

The vast majority of sites are rivers, with data held in WIMS.

2.4.3 Holdings by year

Record duration is extremely variable for the 30,580 sites held in the Archive. On average, EA records have been collected over 14 years or less (Table 10). On average high frequency records for rivers (TIMS, WISKI) and lakes (EA Cumbria, UK AWMN) were initiated in the late 1980s and mid-1990s, but many of these are operated on a project basis with records terminated within 5 years.

In all, less than 10% of all sites have a sufficient numbers of records to be analysed for long-term trends between 1990 and 2006 (chapter 5).

2.5 Metadata

The Metadata component of the Archive holds EA and external metadata in a common framework, with indications of the data extent, location and availability. It also provides metadata obtained from the geographic information layers.

Following the project brief, the metadata database (Microsoft Access) can be used to select time-series length, frequency, region, water body type, [data] quality and availability. In addition, the metadata indicates sites for which statistical models have been fitted.

Table 11 Archive Surface Water Temperature – number of sites and records by Water Body type and Region

siteType	AN	MD	NE	NW	SO	SW	TH	WA	Sites
CANAL	45	275	89	195	11	63	47	64	789
COASTAL	16		21	81	61	31		59	269
DRAIN	5		17	1		4		30	57
LAKE	269	61	70	142	26	139	117	153	977
RIVER	3,413	3,663	3,564	3,155	1,541	5,689	2,176	4,830	28,031
TRANSITIONAL	81	16	86	34	41	68	30	101	457
Total Sites	3,829	4,015	3,847	3,608	1,680	5,994	2,370	5,237	30,580
siteType	AN	MD	NE	NW	SO	SW	TH	WA	Records
CANAL	7,503	35,128	104,563	22,774	2,192	4,988	35,642	39,813	252,603
COASTAL	927		619	3,421	6,793	772		41,553	54,085
DRAIN	93		531	2		72		1,225	1,923
LAKE	18,426	3,795	1,711	609,491	525	4,278	2,160	70,843	711,229
RIVER	1,160,991	11,948,497	4,859,984	949,261	647,813	1,812,082	5,559,182	9,123,913	36,061,723
TRANSITIONAL	437,637	2,775	1,814,909	5,161	32,484	12,292	2,690,176	23,538	5,018,972
Total Records	1,625,577	11,990,195	6,782,317	1,590,110	689,807	1,834,484	8,287,160	9,300,885	42,100,535

3 Statistical Methods

3.1 Introduction

Time series data have properties that require special attention, in particular non-independence of residuals due to autocorrelation and non-constant variance of residuals. These problems violate the assumptions of standard statistical methods such as linear regression. However, simple extensions to the linear regression method allow us take account of these properties of time series by explicitly modelling these features of the data.

Another feature of many environmental time series is non-linear patterns and trends. Simple linear regression is often too inflexible to accurately describe these non-linear patterns. Additive models extend linear regression by including smooth functions that are more flexible than the linear parametric approach. Thus, additive models provide a robust modelling tool that allows the data themselves to control the form of the trend and other patterns fitted to the observations.

In this chapter we report on the statistical modelling component of the research project, namely the analysis of over 3000 temperature time series from England and Wales using additive mixed models and the subsequent analysis of these models to provide temperature indices for the case studies.

3.2 Data Sources

Early in the course of the project it was decided to fit time series models to as many of the river sites in the Archive as possible, with the constraint that the modelled series covered a suitably long time period to allow for good estimation of temporal trends in temperature. Several criteria were used to select sites from the Archive to provide sufficient length of record and frequency of sampling for selected sites. Selected sites needed to meet the following criteria:

- Start prior to 1st January 1985
- End after 1st January 2007
- Comprise 250 or more individual measurements
- Measurements to be present in 120 or more months

The first two conditions were chosen to give a suitable length of record, whilst the latter two conditions were chosen to evaluate the role of observation frequency within each time series. A compromise had to be made in terms of the length of record, observation frequency and the number of sites selected as computer time needed for the modelling was known to be a limiting factor.

2,687 sites met these criteria, a sample which represented reasonable spatial coverage for England and Wales, with the exception of the Midlands EA region, where very few sites were selected. This lack of data may be due to routine monitoring of water temperatures not being undertaken in this region until after 1985, or, more likely, to the fact that data for the relevant period were not in the WIMS database made available to us.

To increase the spatial coverage and include sites in the Midlands region in the statistical analysis, a second tranche of sites were selected where the start date criterion was relaxed to include series that started on or before 1st January 1990. The other criteria remained as per the above, so as obtain only good quality, shorter time series. A further 470 sites were selected in this manner, to give a total of 3,157 sites.

Figure 1 shows a map of river site locations.

A separate analysis of lake sites was also undertaken. The Archive meta-database contains far less information on lake spot-temperature measurements. We retained the same selection criteria for the lakes as for the rivers described above. 26 lake sites had time-series that started prior to 1985 and a further 5 sites started prior to 1990, giving a total of 31 lake sites analysed. A map showing the locations of lake sites is shown in Figure 3.

3.3 Trend analysis of spot-sampled temperatures

Following initial exploratory data analysis on selected time-series data from the Archive, we recognised that there were large variations in the sampling regime within an individual site and often significant changes in sample frequency. We concluded that working with aggregated monthly data was not appropriate, especially since the frequency of observations changed markedly through time in many records. A trend in the monthly minimum temperature could be induced in the data simply by virtue of the sampling frequency per month declining through time as there is reduced chance of observing an extreme temperature in any given month, for example.. A decision, therefore, was made to use the primary spot data for analysis and develop additive models to identify trends and patterns in the temperature time-series (cf Ferguson et al 2006, 2008).

This modelling approach allows for the lack of independence of the observations in the time series arising from the fact that the same entity is being observed through time and for the irregular spacing of the samples. We also used the sample record day of year (doy) to model the seasonal component in the time series, allowing predictions from the models to be made at a daily time step.

To determine whether there were significant trends in the temperature time series, we have used a likelihood ratio test (LRT) of models with and without trends. Likewise, models with linear and non-linear trends were compared using LRTs to determine the type of trend present in the data In cases there the trend has been found to be linear we have fitted a semi-parametric version of the additive model. Full details are provided in Appendix.

3.4 Estimation of temperature indices

A number of temperature indices have been devised from the best-fitting model results for each site. To ensure that all sites are comparable, we have used simulations from the fitted models to provide daily predictions for the period 01-01-1990 to 31-12-2006 for each model. From the simulated predictions we have then computed the expected mean, minimum or maximum temperatures per year and per quarter for each year. For the 2,687 sites where recordings began before 1985, the models used to produce the simulations were fitted to the observations from 01-Jan-1985 to 31-Dec-2006, but simulations were only taken from the period from 1990 onwards.

The systematic component of the model (the part excluding the residuals, ε, see Appendix) is not likely to provide predictions that are accurate enough for this purpose as the model is fitted to the average pattern within the time-series and does not capture the stochastic nature of the original observations. To replicate the stochasticity in the observations, we have simulated 1000 time series from the model using the model predictions plus random draws from a normal distribution with mean 0 and variance equal to the variance of the residuals of the fitted model.

For example, given a time-series of observations and a model fitted to those observations, we have first taken the daily predicted values from 1990 to 2006 from the model itself, yielding predictions for 6,208 days. We have taken 6,208 random samples from a normal distribution with mean 0 and variance equal to the variance of the model residuals. We have then added the 6208 predicted daily values to the 6208 random normal deviates on a one-to-one basis. In this way, each daily simulation is the sum of the prediction from the model for that day plus a stochastic component provided by the corresponding random normal deviate.

This process is repeated 1000 times, and to obtain estimates of the daily temperatures predicted from the model, we have calculated daily averages over the 1000 simulations. To assess the uncertainty in these simulations, we have also calculated the upper and lower 95% prediction bands, by taking the upper and lower 0.025 quantiles of the 1000 simulated values for each day.

The simulations are aggregated by year, to give annual estimates of minimum, maximum and average daily temperatures.

For the dragonfly case study, simulated daily temperatures are aggregated by quarter and by year to give a time-series of quarterly minimum, maximum and average daily temperature. For the salmon case study, the number of days less than 10°C, greater than 21 and 20°C and between 15 and 17°C are computed for each year.

4 Reconstructing missing data from air temperature

4.1 Introduction

Most time-series in the Archive have periods of missing observations, due lost or missing data, data entry error, instrumentation failure or funding cuts.

The modelling framework used above allows for irregularly spaced records by using data in the rest of the year and from other years to fit its seasonal cyclic component. But when data are missing over a year or more or during periods that are crucial to monitor, it may be beneficial for the missing values to be in-filled in some way using widely available air temperature data.

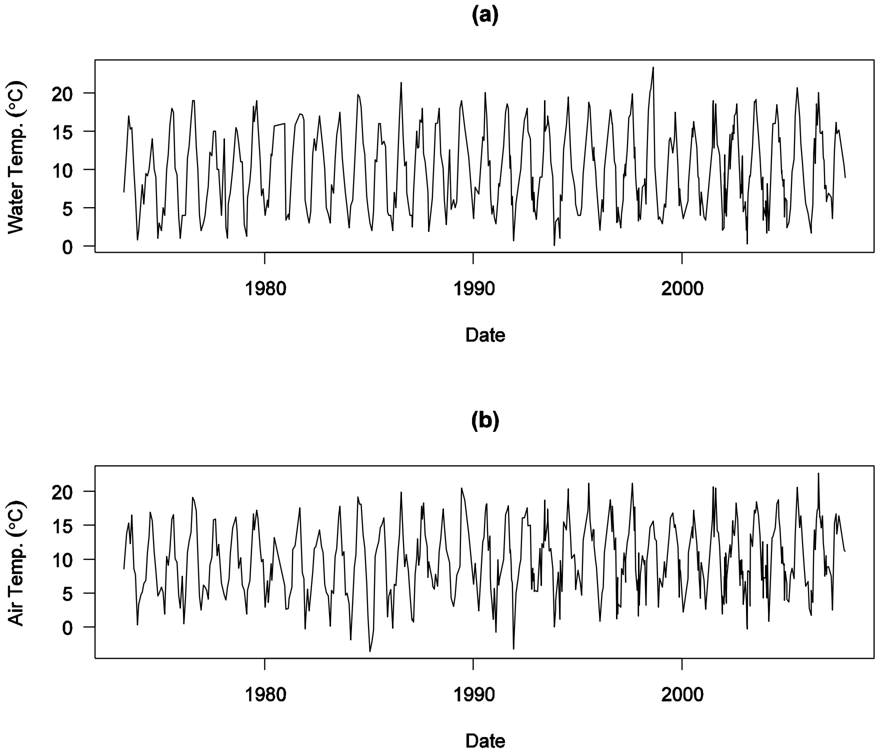

Figure 8 (a) Water temperatures for the Coquet at Warkworth Dam - NE (b)Central England Air temperatures

The strong covariance between air and water temperatures is illustrated in Figure 8 and Figure 9 for the Coquet at Warkworth Dam in the Northeast Region, a site (42300080) sampled quasi-monthly from April 1973 to date. The relationship between daily air temperatures from the Central England Temperature time series and the Coquet water temperatures for the days when water temperature is generally linear but its slope varies from month to month (Figure 9).

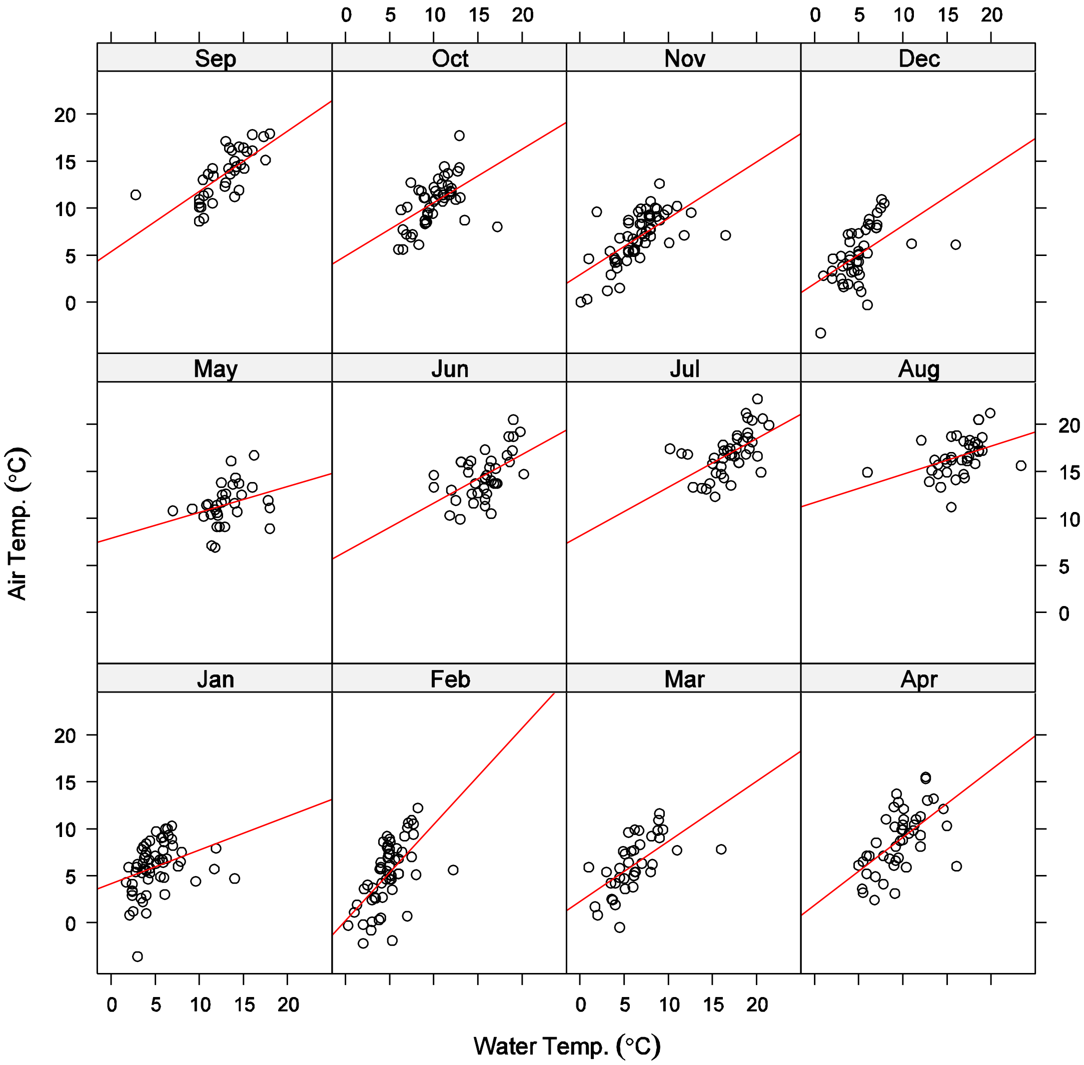

Figure 9 Coquet water and Central England Air daily temperatures 1973-2007

4.2 Air-Water temperature model

The relationship between air and water temperatures is described with an additive model with a cyclic smoother for day of year of observation (doy) to ensure a smooth transition between December and January temperatures to model the seasonal component in the air-water temperature relationship.

A smoother for air temperature is added to check for linearity in the relationship between air and water temperatures and then dropped on the basis of Likelihood ratio tests and AIC values that both confirm a linear relationship between air and water for the site. The fitted model is significant at the 95% level (F = 457.41 on 1 and 5.56 degrees of freedom, p = << 0.00001). The fitted model explains 82.5% of the deviance in observed water temperatures from the site (minus the “missing” data) and has an adjusted R2 of 0.824, suggesting high predictive ability.

Example for Coquet at Warkworth Dam (site 42300080, NE) Figure 10 shows the fitted smooth function for day-of-year (doy). It seasonality combines with the estimated linear coefficient for the effect of air temperature, which changes by 0.4908°C in water temperature for each 1°C change in air temperature. Thus the actual effect on water temperature of a unit change in air temperature is positive or negative depending on the time of year.

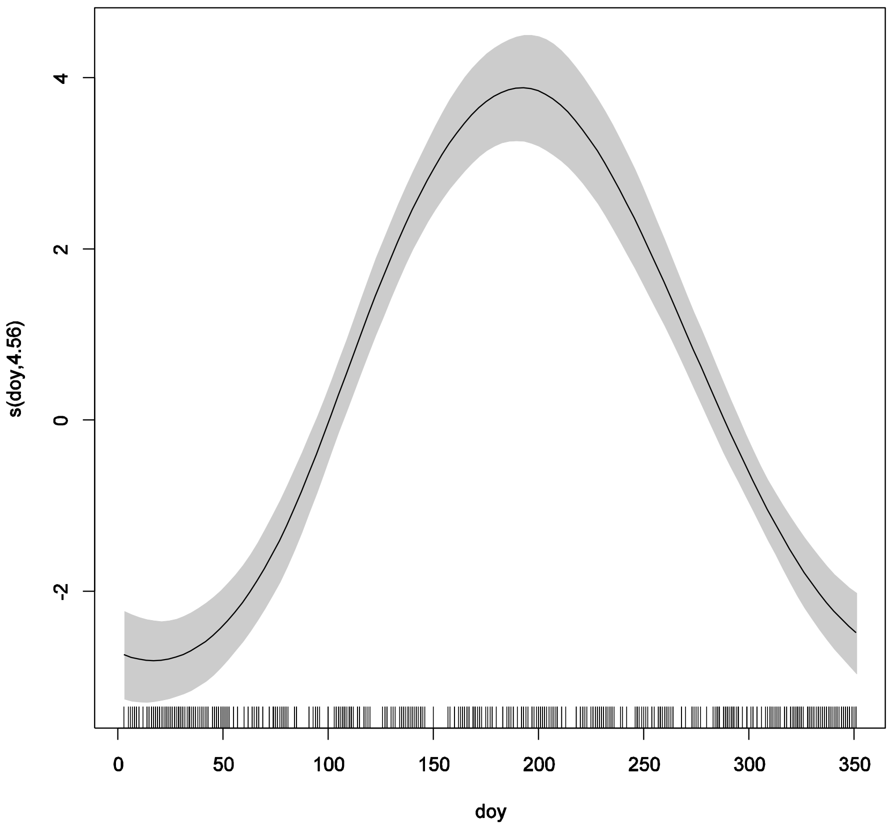

Figure 10 Site 42300080 - fitted smooth function between for day of the year (doy)

The ability of the fitted additive model to predict water temperatures is assessed from the root-mean squared-error of prediction (RMSEP) by predicting for the observations that were removed (years 1985-1987) using the fitted model. Two estimates of the RMSEP are computed, one based on the direct model predictions themselves, and the other based on predictions for the missing values obtained via simulation. The process of simulating from the model is the same as that described in section 3.4 to estimate temperature indices from the model-fitted trends. The mean of the 1000 simulations gives the predicted value, and the 95% prediction bands are given by the upper and lower 0.025 quantiles of the 1000 simulated values for each missing observation.

The RMSEP based on simple model predictions and computed on the predicted values for the “missing” data is +/- 2.26°C. A plot of the fitted versus observed water temperatures is shown in Figure 11 for the “missing” data. The predictions follow the diagonal 1:1 line closely with no systematic variation from this line.

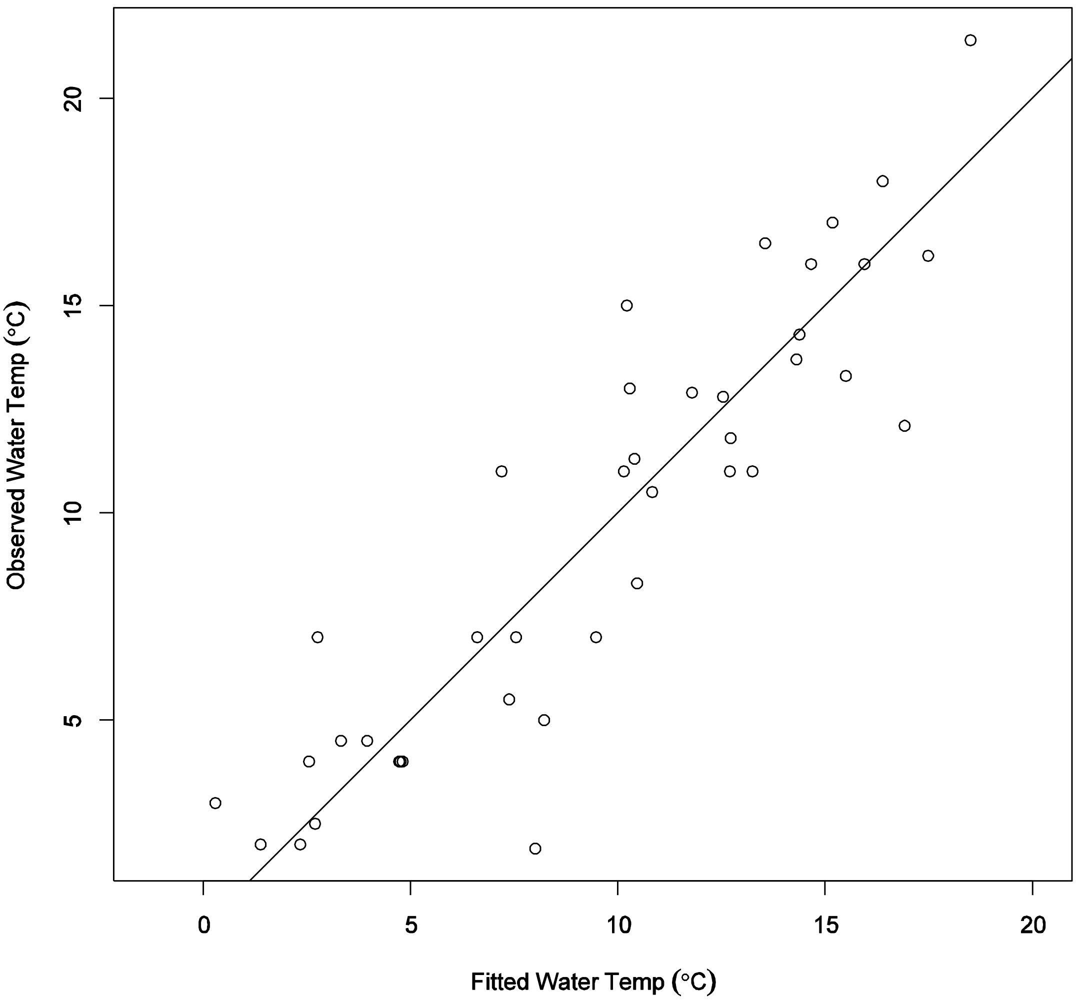

Figure 11 Site 42300080 - Observed and reconstructed water temperatures

The predicted values follow the observations very closely. Figure 12 shows a close-up view of the "missing" data section, with the fitted time-series (solid line) and dashed lines giving approximate 95% confidence bands on the fitted function. It also shows some discrepancy at the start and end of the reconstructed section, especially at the end of the period. There is also discrepancy between the observation in the summer of the middle missing year and the predicted value. Apart from these, predictions agree well with observed values.

Finally, predictions based on the 1000 simulations from the fitted model (Figure 13) show that the actual observations are consistent with the form of the fitted model. Not much significance should be attributed to the fact that a single observation lay outside the 95% prediction intervals as, for example, we would expect 2 such observations in the long run to lie outside the prediction interval for a sample of 40 observations. With the exception of the last "missing" observation at the end of the three-year period, all the remaining observations lie within the prediction intervals.

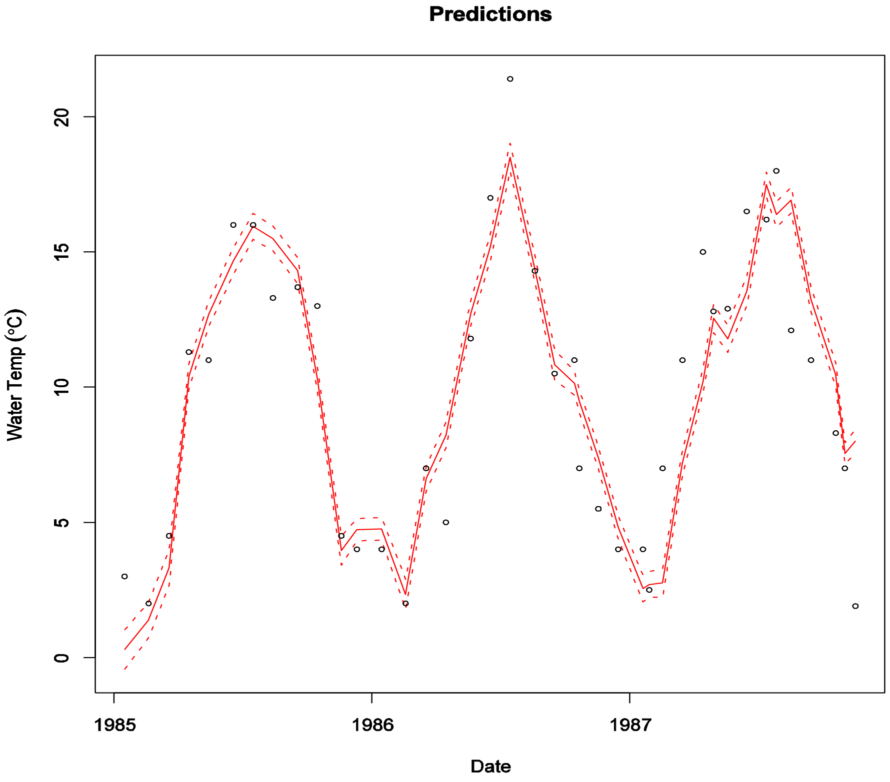

Figure 12 Observed (dots) and reconstructed (lines) water temperatures

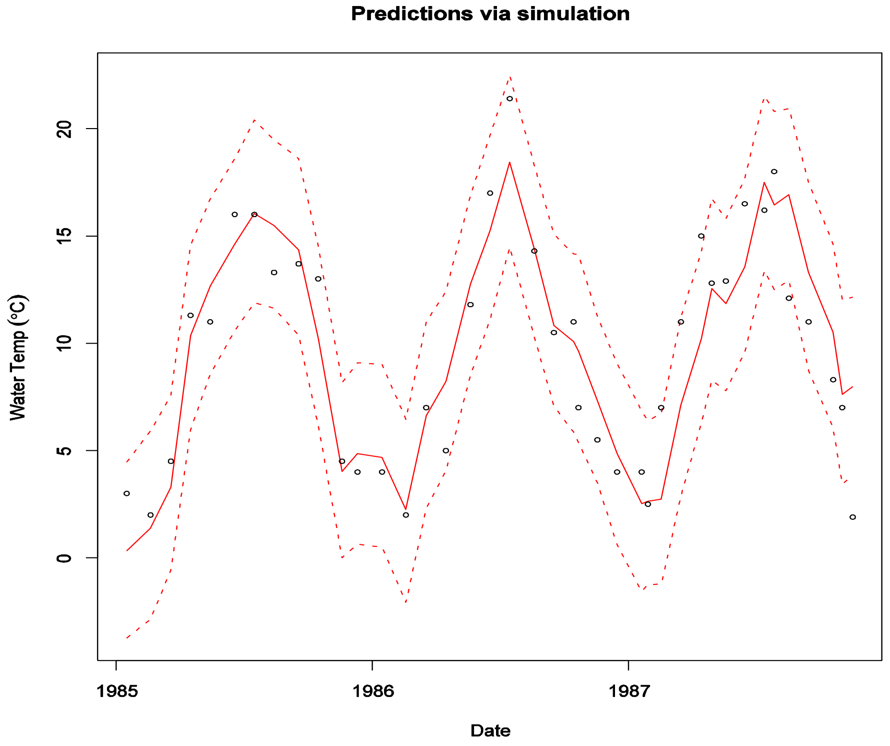

Figure 13 Observed (dots) and simulated (lines) water temperatures

There is very little difference between the two sets of predicted values, suggesting that both methods of predicting from the model perform well. The calculated RMSEP for the “missing” data is 2.28°C, effectively the same as the RMSEP for the simple predictions.

This example shows the utility of infilling or predicting water temperatures from air temperatures. High predictive power is achieved, even when using none co-located temperature data;

Because air temperature is entered in the model as a linear, parametric term, it raises the potential of using models, like the one fitted here to the Coquet, for forecasting future possible changes in water temperatures under climate change scenarios using GCM output. Forecasts from the model can be performed on a daily time-step and, therefore, the temperature indices described in 3.4 for the case studies from the fitted trend models could also be computed for future water temperatures under different climate change scenarios. This will allow forecasts to be made of the effects of varying levels of climate change on sensitive organisms or those of conservation importance.

The approach presented here may be taken to infill missing observations within time-series and also to predict future time-series given General Climate Models (GCM) output for air temperature under climate change scenarios. The approach is conceptually similar to the one used to model trends in observed time series, although time in this case is not used as a covariate in the model.

5 Temperature Trends

5.1 Introduction

The Scoping study (Hammond and Pryce, 2007) analysed monthly, seasonal, annual and decadal mean temperatures for selected river sites in three separate steps, and estimated trends in linear rates of temperature change, within and between regions.

The methodology used in this project and presented in the previous Chapter is both more complex and more flexible, and makes it possible to extend the analyses to a large number of sites and to water-body types other than rivers where water temperature data have been sourced.

The project was tasked to explain past temperatures, but the analysis of data from all eight EA Regions in England and Wales rules out the development of detailed thermal regime models such as reviewed by Caissie (2006) and recommended by Webb et al. (2008) at the sub-catchment scale.

The primary aims of the data analyses are:

- to explore the changes in temperature over the years in the different regions and water body types; and
- to establish how significant the identified changes are.

5.2 Data Analysed

This project has made no attempt to correct the data in the Archive, but a series of filters are devised to select sites with adequate records for analysis.

The first selection used dates and record numbers as follows:

- start date prior to 1st January 1990 and end date after 1st January 2007;
- at least 250 records in at least 120 months.

These conditions yield 3133 River sites and 31 lake sites for which past temperatures have been modelled. The second step introduces a more stringent record date condition and uses temperature record values and predicted temperature increases between 1990 and 2006 in the criteria below:

- one or more entire year of records missing between 1990 and 2006
- sites with one of more temperature record >35°C or <0°C, and
- 4% of the 2890 river sites with extreme predicted annual temperature increases (58 sites>1.005°C and 59 sites<-0.527°C).

A further river site (88002704, NW Region) with severe recording anomalies in the early 1990s summers has also been omitted.

A total of 2,799 sites, 2772 river sites, 26 lake sites and the coastal site of Port Erin (coded as being in Wales), are analysed further in this chapter (Table 12);

Table 12 Sites analysed for 1990 - 2006

siteType	AN	MD	NE	NW	SO	SW	TH	WA	Sites
COASTAL								1	1
LAKE	13			7				3	23
RIVER	544	286	266	278	348	411	323	316	2,772

5.3 Data quality problems

Our two-step filtering process cannot entirely address the lack of water temperature data validation, which will need to be addressed by regional and national data providers if the Archive is to be developed in the future.

Problems of data quality in the Archive cannot be overstated. Some have been raised in previous chapters, but it is clear that the water temperature data, apart from the sites from non-EA providers, have not been validated in any consistent fashion.

Data validation needs to be done by the data owner at source. Our attempts at filtering the worst cases such as exemplified below cannot replace a rigorous quality assurance process by data providers.

Some of the most obvious data quality problems illustrated below are given as a warning to any future Archive user. We stress the need to scrutinise the data for each and every site before use, something that could not be done for this project. Thus, as stated in other parts of this report, and even though the analyses procedures have been thorough, the results presented here must only be taken as indications of general trends.

5.3.1 Outliers and other recording problems

Data entry errors

Of the 3,133 River sites with enough data to be statistically analysed, 42 were found to have one of more records of a water temperature greater than 35°C, or below 0°C. The example below (Figure 14) shows how such records can influence a linear rate of change over time given here by the slope of a fitted straight line, particularly when the erroneous outlying value is at one or the other end of the time-series.

It would seem that many extreme outliers are due to a keying in error, with a decimal point missing, leading to near-boiling temperatures in winter as for the Shalbourne Stream Site (PKER0079) in the Thames Region. For future use, such records could be filtered out using regionally or locally defined known min-max boundaries rather than excluding from analyses in the entire site time-series as was done here.

Other cases may be more complicated as illustrated next.

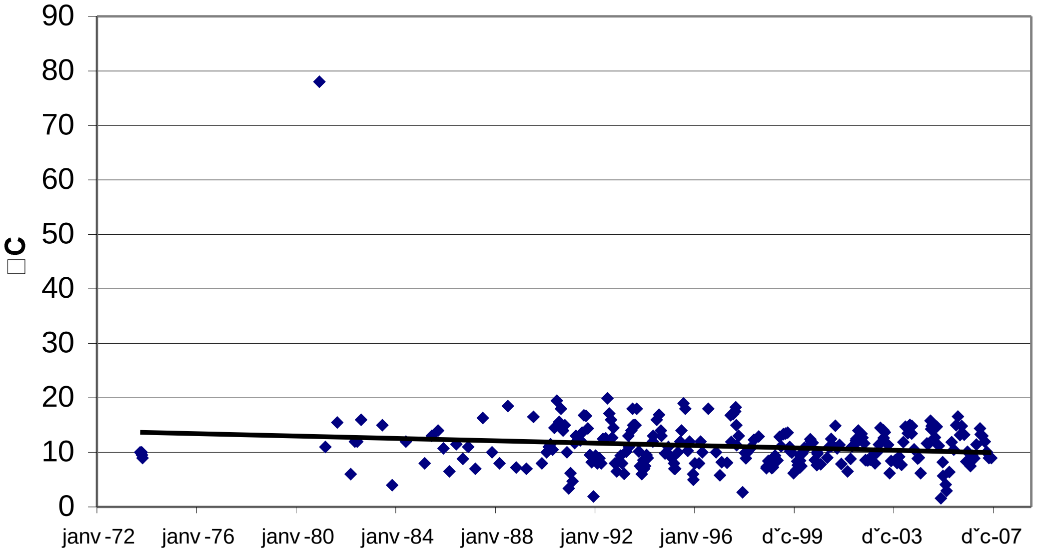

Figure 14 Typing error outlier - Site PKER0079 Shalbourne Stream - Thames

Temperature recording errors

Some recording errors are probably due to thermometer malfunction rather than data entry. This was signalled to us for some NE transitional sites where recorders may have been fixed on a jetty and thus may hang high and dry at times. The site below shows a less obvious problem that was picked up from an estimated decadal increase in summer temperatures of 2.34°C, with an annual increase less that the 1.005°C cut-off point of 2% outlier values indicated above.

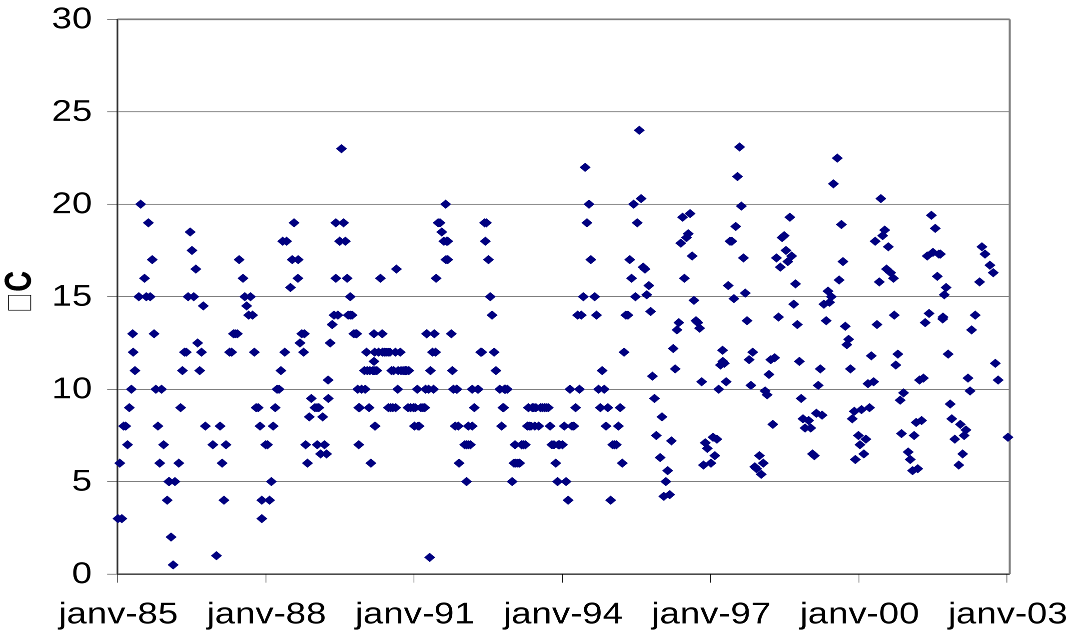

Figure 15 Recording errors - Site 88002704 Sankey Brook – Northwest

The points we want to make are that

- estimated trends are highly sensitive to irregular breaks in the temperature records, particularly those that affect seasonal and annual high and low values, even in the middle of the time series; and that
- a large number of sites, particularly those with longer time series that can be used in trends analyses, may have problematic records.

Missing records

Missing records can also introduce bias in time-series analyses when they affect specific time periods in a way that interferes directly with the statistics being estimated. In the case of long-term trends, records missing at the beginning or end of the time-period can introduce higher bias than records missing in the middle. Similarly records missing in the summer and winter seasons may unduly influence the estimation of annual mean temperatures. The worst-case scenario, for the models used here that estimate seasonal and long-term trends together, is illustrated by Sites in Figure 16 and that have a combination of missing records at one end of the time-series except for a few relatively warm records.

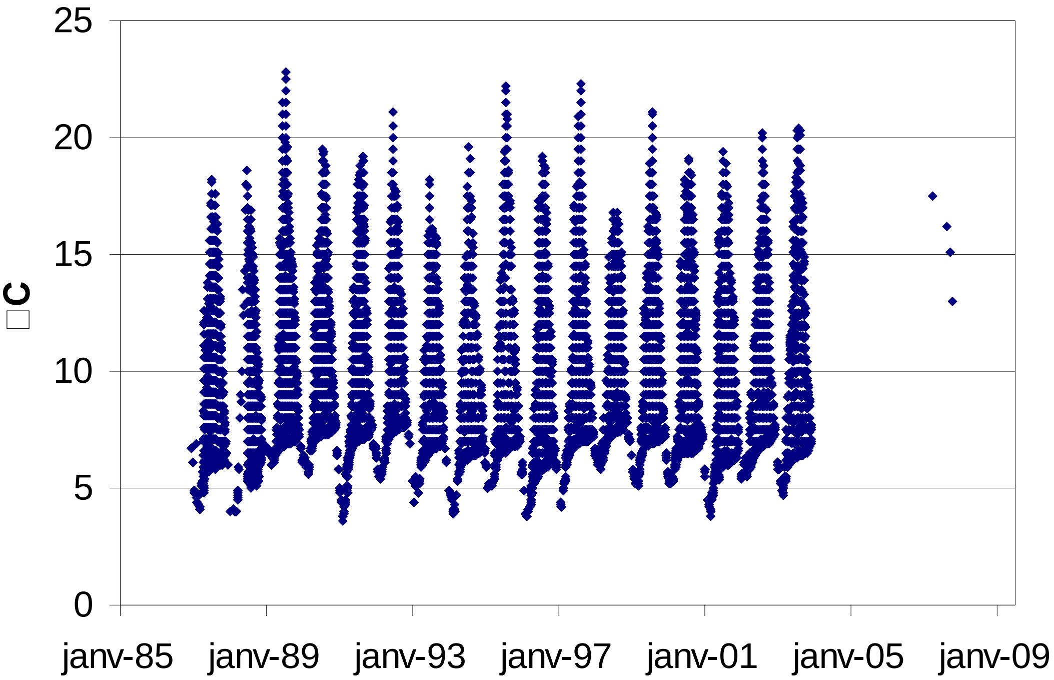

Figure 16 Missing records - Site 88016097 Windermere North Basin - Northwest

Both Site 88016097 (Figure 16) and Site 49301483 (Figure 17), and in total 178 river and 5 lake sites, are left out of further analyses for missing one or more whole year of data between 1990 and 2006.

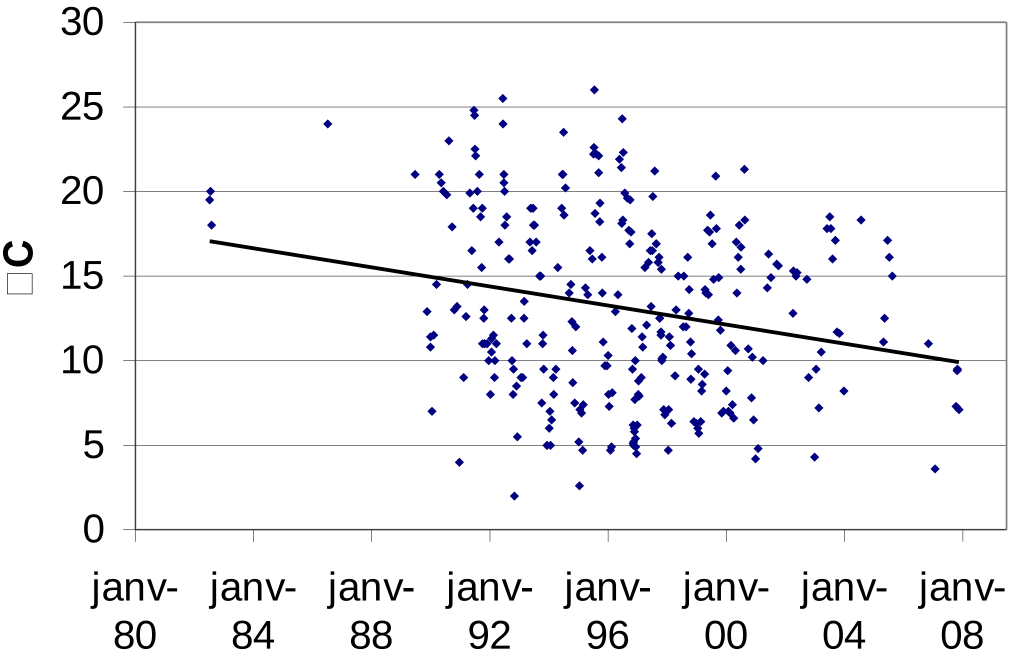

Figure 17 Missing records - Site 49301483 Doe Lea – Midlands

Other problems

The case is more complex for Site 40350 on the Ebbw Fawr at Victoria Bridge in Wales illustrated in which shows a wide and untypical amplitude of recorded temperatures in the first half of its time-series and overall large decrease in temperatures, seemingly on both an annual and a seasonal basis.

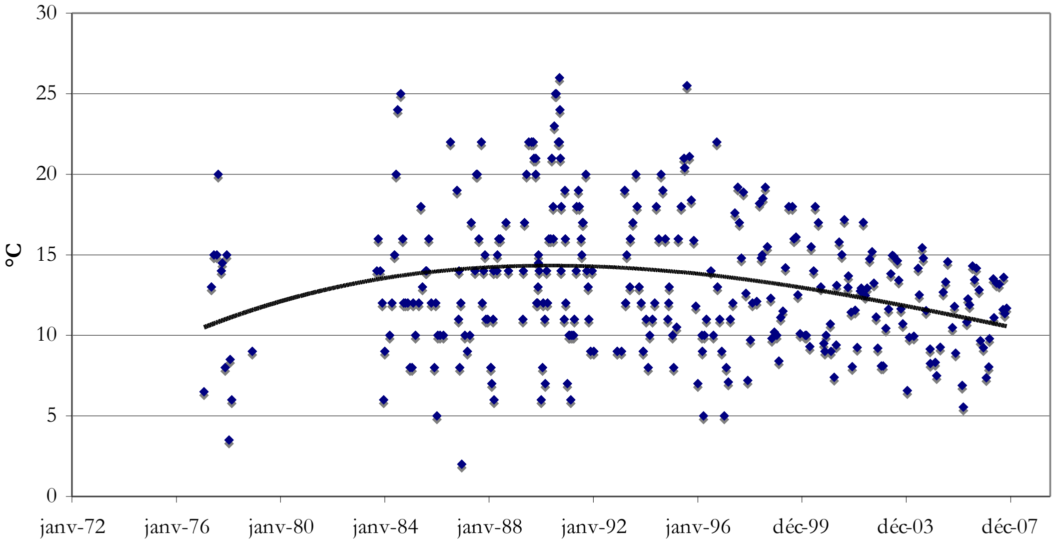

Figure 18 Uneven sampling frequency - Site 40350 Ebbw Fawr - Wales

One contributing factor for the change in amplitude of recorded temperatures over time lies with the changes of sampling effort expanded during the 31-year period. From Table 13 we see that the beginning of the time series is patchy, with few records in 1977, 1978 and 1983 and years missing in between. 1977 and 1984 have nearly one record per month, but 1978, 1983, and 1988 to 1994 included have winter records missing or under-represented, leading to a relative predominance of warmer records until 1994.

In Figure 19, sampling effort at the site is represented as an index of record numbers by month, with month numbers recoded from -6 for January to +6 in December. An average sampling index near zero or zero is obtained when sampling is regular and each month has the same number of records, such as for 1995 and 1997. It is negative from relatively more records in the first 6 months of the year (1989), and positive with more records for the second half of the year such as in 1988.

Table 13 Records per months and year for Site 40350 Ebbw Fawr - Wales

40350	01	02	03	04	05	06	07	08	09	10	11	12	Rec.
1977	1				1	1	1	1	1	1	1	1	9
1978	2	1										1	4
1983									1	1	2	1	5
1984	1		1	1	1	1	1	1	2	1	1	1	12
1985	1	1	1	1	1	1	1	1	1	1	1	2	13
1986	1	1		1			1			2	2	2	10
1987	1		1	2		1	2	1	2	1	2	1	14
1988	2	2	3	2	1	1		1	1				13
1989				2	1	1	1	2	2	3	4	1	17
1990	3	2	2	1	2	2	3	1	5	2	2	2	27
1991	2	2	2	2	2	2	2	2	1	2	2	1	22
1992	1											2	3
1993		1	4	1	1	2	1	1	2	1	1	2	17
1994	1	1	1	1	1	1	1	1	1	1	2	1	13
1995	1	1	1	1	1	1	1	1	1	1	1	1	12
1996	1	1	2	1	1		1	1	1	1	1	1	12
1997	1	1	1	1	1	1	1	1	1	1	1	1	12
1998	1	1		1	1	2	1	1	1	1	1	1	12
1999	1	1	1	1	1		1	1	1	1	1	1	11
2000		1	1	1	1	1	1	1	1	1	1	1	11
2001	1	1	1	1	1	1	1	1		2	1	1	12
2002	1	1	1	1	1	1	1	1	1	1	2		12
2003	1	1	1	1	1	1	1	1	1	1	1		11
2004	1	1		1		1	1	2		1	1	1	10
2005		1	1	1	1		1	1		1	2		9
2006		1	1	1	1	1	1	1	1	1	1	1	11
2007	1	1	1		2	1	1		2	1	1		11

The erratic sampling regime may explain the observed non-linear increase in annual temperatures (illustrated by a cubic spline in Figure 18) to 1992, but it cannot be invoked to account for the decrease after that period, and one would need to look into site-specific, local and regional conditions in order to explain this further. However, with a predicted decadal change in average annual temperatures of -2.247°C over the 1990 to 2006 period, this site was one of the 59 with a prediction lower that the 98% lower percentile value of -0.527°C per decade.

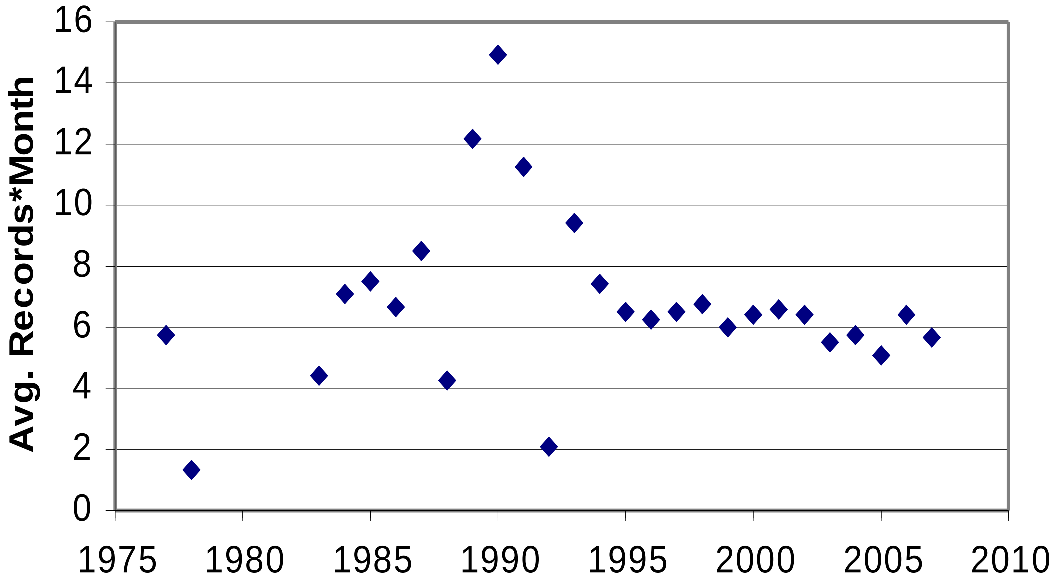

Figure 19 Sampling effort index – Site 40350 Ebbw Fawr - Wales

A further 58 sites that had an expected average decadal increase in annual temperature greater then 1.005°C, and another (8800274 NW) with a predicted seasonal decadal increase >2°C were excluded, leaving 2,772 River sites in our analyses.

5.4 Trends for Port Erin

The only coastal site analysed for this project is the time-series of daily records from the Port Erin Marine Laboratory on the Isle of Man, collected since 1 January 1904 and currently supported with funding from the Department of Local Government and the Environment (DLGE)[2].

5.4.1 Published Trends in Sea Surface Temperature (SST)

Trends in Sea Surface Temperature (SST) around the British Isles are well documented and provide useful background to discuss estuarine trends. Winter usually brings colder temperatures from the Atlantic to the coasts of the Southwest and Southern regions up to the Anglian region in the North Sea, while the North Sea (Anglian, Northeast) and Irish Sea (Wales) experience warmer summer temperatures (see Hughes and Holliday, 2007).

In its 2007-08 Annual Report Card, the Marine Climate Change Impacts Partnerships (MCCIP, 2008) reports with 'High confidence':

- marine air and SST have been rising at a similar rate to land air temperature, but with strong regional variations;

---

[2] We are grateful to Theresa Shammon for the Port Erin marine Laboratory for kindly providing the data files.

- since the 1980s the rate of rise has been about 0.2–0.6°C per decade;
- warming has been faster in the English Channel and southern North Sea than within Scottish continental shelf waters;
- 2006 was the second-warmest year in UK coastal waters since records began in 1870; seven of the 10 warmest years have occurred in the last decade;
- climate change models indicate that SST will continue to rise in all waters around the UK coast, with stronger warming in the south-east (~0.15–0.4°C per decade in the southern North Sea) than the north-west (~0.05–0.2°C per decade at Rockall).

SSTs at offshore stations do not always closely reflect surface water temperatures along the coast or in estuaries, although covariance has been demonstrated (MacKenzie and Schiedek, 2007). A map of mean annual SST for 2006 in the Report Card provided by the NERC NEODASS satellite service shows important differences in temperatures around the coasts and estuaries in 2006, with colder waters along the coast of the NE region and warmer water around the Southwest. A thorough investigation of available SST data is needed to underpin a better understanding of changes in coastal and estuarine waters.

5.4.2 Estimated Trends

The analysis of Port Erin Sea Surface Temperatures gives an estimated decadal rate of increase of 0.625°C over the period 1990 to 2006.

It confirms previous analyses of the time-series (see Feeley et al, 2006 and [3]). However, average annual temperatures have kept increasing year on year since last analyses, as show Figure 20.

The estimated annual mean SST at Port Erin for 2007 was 0.56°C warmer than that for 1998, and 1.17°C higher than the 1961 to 1990 reference period used by UKCIP08 and on Figure 20.

---

[3] http://www.oceannet.org/medag/reports/IACMST_reports/MCP_report/ch_temp/ MCPreport_ temp. htm #temp_sub4

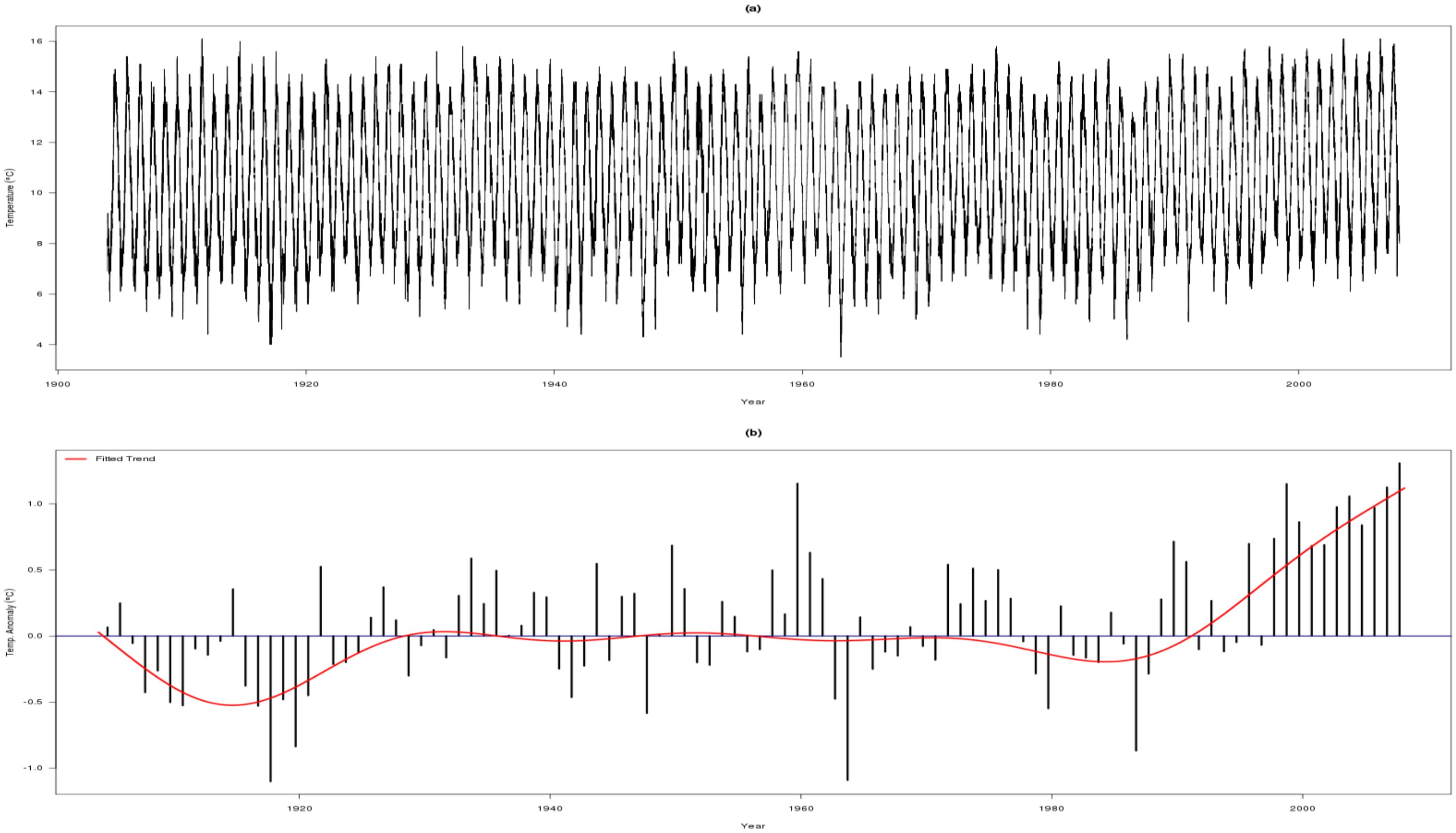

Figure 20 Port Erin SST records- annual anomalies to 1961-1990 and estimated trend

5.5 Trends for River sites 1990 – 2006

5.5.1 Published Trends

River temperatures have been chosen as potential ‘Main Indicators’ for the 2008 EEA report on Climate Change Status and Impact Indicators. In its preliminary report (Task 14 in prep), the EEA European Topic Centre on Water has found, despite few long-term records of river temperature, that positive trends dominate in streams and large rivers such as the Rhine and the Loire showing “significant increases of 0.05 to 0.3^{o} C decade^{-1} while negative trends are lacking”.

The UKCIP08 review of air temperature change in England and Wales (Jenkins, Perry and Prior, 2007) shows clear regional and seasonal differences that follow a South-North and East-West gradient, with the Southeast of England (SO, TH, AN Regions and part of MD and SW) experiencing the highest annual increases between 0.3°C and 0.4°C per decade over 1971 and 2000, with reference to the 1961-1990 period (see their Fig 2.8).

The EEA report (deWit, in prep) also notes many streams have shown an increase in water temperature of 0.6 to 0.8^{o} C upon each 1^{o} C increase in air temperature.

5.5.2 Annual averages

The estimated annual average temperatures by region for the 2,772 river sites with enough data between 1990 and 2006 are given in Table 14 together with the estimated decadal change over the 1990-2006 period[4].

In 1990, the annual average river temperature is 10.78^{o} C. Regional averages range between 10.01^{o} C and 11.57^{o} C. Baseline temperatures in 1990 are mapped on Figure 21 for each river site analysed. To allow for easier comparison, the colour scheme used for this map is the same as that used by UKCIP08 for their map of reconstructed mean annual air temperatures over 1971-2000 (their Fig. 2.6).

Despite caveats regarding data quality and modelling limitations raised in the previous two chapters, reconstructed 1990 river water temperatures show the following:

- estimated annual river temperatures in 1990 and overall higher than the 1971-2000 annual average air temperatures. Overall, the colouring of Figure 21 is one colour bin (2^{o} C) higher;
- geographical differences in air temperatures are very apparent in river temperatures, with lower annual average water temperatures in areas of higher relief in the West and North and higher annual averages in the lowest areas of the South, Southwest up to the Anglian fens and the coastal lowlands of south and north Wales and Merseyside (see also Figure 5).

---

[4] Daily temperatures time series estimated for each site between 1st Jan. and 31st Dec. are averaged for each year; decadal change over the 17 years between 1990 and 2006 is: 10*(Avg.06-Avg.90)/17

Figure 21 Estimated 1990 Annual Surface Water Temperatures

Table 14 Estimated Average Annual Temperature 1990 and decadal change to 2006

EA Region	AN	MD	NE	NW	SO	SW	TH	WA	Overall
Sites	544	286	266	278	348	411	323	316	2772
Avg. 1990	11.18	10.52	10.01	10.16	11.11	10.94	11.57	10.12	10.78
Dec.06-90	0.21	0.29	0.21	0.33	0.27	0.37	0.30	0.34	0.29
Avg. 2006	11.54	11.01	10.36	10.73	11.57	11.56	12.08	10.70	11.26

5.5.3 Trends for Annual averages

The overall temperature change equivalent per decade between 1990 and 2006 is 0.29°C, from the annual average river temperatures across all regions, sites and catchment types of 10.78°C.

There are differences in both annual mean temperatures and decadal changes between Regions, although none of them is significant, given a very large variability within Regions. We first note that average decadal changes are increases in all Regions, and in agreement with published figures for water and air temperatures. Second, we also see South to North and West to East differences in the 1990 annual means Annual mean water temperatures are cooler in the North (NW, NE) and uplands of Wales (WA), and warmer in the South (SO, SW) and lowlands (TH, AN).

The picture is more complex on a site by site basis. The map of decadal increase over 1990-2006 (Figure 23) shows a large within region variability, with some sites showing a decrease over the period (blue spots) in all regions. Its legend has been devised to be comparable with the UKCIP08 map for the change in annual average daily mean temperature between 1961-1990 and 1971-2000 (their Fig. 2.8). The following points can be made:

- the overall decadal increase of 0.29°C is higher than the 0.2°C/decade over the past 25 years estimated by UKCIP08 (Jenkins et al, 2008). This may be due to our estimates over the 17 years between 1990 and 2006, which have been warmer than the previous 8 years;
- overall, the decadal change in Figure 23 shows a more complex picture for river than for air temperatures (UKCIP08, Fig. 2.8);
- there are areas of higher river water warming not just in the South of England, but also in Cornwall, near Bristol and in the NW region;
- some higher warming is associated with river sites than were warmer than average in 1990, but sites in the SW, NW and south WA regions are estimated to have warmed up more than their baseline temperatures or the decadal air temperature increase suggest.

Differences between regions is higher for the estimated decadal change over the 1990-2006 17-year period than for the 1990 regional means (Figure 23, Figure 24), but it is worth noting that the western Regions (NW, SW and WA) show a somewhat higher increase than the others, which may be linked to higher recent SST increases in the Irish and Celtic Seas over the period, as was illustrated by the Port Erin records (Figure 20).

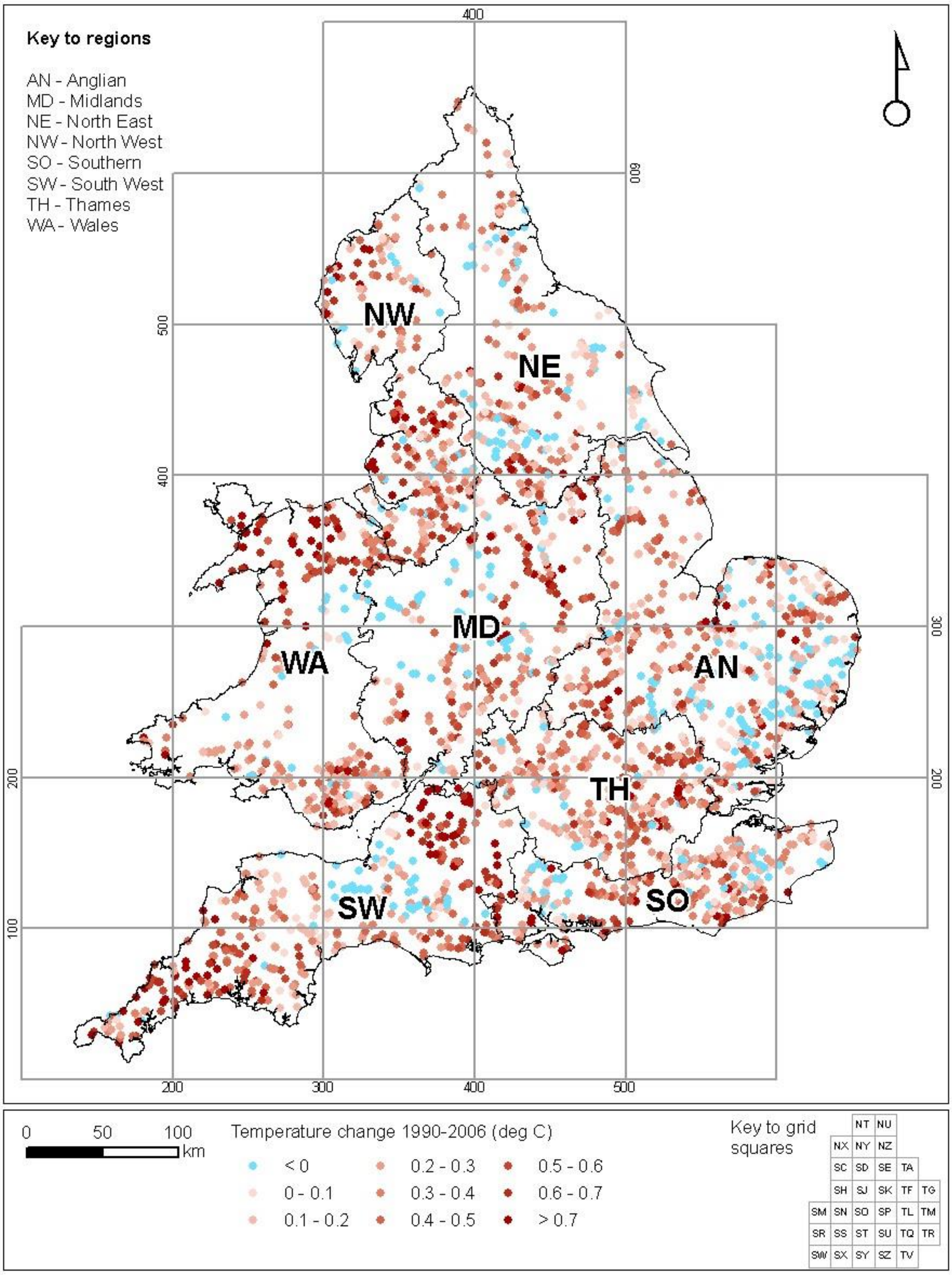

Figure 22 Map of estimated decadal 1990-2006 Annual Surface Water Temperature change

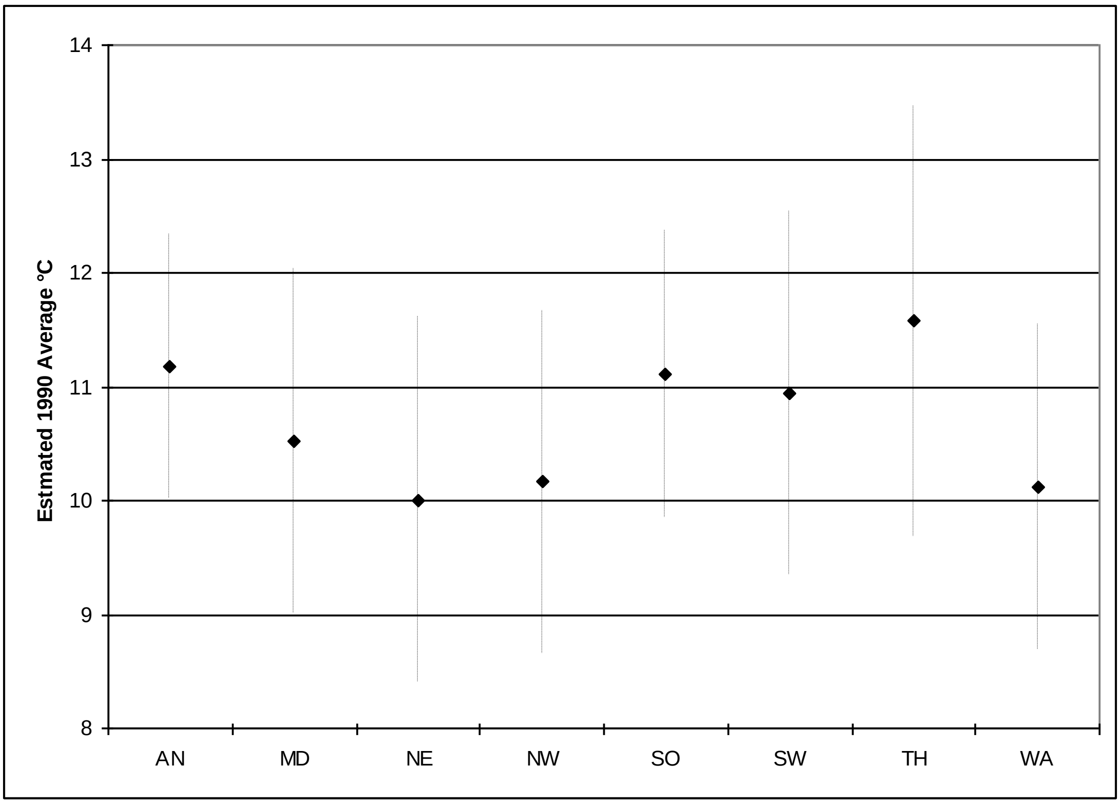

Figure 23 Estimated 1990 Mean Temperature +/- 1.96 standard deviation

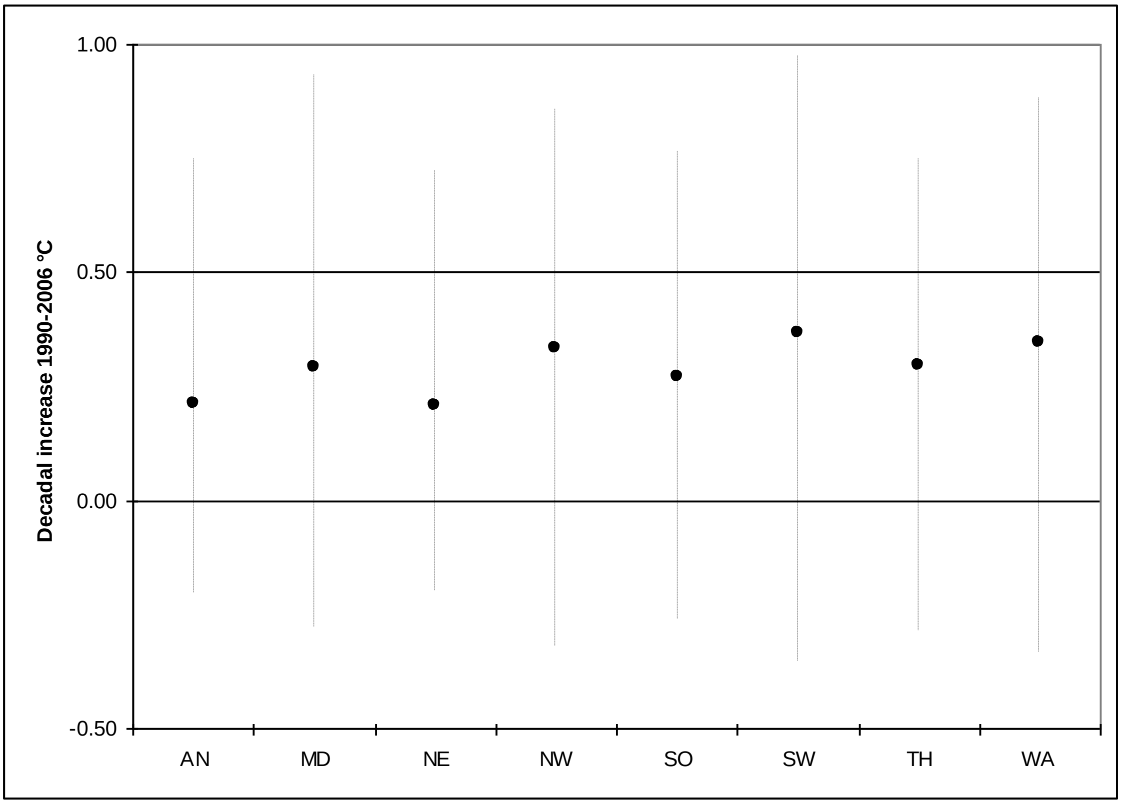

Figure 24 1990-2006 Decadal change in annual temperature +/- 1.96 stdev.

Thus by 2006, at the EA Administrative Regions scale, a higher water temperature increase in the Southwest (SW) Region brings its annual mean temperatures on a par with the Anglian (AN) Region, even though its regional average was initially lower in 1990 (Figure 25, and Table 14).

The extent of the variability in estimated change is worth noting. This is illustrated by the +/- interval of 1.96 standard deviation around the means in Figure 24 showing that a number of sites, particularly in the Southwest, have estimated decadal increases close to 1°C per decade, while in every region some sites experienced no change or temperature decreases over the 1990-2006 period.

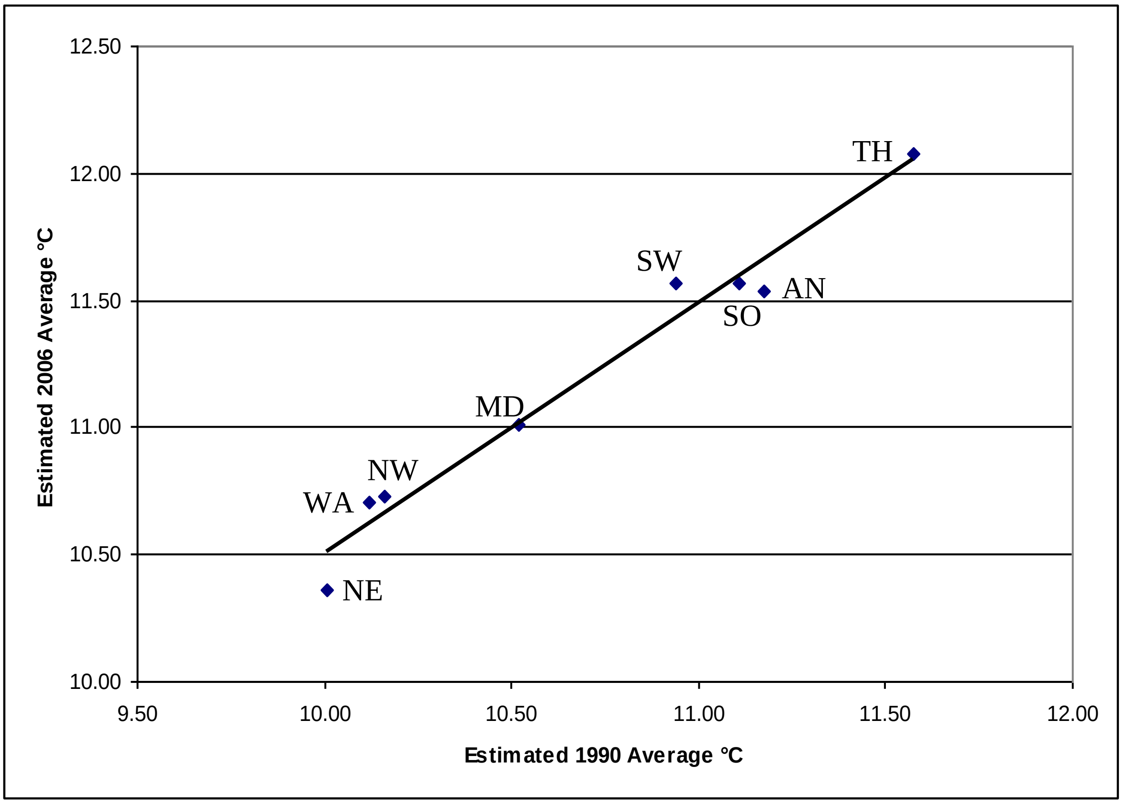

Figure 25 1990-2006 Decadal change in annual temperature by region

WFD River Typology

The Water Framework Directive typology (Type) provides a framework to compare sites within and between regions and a structure to explain some of the variability between sites in each Region.

As we split the 2772 river sites into smaller groups, sites with anomalous data may influence mean values disproportionately. Thus we have decided to leave temperature results out of summary tables when there are fewer than 10 sites.

Of the 2772 River sites, 78 had missing typology information (Table 15), leaving 2694 sites with 18 different Types. Organic geology (OR: Types 3, 6, 12, 15 and 43, have no or less than 10 sites in the Archive with enough data to be analysed over the 1990-2006 period. The same applies to Types 16, 28, 37, 38, 40 and 43. The proportion of

WBs with at least one site analysed to the WB types and numbers in England and Wales will be discussed with monitoring in chapter 7.

Table 15 Typology of River sites analysed between 1990 and 2006

TYPE	AN	MD	NE	NW	SO	SW	TH	WA	Sites	ALT	SIZE	GEOL
0 - missing	18	15	7	6	12	8	5	7	78	U	U	U
1	1	4	8	13	111	104	20	37	298	LOW	S	SI
2	252	90	56	88	108	113	111	40	858	LOW	S	CA
3	2								2	LOW	S	OR
4			14	7	17	25	8	15	86	LOW	M	SI
5	219	98	63	44	80	73	131	20	728	LOW	M	CA
6	5								5	LOW	M	OR
7		9				2		1	12	LOW	L	SI
8	43	29	14	6	13	16	39		160	LOW	L	CA
10		10	18	22		41		91	182	MID	S	SI
11		8	14	23		2	7	28	82	MID	S	CA
12		1	2	3		1			7	MID	S	OR
13		10	20	31		23		49	133	MID	M	SI
14		5	42	22				23	92	MID	M	CA
15				1					1	MID	M	OR
16				1				2	3	MID	L	SI
17		7	8	10				3	28	MID	L	CA
28				1					1	LOW	S	SA
37					4	3			7	LOW	XS	SI
38										MID	XS	SI
40	4				3		2		9	LOW	XS	CA
43										LOW	XS	OR
Totals	544	286	266	278	348	411	323	316	2772			

The WFD river typology is based on three variables described in Table 8. Their codes are listed again in Table 15 and each component is examined in more detail below.

Altitude

The sites with enough data are mostly in the WFD Low (<200m) Altitude category, with only 1/5 of Medium (200-400m) altitude. From Table 16, the combined effects of easting and altitude show higher warming of medium attitude sites and higher warming in the South and West.

Table 16 River sites altitude and decadal t° change 1990 - 2006

ALT_CAT	AN	MD	NE	NW	SO	SW	TH	WA	Sites
0 or null	18	15	7	6	12	8	14	8	88
LOW	526	230	155	159	336	336	302	113	2157
MID		41	104	113		67	7	195	527
Dec06-90	AN	MD	NE	NW	SO	SW	TH	WA	
LOW	0.21	0.29	0.23	0.33	0.27	0.37	0.29	0.36	
MID		0.36	0.17	0.32		0.31		0.34	

Catchment Size

More than half of the sites are in Small (10-100km^2) catchments, followed by Medium size (100-1000km^2) catchments with a few in Large (1000 – 10000km^2) catchments.

The typology information available to us does not include catchment names, but site names can be searched to show, for example, that most L sites in the TH region are on the Thames river, and those in the SW on the Bristol Avon, Hampshire Avon, and the Stour.

Table 17 River sites catchment size and decadal t° change 1990 - 2006

SIZE_CAT	AN	MD	NE	NW	SO	SW	TH	WA	Sites
0 or null	18	15	7	6	12	8	14	7	87
L	43	45	22	17	13	18	30	6	194
M	224	113	139	105	97	121	139	107	1045
S	255	113	98	150	219	261	138	196	1430
XS	4				7	3	2		16
Dec06-90	AN	MD	NE	NW	SO	SW	TH	WA	
L	0.41	0.32	0.20	0.34	0.41	0.56	0.28		
M	0.19	0.32	0.22	0.34	0.25	0.35	0.30	0.33	
S	0.18	0.26	0.19	0.32	0.26	0.35	0.27	0.35	

Bearing in mind the small number of sites concerned and large variability between sites, it seems that sites from Large catchment sizes have experienced higher decadal warming in the AN, SO and SW Regions.

There are no noticeable differences between sites from Small and Medium catchments, but we note that regional differences are conserved, with north-eastern regions (NE, AN) surface waters experiencing smaller decadal warming than sites in south and western regions (SW, NW, MD, WA, SO). This may be due to a cumulative warming effect from sub-catchments in the AN, SO and SW Regions.

Geology

More than 70% of the sites analysed are in Calcareous sub-catchments, 26% are in Siliceous sub-catchments and the few remaining for which Geology has been documented are either in Organic (15) or Salt (1) sub-catchments.

Looking at the main two categories sheds a different light on regional differences. For regions that have enough sites of both geology types, the 1990-2006 decadal warming may be higher in CA catchments (MD, NW, WA) or higher in SI catchments (NE, SO, SW, TH).

Table 18 River sites geology and decadal t° change 1990 - 2006

GEOL_CAT	AN	MD	NE	NW	SO	SW	TH	WA	Sites
	18	15	7	6	12	8	14	7	87
CA	518	237	197	193	204	204	281	114	1948
OR	7	1	2	4		1			15
SA				1					1
SI	1	33	60	74	132	198	28	195	721
Dec06-90	AN	MD	NE	NW	SO	SW	TH	WA	
CA	0.20	0.31	0.20	0.34	0.25	0.35	0.28	0.37	
SI		0.23	0.22	0.30	0.30	0.38	0.35	0.33	

Although differences are again not significant in statistical terms due to high within category variability, the WFD Geology categories seem to bring another dimension to the overall picture, which is not captured by Altitude or Catchment Size.

5.5.4 Regional differences

Regional differences that were apparent from one dimension of the WFD Typology at a time can be obscured in Table 19, even when categories with fewer than 10 sites are taken out.

Table 19 River sites WFD types and decadal t° change 1990 – 2006

TYPE	AN	MD	NE	NW	SO	SW	TH	WA			
1				13	111	104	20	37			
2	252	90	56	88	108	113	111	40			
4			14		17	25		15			
5	219	98	63	44	80	73	131	20			
8	43	29	14		13	16	39				
10		10	18	22		41		91			
11			14	23				28			
13		10	20	31		23		49			
14			42	22				23			
17				10							
Dec06-90	AN	MD	NE	NW	SO	SW	TH	WA	ALT	SIZE	GEOL
1				0.19	0.28	0.40	0.35	0.39	LOW	S	SI
2	0.18	0.26	0.18	0.36	0.24	0.32	0.26	0.34	LOW	S	CA
4			0.40		0.39	0.40		0.18	LOW	M	SI
5	0.19	0.33	0.24	0.33	0.22	0.35	0.30	0.50	LOW	M	CA
8	0.41	0.34	0.17		0.41	0.60	0.37		LOW	L	CA
10		0.36	0.10	0.32		0.34		0.35	MID	S	SI
11			0.22	0.27				0.29	MID	S	CA
13		0.35	0.15	0.33		0.31		0.30	MID	M	SI
14			0.16	0.36				0.37	MID	M	CA
17				0.40					MID	L	CA

One reason for the confusing picture lies in the variability within each Region. Another important source of variability, data quality issues set aside, comes from differences between regions, which may not be readily comparable, even within WFD types. Finally, the three Typology variables have very broad definitions and even in combination cover a large range.

The complexity of regional differences is visible on the map in Figure 22, which gives estimated differences for the sites on the map in Figure 21. These are now examined one region at a time.

Anglian

All WFD river sub-catchments in the Anglian Region are in the Low Altitude category. Anglian sites analysed for trends are in Typology classes 2, 5 and 8, in the Calcareous Geology type, with increasing catchment sizes. The average decadal increase over the 1990-2006 period is estimated to have been 0.21°C, leading to an average surface water temperature of 11.54°C in 2006 for 554 different sites (Table 14).

Even though differences between estimated decadal temperature change for the three Typology classes are not statistically significant, standard deviations are nearly identical, which suggests that the much higher value for larger sub-catchments is not due to a smaller number of sites. It is not possible to look into catchment size details any further because of inconsistent Water Body Types and codification information, but Figure 26 shows a predominance of higher warming in the West of the Region (450 to 500,000 km Easting), which is also where the larger catchments are. Relatively, sites to the East (600 to 650,000km E) show a high variability but a much lower decadal warming on average, which are possibly be linked relatively cooler Sea Surface and Air Temperatures over the North Sea.

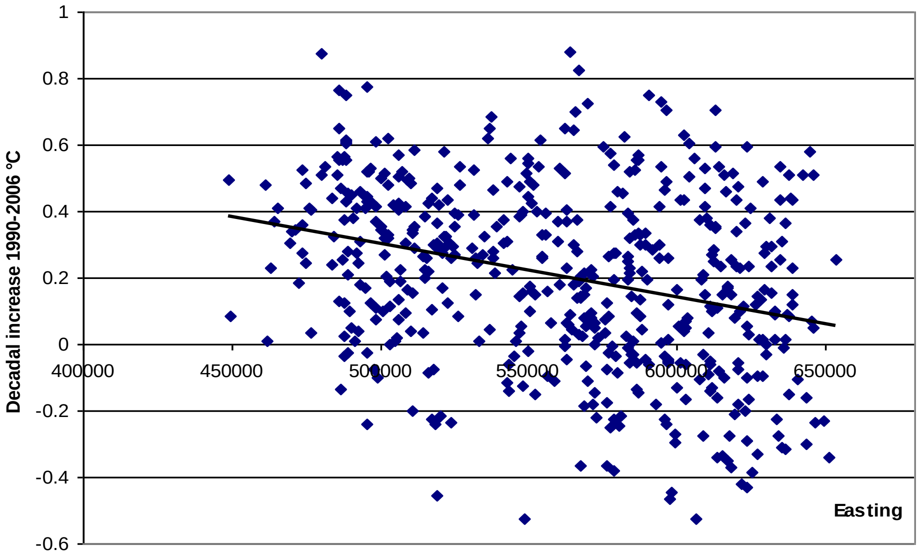

Figure 26 Anglian Region decadal t° change 1990 – 2006 with easting (km)

Midlands

Sites amenable to Trends analyses in the Midlands Region are found mostly in Types 2 and 5, with fewer in Types 8, and 10 sites only of Types 10 and 13 (see summary in Table 19). With an regional average decadal warming of 0.29°C for the period 1990-2006 over 286 sites, the Midlands is very much average with a slightly lower than average annual mean surface water temperature estimated at 11.01°C (Table 14).

The only difference in decadal warming is in WFD Type 2, the Low, Small size Calcareous catchments, for which sites have noticeably lower warming than for other Types. Taken independently, each of the SI Geology (Table 18) showed lower values, but for an altogether small number of catchments. An exploratory analysis, which is probably too detailed for the current data quality, suggests that lower decadal increases are generally associated with sites between altitudes of 50m and100m and lower Eastings (<400,000km).

Northeast

The Northeast Region has the more diverse WFD Typology and the wider amplitude in latitudes of all eight regions. In 1990, the estimated average annual surface water temperature was 10.01°C, making it then an average 0.11°C colder than Wales, a gap that has increased to 0.34°C in 2006.

The average decadal increase for 266 sites analysed is 0.21°C sharing the lowest value across all regions with Anglian, which may reinforce the likelihood of a common influence for the two regions along the North Sea coast.

Differences between eight Types with not much more than ten sites each are difficult to interpret, and are not apparent one Typology variable at a time (Table 16 to Table 18).

Northwest

Sharing the same latitudes as NE but facing the much warmer Irish Sea, the 278 sites in the Northwest Region have experienced a combined estimated decadal change of 0.33°C.

None of the Typology variables leads to noticeable differences between Types. Overall, the sites individual Easting shows lower warming from West to East, corroborating a coastal influence.

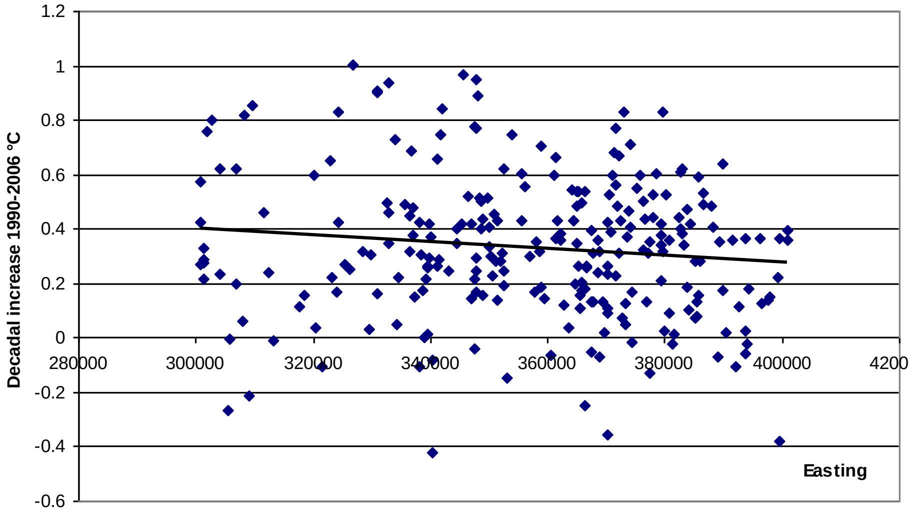

Figure 27 Northwest region decadal t° change 1990 – 2006 with easting (km)

Southern

All 336 sites with Typology information from the Southern Region are in the LOW Altitude category (Table 16), for a variety of catchment sizes with either CA or SI Geology. Larger catchment sizes appear to lead to higher decadal increase than for MID or S sizes. Sites in the SI sub-catchment category also appear to have experienced higher warming. The region has an extended Easting amplitude, but closer scrutiny does not reveal any strong West to East gradient, but isolates groups of sites along the Western Region boundary that are either colder or warmer than others. These correspond to the chalk (or not) streams area where SI sites experience higher decadal warming that CA sites in the same catchment size categories (Table 19).

Southwest

The Southwest Region is the southernmost and has the widest longitude/Easting span of all EA regions. In 1990, the Region's surface waters average annual temperature was above average at 10.94°C, but the highest decadal increase (0.37 °C, Table 14) of all eight Regions brings SW to the second highest estimated annual average in 2006 narrowing the gap with the Thames Region.

SW has a wide variety of sub-catchment Types. The 411 sites analysed are from 12 Typology categories. In the seven Types with more than 10 sites (Table 19), the most prevalent are Types 1, 2, 5 and 10.

Overall, decadal increases appear higher in sites from larger catchments (L) and for those of LOW altitude (Table 16 and Table 17), with no obvious structure between the SI and CA two main Geology categories. Figure 28 shows some trend for Cornish sites, predominantly SI Types 1, 4, 10 and 13 to warm less from West to East, and a switch to a different pattern in the East of the Region for CA site Types 2, 5, 8. CA sites in the East also warm up faster in the north of the region. Neither site altitude of Base Flow Index explains much of the remaining variability.

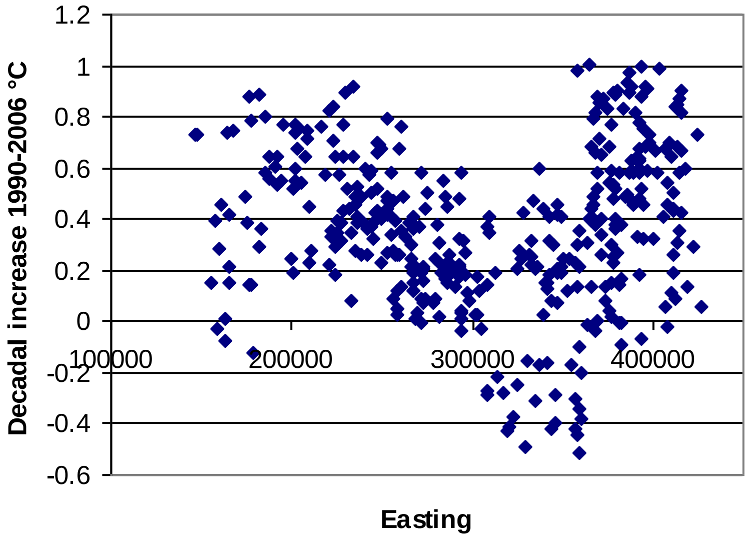

Figure 28 Southwest Region decadal t° change 1990 – 2006 with easting (km)

Thames

Of all 8 EA Regions, the Thames has the warmest annual surface water temperature estimated for 2006, at 12.08°C (Table 14). The entire Region is in the WFD LOW Altitude category, with more than 90% of its sub-catchments in the CA Geology category. Most sub-catchments are in the M or S categories, but decadal warming does not appear to obviously increase with catchment size as in the AN or SO Regions. Overall, there are no obvious links between WFD Types and average decadal warming (Table 19).

Wales

The variety of Types in Wales is similar to that of the NW Region to the North along the Irish Sea coast. The 1990 base temperature, estimated decadal change of the 1990-2006 period and resulting 2006 annual estimate are equally similar, with possibly as slightly higher warming rate than NW, although not as fast as SW. Overall, the three western regions have the highest decadal warming rates.

Individually, the Typology variables show a slightly higher decadal increase at LOW altitude, Small catchment size and Calcareous Geology, without any single type leading to systematic differences once the sites are spread thinner into 8 Types.

Within Wales, sites show a marked South-North gradient, which nearly splits the country into two different groups down the middle (300,000 km Northing), where altitude and easting probably explain some of the remaining variability. Perhaps counter-intuitively, nearly all sites in North Wales experience much higher warming, with more variable but on average obviously lower rates estimated for sites in South Wales (Figure 29).

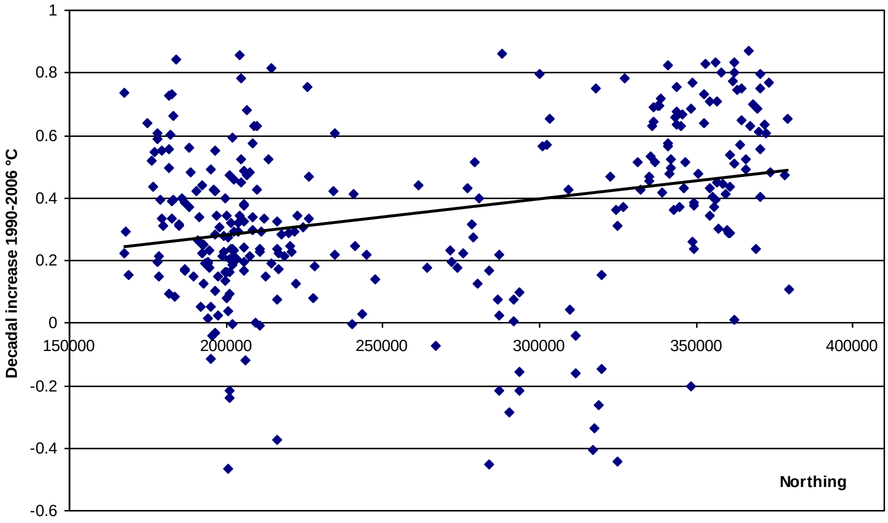

Figure 29 Wales Region - decadal t° change 1990 – 2006 with northing (km)

Once split into two latitudinal groups, sites in North Wales (Northing Y >= 300,000km) have quite evidently a higher average decadal warming between 0.5 and 0.45°C over the 1990-2006 period, with no systematic effect of Geology categories CA and SI or site altitude Z. Although within groups variability is still very high (cf. standard deviations STDev0690), these preliminary results warrant further analyses.

Table 20 North and South WA - River sites decadal t° change 1990 – 2006

Y>=300,000 **North**

GEOL	Sites	Avg0690	StDev0690	AvgZ
CA	41	0.45	0.21	56.05
SI	65	0.50	0.31	102.23

Y<300,000 **South**

GEOL	Sites	Avg0690	StDev0690	AvgZ
CA	73	0.32	0.20	72.60
SI	115	0.25	0.25	90.11

5.5.5 Seasonal baselines

The complexity of the overall picture for decadal increase over the 1990-2006 period (Figure 22) can be examined further by looking at the seasonal baseline temperatures for 1990 (Figure 30).

In order to facilitate comparisons with UKCIP08 reconstructions of seasonal Air temperatures over 1971-2000 (their Fig. 2.5), we have used their definition of seasons, with Spring (Q2) from March to May included, Summer (Q3) from June to August included, Autumn (Q4) from September to November, and Winter (Q1) from December to February. We also have used a colour representation as close as possible as theirs although the amplitude of river temperatures does not match that of air temperatures entirely.

The models and time series start on 1st January, and thus in the analysis of temperature records between 1st January 1990 and 31st December 2006, the first Winter season Q1 of 1990 has only two months of data (January and February). We use the 1990-91 following Winter season in our comparisons.

Some of the most salient features of the estimated seasonal temperatures for river sites in 1990 are as follows:

- the four maps of modelled seasonal river temperatures over England and Wales in Figure 30 show a strong seasonal cycle, and a strong geographical structure within the structure provided by the 1990 annual average (Figure 21);
- the range of water temperatures in each season is larger for river temperatures than for air temperatures. It lacks negative values but, as expected, reaches higher values than for air temperature in all regions;
- the greatest similarities between average seasonal air and river water temperatures across England and Wales are found in the Spring (Q2), Autumn (Q4) and Winter (Q1) seasons;
- some of the most visible differences between air and river temperatures noted for the 1990 annual average (Figure 21) are clearly determined in the Summer (Q3) season, particularly for sites in the AN region.

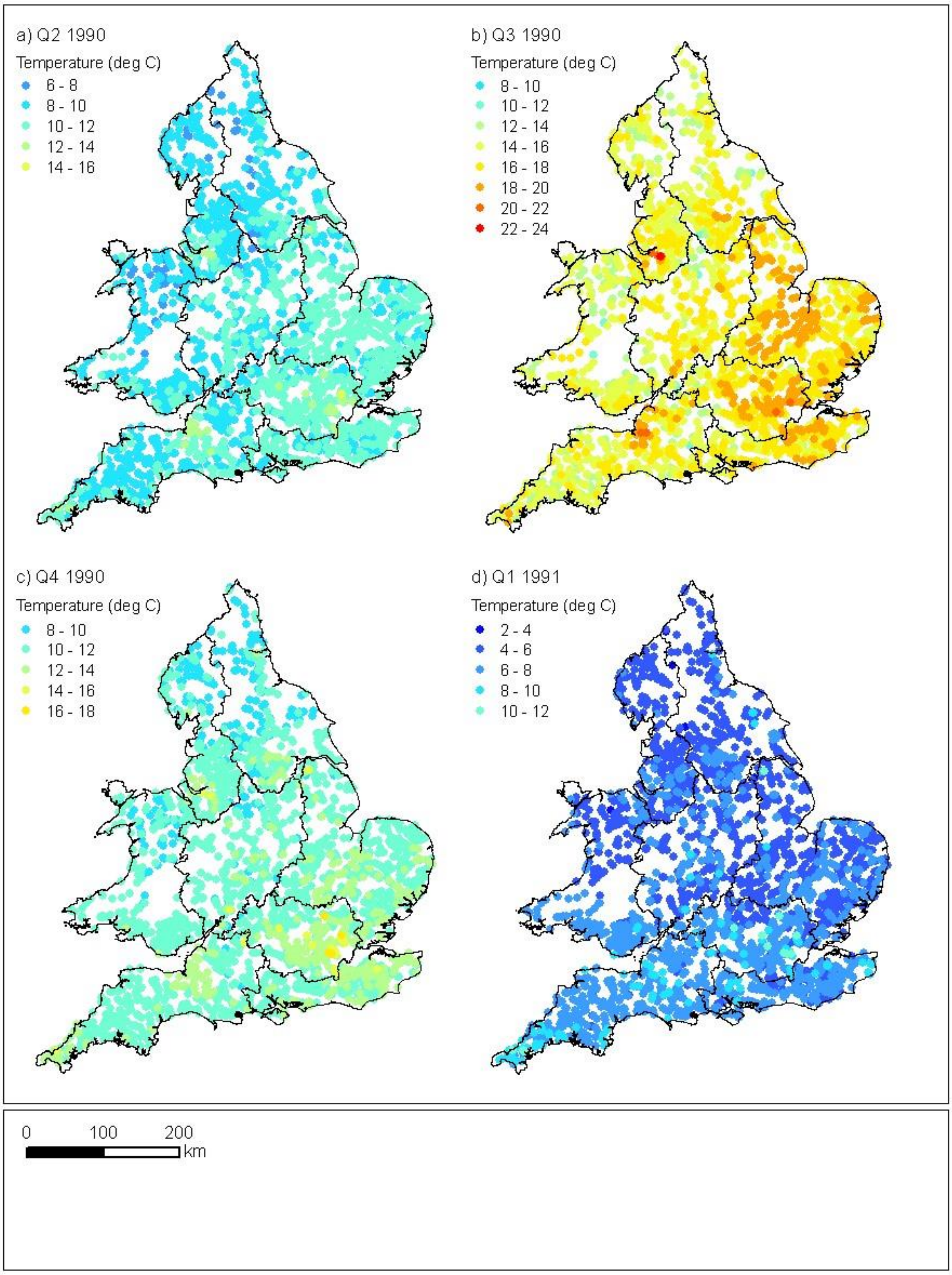

Figure 30 Estimated seasonal average daily river water temperatures for 1990

5.5.6 Seasonal Trends

Table 21 shows predicted annual temperatures and changes (copied from Table 14) with the estimated average temperatures for the 2001 seasons and predicted decadal increases over the previous 17 or 16 years depending on the season. From these, the constrained seasonal component imposed by the models is apparent.

The current models fit a single seasonal cyclic smoother over the entire time-series at each site. Therefore predicted daily river temperatures are made up from the estimated cyclic component within a year (from doy, the day of year, see section 3.3), and the linear (or non-linear) long-term trend that affects the entire seasonal cycle equally. This is evident in the last 4 lines of Table 21, which show decadal change for each quarter to be the same as the annual change.

Table 21 River sites annual and seasonal decadal t° change 1990 – 2006

EA_REGION	AN	MD	NE	NW	SO	SW	TH	WA
Sites	544	286	266	278	348	411	323	316
AvgOf1990	11.18	10.52	10.01	10.16	11.11	10.94	11.57	10.12
AvgOf2006	11.54	11.01	10.36	10.73	11.57	11.56	12.08	10.70
Avg0690	0.21	0.29	0.21	0.33	0.27	0.37	0.30	0.34
2005_Q1	5.96	6.19	5.59	5.81	6.86	7.62	7.06	6.63
2006-Q2	10.73	10.18	9.46	9.75	10.65	10.53	11.19	9.68
2006_Q3	17.40	16.14	15.57	15.98	16.52	15.91	17.41	15.12
2006-Q4	11.88	11.37	10.67	11.20	12.10	12.04	12.48	11.24
Q2_06-90	0.21	0.29	0.20	0.33	0.27	0.37	0.30	0.34
Q3_06-90	0.21	0.29	0.21	0.33	0.27	0.37	0.30	0.34
Q4_05-90	0.20	0.29	0.21	0.33	0.27	0.36	0.30	0.34
Q1_06-91	0.20	0.30	0.21	0.34	0.27	0.36	0.30	0.34
Avg(Q3-Q1)	11.44	9.95	9.98	10.17	9.66	8.29	10.35	8.48

Thus decadal differences in seasonal river temperatures predicted by our models are probably best evidenced by estimated values for the 2006 seasons shown in Table 21.

As illustrated in Figure 31, quarterly averages show obvious seasonal differences in river temperature regimes between regions, with generally milder winters in the South (SO, SW, TH). Among these three regions, SW has higher Winter (Q1) temperatures than SO and TH, but the Thames region has higher summer (Q3) and to a lesser extent higher autumn (Q4) average river temperatures.

A measure of amplitude in seasonal temperatures is given by the average of site differences between summer (Q3) and winter (Q1) quarters in each region (last line in Table 21). There is some decrease in amplitude with the predicted decadal warming at regional level, while amplitude differences do not appear to be related to average 2006 temperatures (Figure 32).

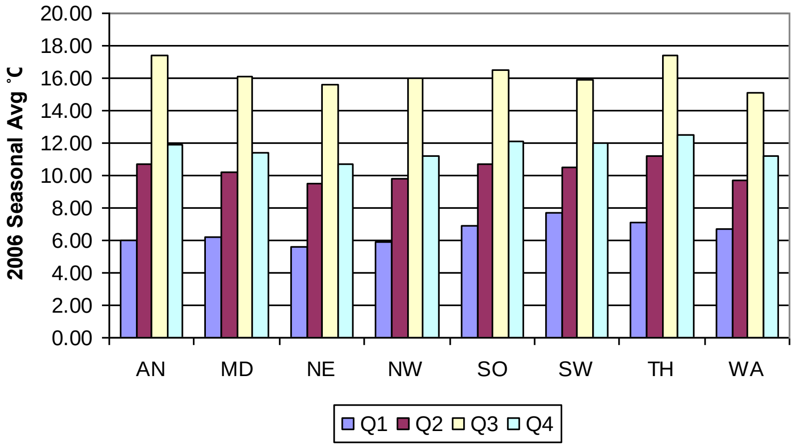

Figure 31 Seasonal t° averages for 2006 by region

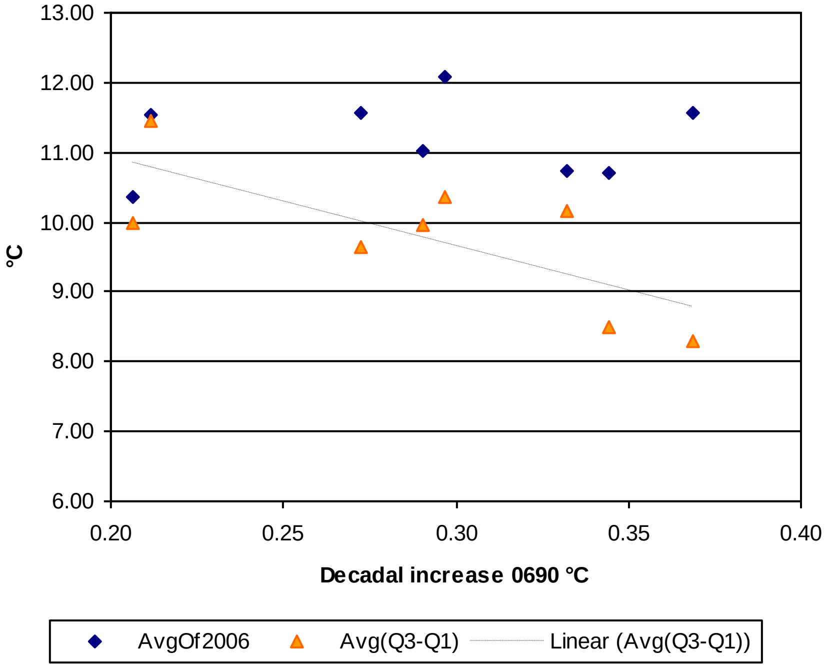

Figure 32 Seasonal t° amplitude and 2006 average with estimated decadal t° increase 06-90 by region

5.6 Estuaries and Transitional Waters

Water temperature in estuaries are influenced by both river and sea surface temperatures (SST) to an extent that depends on the length and width of the estuary, the river flow and the tidal regime. Estuarine water temperature records are therefore more complex to validate and to analyse statistically than for rivers.

Although SSTs are extensively monitored (cf. 5.4) and changes in air temperatures are well described in England and Wales, this is not the case for water temperature changes in coastal waters and estuaries. This reflects added complexities at the land-water interface.

5.6.1 Data Holding: Estuaries

The Archive holds records for 457 sites in Transitional waters (Figure 3 and Table 11), but for most regions, on average, records span less than17 years or have been discontinued (Table 22). Most Transitional sites are in WA (22%), NE (19%), AN (18%) and SW (15%).

Table 22 Transitional sites in the Archive

Region	sourceCode	Min_Yrstart	Avg_Yrstart	Avg_Yrendt	Sites	Avg_Yr
AN	EA TIMS	1986	1996	2007	2	10.9
AN	EA WIMS	1981	1990	2003	77	12.7
AN	EA WISKI	1991	1992	1997	2	4.7
MD	EA WIMS	1962	1986	1999	16	13.1
NE	EA WIMS	1974	1991	2003	68	11.4
NE	EA WISKI	1994	1998	2004	18	6.0
NW	EA WIMS	1955	1984	2001	34	17.1
SO	EA TIMS	2005	2005	2006	1	1.4
SO	EA WIMS	1976	1988	2004	40	15.9
SW	EA WIMS	1965	1988	2000	68	12.0
TH	EA TIMS	1986	1997	2005	22	8.7
TH	EA WIMS	1972	1981	1999	8	18.2
WA	EA WIMS	1977	1992	2000	101	7.4

5.6.2 River sites within 500m of Transitional waters

In order to obtain a first estimate of temperature changes in estuarine waters, we have selected river sites that are with 500m of Transitional Waters using the GIS typology information. The selection produces 125 sites from those that have been modelled.

Numbers are quite small in each region (Table 23), but it can be noted that both the estimated annual average and decadal change values for these sites are systematically higher than the general averages for all sites for each region given in Table 14.

Table 23 Transitional sites - 1990 annual mean and decadal t° change 1990 – 2006 by Region

EA_REGION	AN	MD	NE	NW	SO	SW	TH	WA
Sites	33	5	13	8	22	23	5	16
Avg.1990	11.56	11.42	10.55	10.40	11.60	11.19	12.72	10.58
Dec. 0690	0.35	0.30	0.27	0.44	0.34	0.41	0.40	0.32
Avg.2006	12.15	11.92	11.00	11.14	12.17	11.89	13.41	11.13

5.7 Trends for Lakes

The EEA report on Climate Change (deWit, in prep.) estimates that European Lake water temperatures have experienced significant increasing trends between 0.10 to 0.35° C decade^{-1} at the surface and between 0.10 and 0.24° C decade^{-1} for deep waters.

5.7.1 Archive Lake data holdings

The Archive holds a total of 711,229 records for the surface temperature of 977 Lake sites over all eight EA regions (Table 11 and Figure 3). Of the 31 sites that satisfy the first set data quantity criteria set out for river sites (section 5.2), seven sites had to be omitted for missing a full year of data or more between 1st January 1990 and 31st December 2006.

The NE site is Tunstall Reservoir, the five NW sites correspond to the surface water temperatures for Windermere (North and South basins), Blelham, Esthwaite and Grasmere, all four WA sites are for Bosherston, and the 15 AN sites include the Wing Water Treatment Works Raw Water (left out).

Table 24 Lake sites by region

sourceCode	AN	NE	NW	WA
EA WIMS	15	1		4
FBA-CEH			5	

5.7.2 Lakes decadal t° change 1990 – 2006

A summary for the 25 Lake sites is given in Table 25. It shows a wide variation between regions, with sites in Wales having a much larger estimated decadal temperature change over the 1990-2006 period than sites in other regions.

The NE site aside, we note that annual mean surface temperatures in standing waters (Table 25) are all higher that running water sites in the same regions and that decadal warming has been higher as well (Table 14). This is expected for the surface temperature of deeper stratified lakes, which can accumulate significant latent heat from rising air temperatures through a deeper and more persistent thermal stratification.

Table 25 Lakes estimated decadal t° change 1990 – 2006 by region

EA_REGION	Sites	Avg1990	Min	Decadal 06-90℃	Max	Avg2006
AN	15	11.58	0.14	0.42	0.60	12.28
NE	1	10.12	-0.04	-0.04	-0.04	10.05
NW	5	11.23	0.24	0.35	0.39	11.82
WA	4	12.77	0.67	0.71	0.80	13.98

The NE region site is the Tunstall Reservoir site (200m altitude), which shows a slight decrease over the 1990 to 2006 period. The estimated annual mean temperature for 1990 is similar to that of river sites in the region (Table 14).

5.7.3 Norfolk Broads

Decadal changes estimated for Broads sites (AN) vary widely between a minimum of 0.14°C and a maximum of 0.42°C increase per decade from 1990 to 2006 (Table 25). This warrants closer scrutiny, as there is no obvious relationship with BFI values for the 15 sites, and there is little other information in the Archive that can be used to compare sites such as the Norfolk Broads with one another.

5.7.4 Cumbrian Lakes

The Cumbrian lakes have estimated decadal increases between 0.24 and 0.39°C. Blelham, Esthwaite and Windermere's two basins show similar trends (Table 26), but Grasmere has both a lower estimated mean daily temperature in 1990 and a smaller decadal increase. Altitude does not explain the differences as the Grasmere (60m) and Esthwaite (68m) sites are higher than both Windermere (38m) and the Blelham site (40m).

Table 26 Estimated decadal t° change 1990 – 2006 for Cumbrian Lakes

	SiteID	siteName	1990	Avg10 * (06-90)/17	2006
NW	FBA-BLEL	BLELHAM	11.40	0.38	12.05
NW	FBA-ESTH	ESTHWAITE	11.25	0.38	11.90
NW	FBA-GRAS	GRASMERE	10.97	0.24	11.38
NW	FBA-NBAS	WINDERMERE - NORTH BASIN	11.15	0.39	11.81
NW	FBA-SBAS	WINDERMERE - SOUTH BASIN	11.35	0.35	11.95

The estimated decadal surface water temperature increases for the 5 Cumbrian sites are shown in Figure 33.

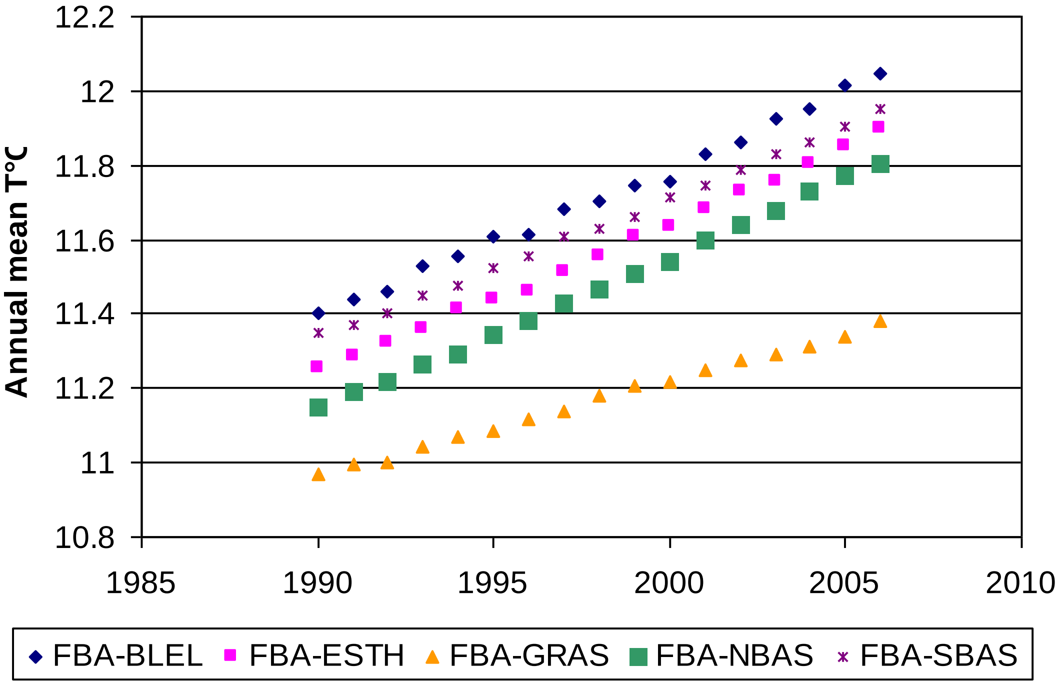

Figure 33 Cumbrian lakes - mean annual t° change 1990 – 2006

5.7.5 Bosherston sites in Wales

Temperature changes for the four Bosherston sites in the WA region, between 0.67°C and 0.8°C per decade over the 1990-2006 period, are much higher than for the deeper Cumbrian lakes.

Table 27 Estimated decadal t° change 1990 – 2006 for Bosherston - WA

	SiteID	siteName	1990	Avg10 * (06-90)/17	2006
WA	32350	LOWER EAST' ARM NR GRASSY BRD	12.75	0.69	13.92
WA	32351	EAST'N ARM @ EIGHT ARCH BRG'	12.85	0.67	13.99
WA	32353	CENTRAL LAKE, EAST SIDE	12.93	0.80	14.29
WA	32355	CENTRAL/LAKE CAUSEWAY	12.56	0.68	13.72

Different rates of increase mean that the difference between annual mean temperatures at sites 32351 and 32353 is increasing, but is decreasing for sites 32351 and 32350.

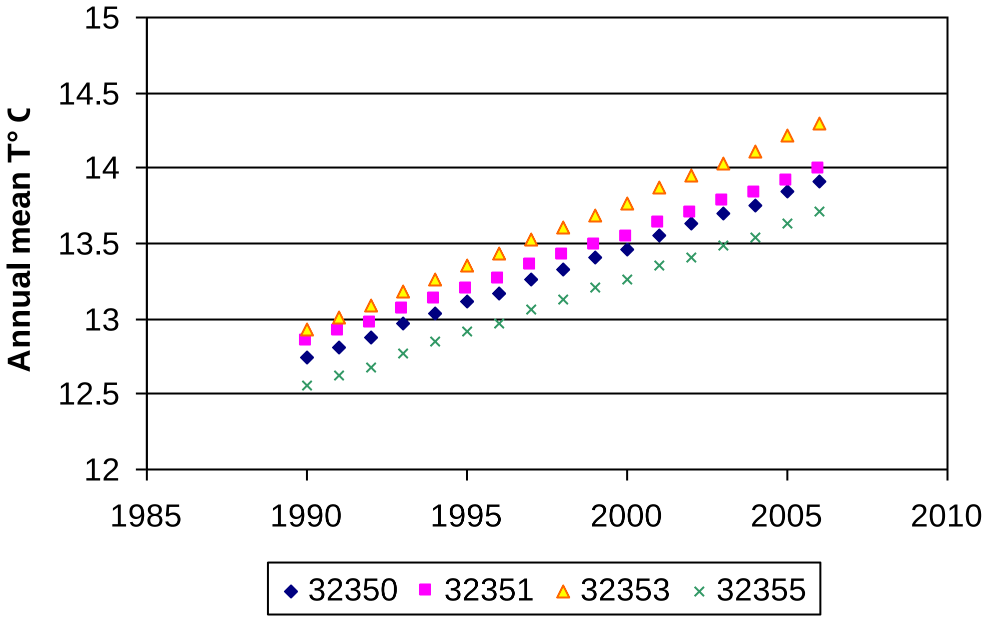

Figure 34 Welsh lakes - mean annual t° change 1990 – 2006

The decadal rates of increase estimated for the four sites (Table 27) are much higher than for river sites in the WA region as a whole (Table 14), and in southern Wales in particular (Table 20), which may be explained by the lake’s proximity to the sea and its shallow depth.

5.7.6 Seasonal Trends

Compared with river sites in the NW region (Table 21), the seasonal cycle for lake sites shows an expected lower amplitude (>10°C for NW river sites), with similar high summer (Q3) temperatures at the lakes’ surface, but much higher winter temperatures (Q1).

Table 28 Cumbrian lakes sites verage seasonal temperatures 1990 – 2006 and Q3-Q1 amplitude (°C)

Sites NW	Q1	Q2	Q3	Q4	Avg(Q3-Q1)
BLEL	8.26	10.57	15.92	12.03	7.71
ESTH	8.11	10.19	15.72	12.18	7.67
GRAS	8.12	9.89	15.26	11.35	7.18
NBAS	8.61	9.55	15.29	12.39	6.73
SBAS	8.62	9.72	15.41	12.75	6.87
Sites WA	**Q1**	**Q2**	**Q3**	**Q4**	**Avg(Q3-Q1)**
32350	7.27	12.21	19.91	13.82	12.77
32351	7.52	12.54	19.76	13.73	12.37
32353	7.49	12.54	20.29	14.01	12.92
32355	7.26	12.26	19.39	13.50	12.25

By contrast, the Bosherston sites (WA) have much a higher seasonal amplitude than the average river sites in Wales (8.48°C, Table 21) characteristic of shallow water bodies (Wetzel, 2001).

6 Effects of temperature change on aquatic invertebrates and fish

6.1 Introduction

The identification of species that best indicate climate change effects on ecosystem communities is a key ecological question (Sutherland, Armstrong- Brown et al. 2006).

The choice of taxa to be assessed in this project as potential indicators was informed by a meeting of Experts held in January 2008 at UCL. The Expert Meeting discussed the potential of different taxonomic groups following presentations from Malcolm Elliott on salmonids in lakes and streams, Martin Attrill on estuarine fish assemblages, Iwan Jones on aquatic macrophytes, Alan Hildrew on caddis flies in streams and Steve Brooks on adult dragonflies (Odonata). The Expert Meeting report is in Appendix.

Eventually, dragonflies and Atlantic salmon were chosen as two case studies for the following reasons:

- both Odonata and Atlantic salmon have been extensively recorded across England and Wales;
- records for Odonata are based on sighting coordinates aggregated to 10km^2, and those for Atlantic salmon are based on the river system, providing an opportunity to illustrate the versatility of the Archive and modelling results; and
- ecological knowledge of thermal preferences and requirements is sufficient for both dragonflies and salmon to make it possible to use the Archive to compute potentially relevant water temperature indicators for these taxa.

Although the analyses presented here are exploratory and essentially comparative, using maps and tabulations of temperature indicators, they are very promising.

6.2 Dragonflies

6.2.1 Introduction

Three species of dragonflies were suggested for analysis by Steve Brooks on the basis of their recent range and expansion. Here we have explored the potential influence of water temperature changes in their distribution.

The three species - the Banded Demoiselle *(Calopteryx splendens)*, the Scarce Chaser (*Libellula fulva*) and the Golden-ringed dragonfly (*Codulegaster boltonii*) - are chosen for their affinity with running waters, which have the most extensive geographical coverage in the Archive.

6.2.2 Dragonfly species distribution maps

The National Biodiversity Network Gateway (NBN[5]) holds records from the British Dragonfly Society and others, and distribution maps by species can be generated directly from the website.

The time periods for the aggregation of presence/absence NBN records have been chosen to fit our modelling period for the Archive temperature records. The break pre- and post-1997 is about half way through our 1990 to 2006 period. Colour codes in the legend of each species distribution map (see Corbet and Brooks, 2008:324) bring the more recent distribution changes out in yellow, which for our purpose illustrates any obvious changes in species range that may be linked to water temperature changes over the 1990 to 2006 period.

Steve Brook has provided the short descriptions of key ecological facts given below, for each of the three species he selected, and advised us to use daily mean temperatures for spring or summer. We use mean summer temperatures (Q3 see 5.5.5) from the 2,772 modelled sites as relevant indicators.

6.2.3 Water temperature maps

The 10 km grid squares used by the NBN for its species distribution data (see Figure 35) are not well suited to summarise temperature records from river sites. Of the 1,055 different km^2 grid squares that include at least one river site, nearly 65% include two or more which may be on different rivers or in different sub-catchments. For these, therefore, the data and estimated temperature indicators cannot be meaningfully averaged or selected.

The spatial scale of WFD sub-catchments is the closest representational scale to the 10km^2 scale that carries meaning in the Archive. Although the WFD river typology does not always explain differences between sites within and between regions, its three classification variables relate to aquatic species and community ecology.

Expert judgment (Steve Brooks, Ewan Shilland and Sophie des Clers) has been used to identify the typology categories that correspond to known habitat requirements of each dragonfly species. Three temperature maps are produced for each to show the average (of sites averages when the sub-catchment includes more than one site) of estimated mean summer (Q3) river water temperatures in 1990, in 2006 and for the corresponding average decadal temperature change over the 1990 to 2006 period. The three maps give a complete picture of river temperatures and of changes over the period for which species distribution changes are indicated in yellow.

6.2.4 River water temperatures and distribution for *Calopteryx splendens*

C. splendens, the Banded Demoiselle, breeds in lowland, slow-flowing rivers, and occasionally standing waters.

Its distribution corresponds most closely to calcareous (CA), low altitude (L up to 200m) waterbodies in all catchment sizes of WFD types 2,5,8 and 40. The Archive has sites in 931 such sub-catchments.

---

[5] http://www.searchnbn.net/ Dragonfly and damselfly records collected and collated by the Dragonfly Recording Network (DRN), a part of the British Dragonfly Society, for the period 1807-2006, with a majority after 1975.

Distribution records suggest the species is currently expanding its northern range northwards with new records over the last few years from Northumberland, Cumbria, Lancashire and Yorkshire. Recent work (Hassall and Thompson, in press) has shown that males from northern locations have a smaller area of wing pigmentation than specimens from localities in southern England. Because the wing pigment, melanin, is used to block the feeding tubes of parasitic mites (Rantala et al., 2000) these authors have suggested that decreased immuno-competence may be one mechanism by which cool climate restricts the northward expansion of the species.

The temperature maps show increasing temperatures throughout the range currently occupied by *C. splendens*. They suggest that temperature thresholds may have been crossed in the northern and north western parts of the species range in England that have allowed post-1990 range expansion. It is interesting to note that there also appears to have been range expansion in the north of East Anglia. At first sight this may be taken as range in-filling with the implication that this may be a response to water quality or habitat improvement. However, the temperature data from the north Norfolk coast suggest that temperature increases in this region could be responsible for the range expansion in this area. It would be useful to analyse these data in more detail to check for such a possibility.

6.2.5 River water temperatures and distribution for *Libellula fulva*

The Scarce Chaser (*L. fulva*) species breeds in lowland, slow-flowing rivers.

It is found mainly in calcareous catchments (any size) and at low altitudes. This corresponds to WFD types 2,5,8 and 40 with an added altitude filter, fixed at 10 m or less. We have sites for 284 such sub-catchments (Figure 36).

The species is apparently more sensitive to organic pollution and river management than *C. splendens*. Historically, *L. fulva* has been rare in Britain but in recent years it appears to be undergoing a significant range expansion not only within catchments that support existing populations but also by colonising new catchments, especially in the north and west of its range in England. The northward and westward range expansion into new river catchments in Devon, Worcestershire and Shropshire is consistent with a response to climate warming. Range expansion within river catchments that already support populations is more likely to be in response to improvements in river water quality and management of the river corridor. However, the temperature maps show higher than average temperature increases in the Ouse catchment south of the Wash and this coincides with a marked range expansion in this river catchment. Temperature increase may therefore be a reason for range expansion in this case.

6.2.6 River water temperatures and distribution for *Cordulegaster boltoni*

The Golden-ringed dragonfly breeds predominantly in small upland streams, on heaths and moors, and in shady woodland streams in more lowland areas.

We have selected siliceous (SI) catchment types of all altitudes and sizes, excluding large catchments. This corresponds to WFD catchment types 10, 13 and 37 (38 no sites). We have sites for 469 such sub-catchments, but they do not completely cover the species distribution map (Figure 37 d), which also includes calcareous catchment types along the SW region East coast.

.

Streams that support populations of *C. boltonii* tend to have higher flow rates than rivers supporting the two other species. There has been no apparent range expansion of this species in recent years. Increased temperatures in eastern England have not encouraged an eastwards expansion. Lack of suitable habitat in the Midlands and East Anglia may be the reason the species is absent from this area. The current distribution of the species in Britain suggests its distribution may not be temperature limited in this country at present. However, its preference for upland and shaded habitats may mean that a range contraction may result from increasing temperatures in the future, a possibility that needs to be evaluated by monitoring into the future.

6.2.7 Conclusions

The selection of WFD sub-catchments that correspond to the distribution of each dragonfly species selected enables a good match to be made with corresponding temperature records in the Archive, although the coverage for the Golden-ringed dragonfly (*C. boltonii*) in South Wales and the east coast of the NW region is less good. This is not owing to the availability of records, but rather the constraints of sub-catchment typology, where the predominant geology CA types omitted may have some SI components.

The results show that the temperature Archive can be used to compare dragonfly distributions with long-term temperature trends. The findings agree with the already well-documented changes in the range of British dragonflies that are considered to be a response to temperature increase (Hickling et al., 2005; Corbet & Brooks, 2008).

However, most of the observed range changes in dragonfly distribution concerns species that breed in standing waters. The taxa included here are riverine species. Long-term temperature indicators for standing waters would also be useful but there are insufficient records of standing water temperature in the Archive for a similar analysis to be undertaken. In addition, northward expansion of dragonflies in Britain is most apparent in northern counties as most of the southern species were formerly restricted to regions south of the English Midlands. Therefore, additional water temperature sites in northern counties and an extension of the Archive to Scotland would be valuable.

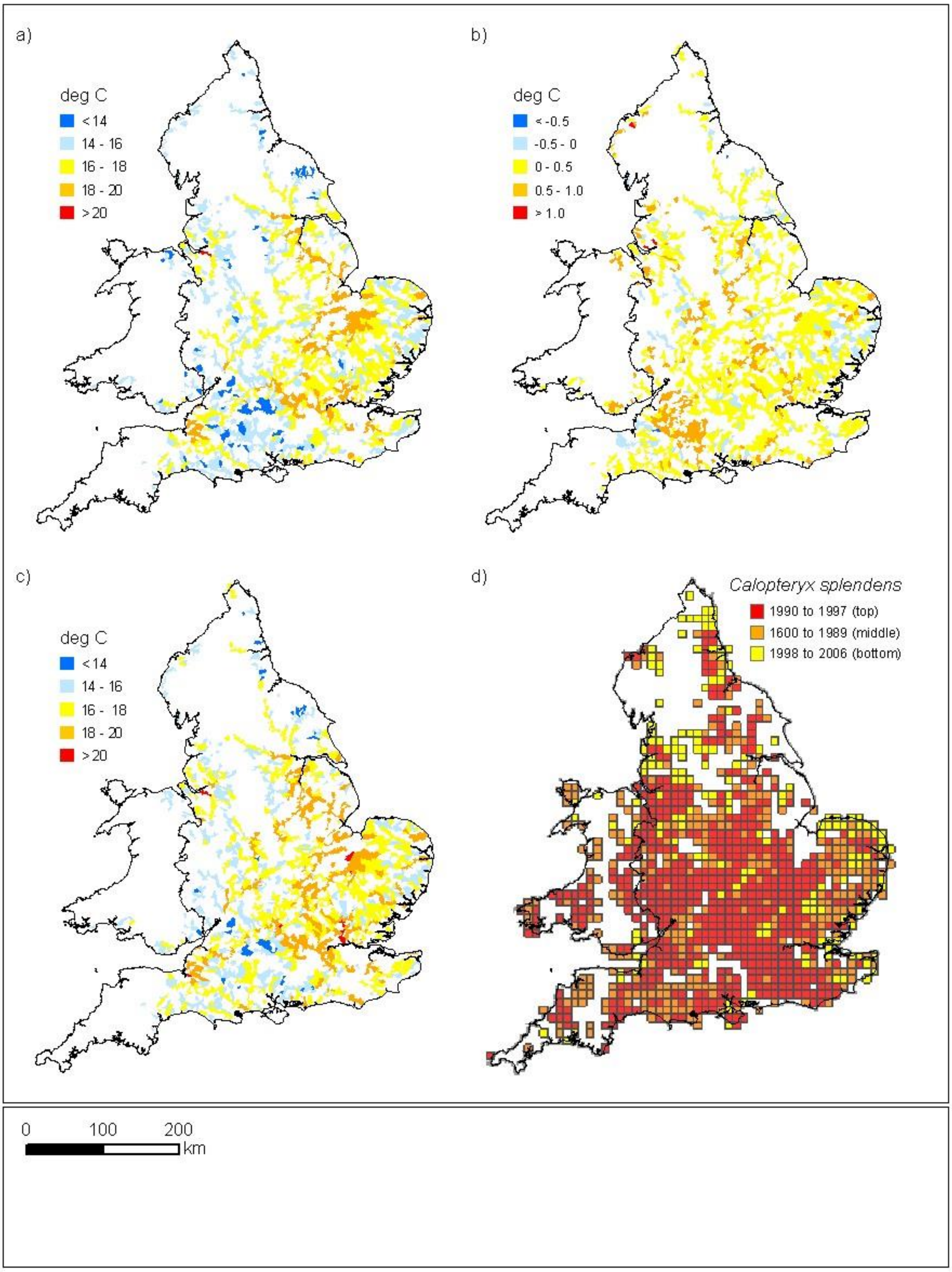

Figure 35 Changes in the distribution of the Banded Demoiselle (*C. splendens*) between 1990 and 2006 (d). Estimated average daily summer temperatures (°C) in 1990 (a) and 2006 (c), and decadal change for selected sub-catchments (c).

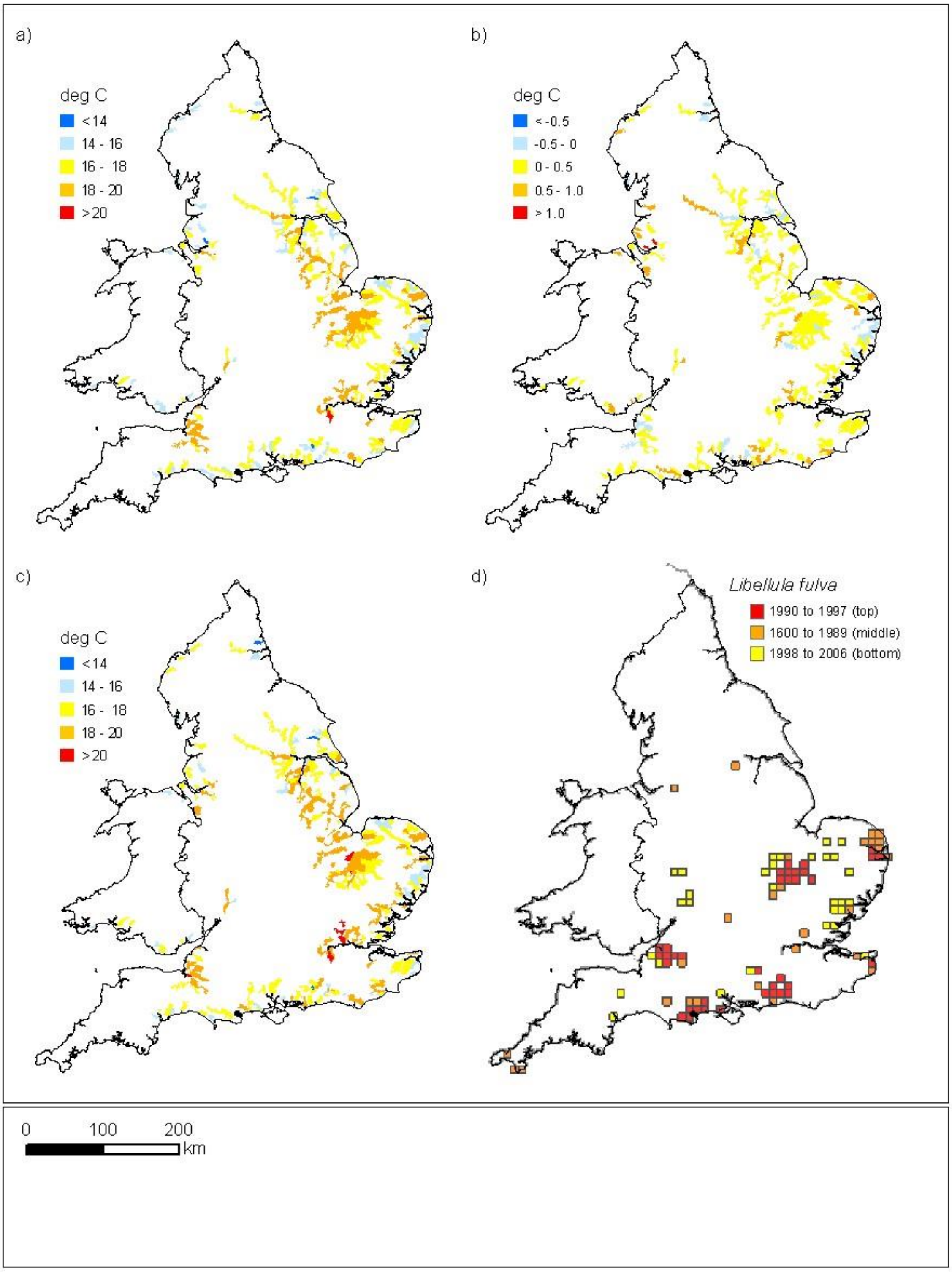

Figure 36 Changes in the distribution of the Scarce Chaser (*L. fulva*) between 1990 and 2006 (d). Estimated daily average summer temperatures (°C) in 1990 (a) and 2006 (c), and decadal change for selected sub-catchments (b).

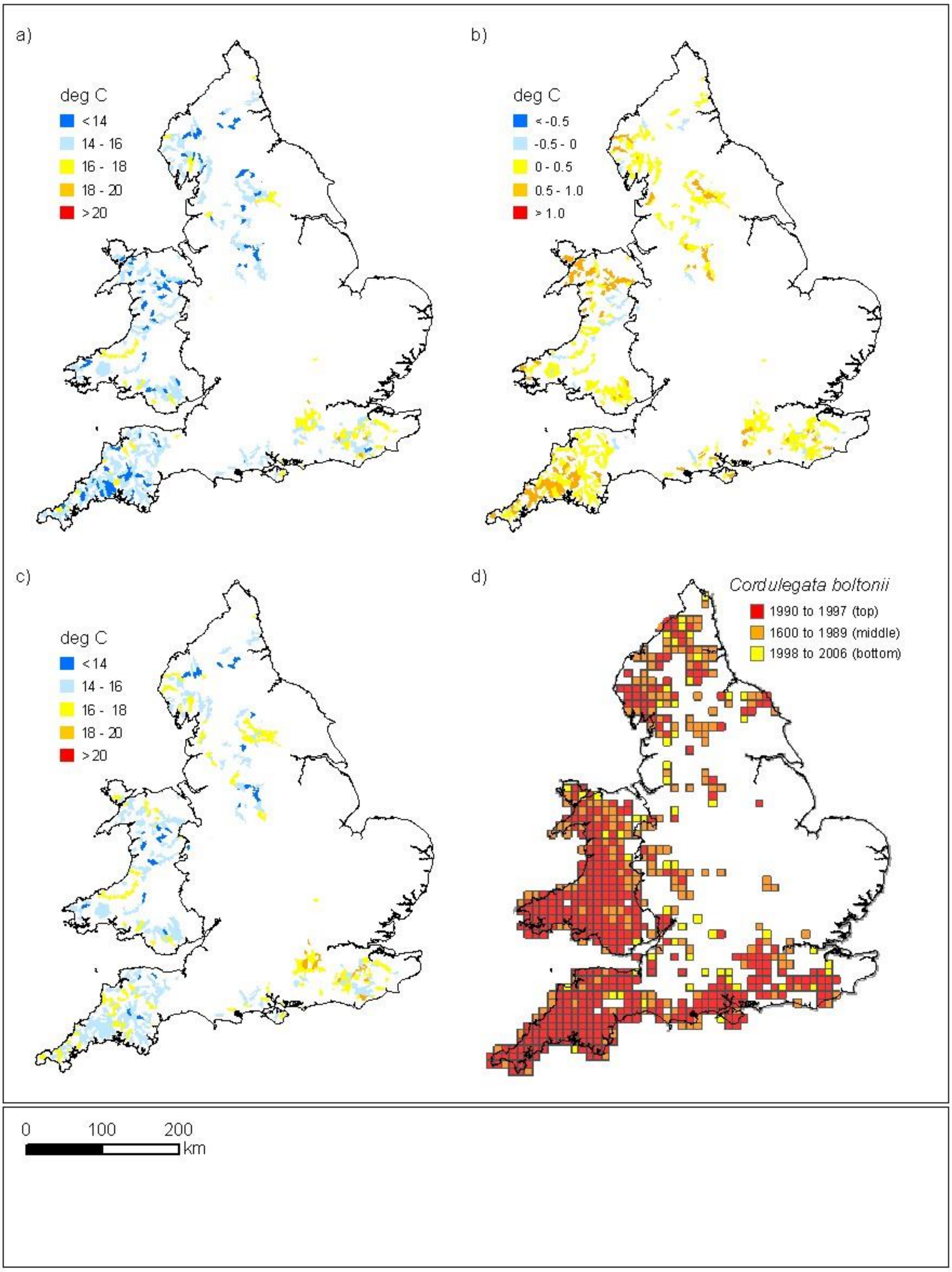

Figure 37 Changes in the distribution of the Golden-ringed dragonfly (*C. boltonii*) between 1990 and 2006 (d). Estimated daily average summer temperatures (°C) in 1990 (a) in 2006 (c) and decadal change for selected sub-catchments (b).

6.3 Salmon Case Study

6.3.1 Introduction

Salmonids provide a number of cold-water indicator fish species with well-documented temperature optima and critical thresholds acting at different stages of their life-cycle. Malcolm Elliott presented a review of critical temperatures for salmonids at the Expert Meeting in January 2008 (see Appendix). This knowledge and the availability of data from the large number of sites from Salmon Action Plan (SAP) rivers led to the choice of Atlantic salmon as a case study.

6.3.2 Salmon Action Plan river sites

SAP river sites are selected using the GIS layer of Salmon River network used by the EA for their annual advice to ICES (Cefas and Environment Agency, 2008). From the 79 Salmon River systems in England and Wales, only the 67 with a Salmon Action Plan (SAP) are considered here (Figure 4).

A simple join with the GIS layer was used to compute the distance of each of the 30,580 sites in the Archive. This identified 437 river sites from the 2,772 sites in our analysis that are within 150m of a SAP river. The Salmon River network spatial definition is higher than the general river network initially provided to us (see 2.3) thus the SAP spatial identification is more limited by the precision of the river site coordinates. Some SAP sites with less precise coordinates may have been left out of the selection while sites located on non-SAP streams but within 150m may have been included.

The SAP sites are mostly in the WA (111) and SW (96) regions, and more than a third of all EA Wales sites in the Archive are on SAP rivers (Table 29). The lone site in the AN region (PCHR0019) is the Cherwell at the Twyford road bridge, effectively in the Thames River Basin District.

Table 29 Salmon Action Plan and non-SAP river site numbers by region

EA_REGION	AN	MD	NE	NW	SO	SW	TH	WA	Sites
SAP	1	57	36	57	14	96	65	111	437
non-SAP	543	229	230	221	334	315	258	205	2335
Total sites	544	286	266	278	348	411	323	316	2772

6.3.3 SAP sites information

Across the whole of the UK, cool (salmonid) waters correspond mostly to river types 1, 2, 3, 4 and 8 (UKTAG, 2007), but the Archive also holds a large number of SAP sites in river types 5 (lowland, CA, medium catchment size) and 13 and 14 (Mid altitude, SI and CA, medium size catchments) (Table 30), which are more typical of England and Wales.

The number of SAP sites in each type is too small to compute meaningful averages in each region and results need to be presented using individual site values. The only site-specific information in the Archive are the site coordinates (easting x, northing y in km), and its elevation (z, in m) computed from the GIS layer (section 2.3).

Table 30 SAP river site numbers by WFD type and region

TYPE	AN	MD	NE	NW	SO	SW	TH	WA	Sites
1			1	2		9		10	22
2	1	7	6	5		4	4	3	30
4				5		16	5	6	32
5		21	5	2	11	26	33	16	114
7		8				1		1	10
8		18			3	6	23		50
10				3		17		17	37
11				1				2	3
13			2	16		17		38	73
14		2	16	13				14	45
16				1				2	3
17		1	6	9				2	18
SAP sites	1	57	36	57	14	96	65	111	437

The WFD typology and BFI information are averages for the sub-catchment, and depending on the site position within the sub-catchment, catchment values can be uninformative (Sandin and Verdonshot, 2006) or even misleading. Thus WFD typology categories are expected to be very informative to compare individual or small numbers of sites.

In the analysis below we use WFD geology categories and refer to sub-catchment BFI values for illustrative purpose only.

Over all regions, there are more SAP sites in calcareous (CA) than in siliceous (SI) sub-catchments (Table 31). Three regions, NW, SW and WA, have large numbers of sites in both types, while SAP sites are dominantly calcareous in the AN, MD, NE, SO and TH regions.

Table 31 SAP sites geology category by region

Sites	AN	MD	NE	NW	SO	SW	TH	WA	Sites
CA	1	49	33	30	14	36	60	37	260
SI		8	3	27		60	5	74	177

The average elevation (m) of SAP sites in each region is given in Table 32.

Table 32 SAP sites elevation (m) by region

EA_REGION	AN	MD	NE	NW	SO	SW	TH	WA
Sites	1	57	36	57	14	96	65	111
Elevation (m)	84	42	61	50	20	64	47	58

The average Base Flow Index (BFI, see 2.3) for SAP sites show differences between regions and geology types (Table 33), although not always in the same direction. The SW chalk stream catchments (CA) have a much higher BFI than SW SI catchments, but less so in WA; and the reverse happens in the MD and NW regions where SI sub-catchments have higher BFI values.

BFI average values for SI sites are very similar, if we leave aside the regions with less than ten SI sites, the values for NW, SW and WA range between 0.54 and 0.58.

For CA catchments, BFI values are much higher in the South (SW 0.77 and TH 0.65) than in the North (NE 0.41, NW 0.44) with intermediate values in MD (0.53) and WA (0.63).

Table 33 Average sub-catchment BFI for SAP sites by region

AvgBFI	MD	NE	NW	SO	SW	TH	WA	AvgBFI
CA	0.53	0.41	0.44	0.70	0.77	0.65	0.63	0.59
SI	0.65	0.40	0.54		0.58	0.62	0.56	0.57

6.3.4 Annual temperature changes

Over the seventeen years from 1990 to 2006, estimates for both the annual average daily temperature for 2006 and the decadal rate of change from 1990 are higher for sites in CA than SI catchments.

The decadal change is much lower than the regional average for SAP CA sites in MD and SO, higher for NW and SW, and the same for NE and TH. For SAP SI sites, NW has a slightly higher warming rate than average; WA sites a lower rate, and TH about the same (Table 34, and Table 18).

Table 34 Predicted 2006 annual t° and decadal change for SAP sites by region and catchment geology

GEOL_CAT	CA	CA	CA	CA	CA	CA	CA	SI	SI	SI
EA_REGION	MD	NE	NW	SO	SW	TH	WA	NW	SW	WA
Sites	49	33	30	14	36	60	37	27	60	74
2006	11.21	10.19	10.61	11.49	11.64	12.21	11.02	10.41	11.23	10.79
Dec_06-90	0.23	0.19	0.39	0.09	0.47	0.28	0.45	0.35	0.39	0.27

Catchment geology is a useful descriptor to separate SAP sites by altitude, easting and northing, as illustrated in Figure 38 (upper), which shows that reconstructed daily average water temperatures for SAP sites in 2006 vary linearly with altitude and latitude (northing) and non-linearly from West to East (easting). Decadal rates of changes show some trend (indicated by linear fits in Figure 38 (lower)) overall, but the variability between sites is still very large, and as previously noted, part of the trend is explained by one type of site being most prevalent in specific locations and geology, such as higher altitude site CA in the West (Figure 39 CA upper and SI lower graphs).

Therefore, a much finer analysis by site within region and river systems would facilitate the comparisons of like for like sites.

6.3.5 Seasonal temperature changes

Seasonal averages show that SAP sites had in 2006 colder winters than average in all but SO (Q1) regions, and cooler than average summers (Q3) in MD, SO and TH, but warmer than average summers in NE and SW regions (Table 35 and see Table 21).

As mentioned previously, average values must be taken with caution as the number of sites per category becomes smaller.

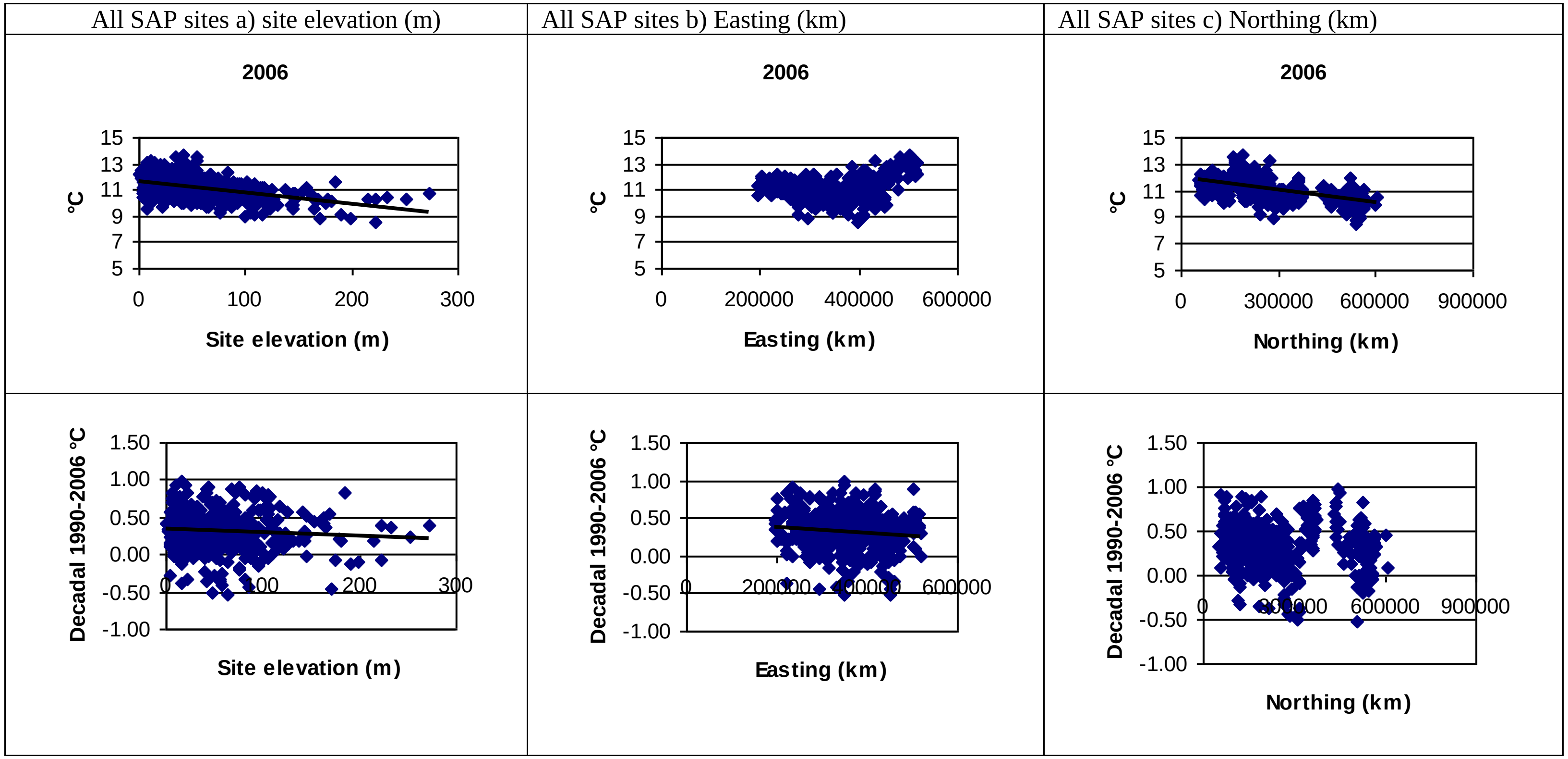

Figure 38 Estimated average 2006 and decadal increase between 1900-2006 (°C) for SAP sites with a) site elevation, b) easting and c) northing

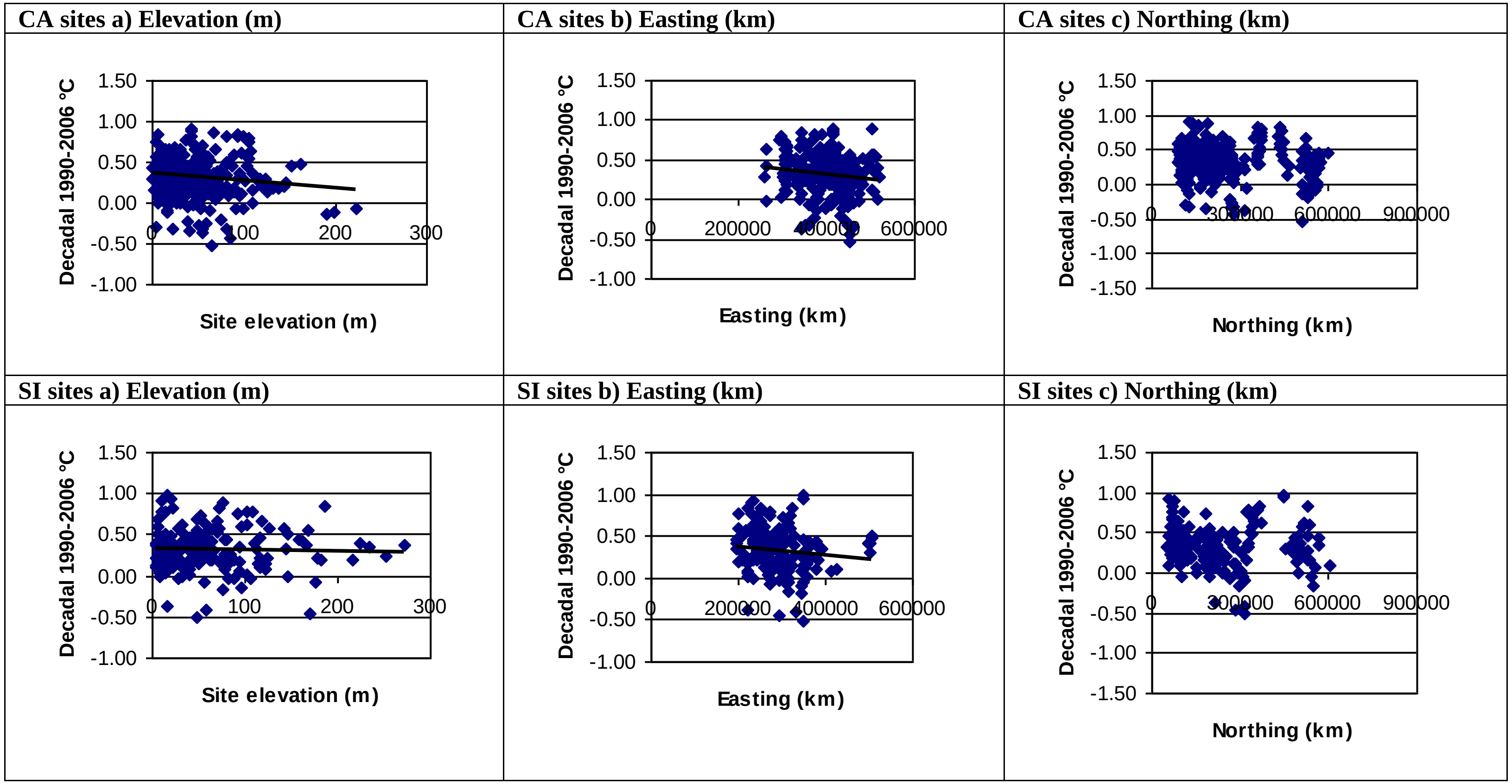

Figure 39 Predicted decadal increase between 1900-2006 (°C) for SAP CA (upper) and SI (lower) sites with a) site elevation, b) easting and c) northing

The EA regional scale makes it difficult to interpret averages by region and type and by season (table not shown), but the complexity of temperature time-series analysis already visible in Table 35 needs to be kept in mind, particularly when interpreting seasonal patterns, which in our models are not allowed to vary in shape over the long-term.

Table 35 Predicted 2006 annual and seasonal t° change for SAP sites by region and catchment geology

EA_REGION	MD	NE	NW	SO	SW	TH	WA
Sites	57	36	57	14	96	65	111
2006	11.18	10.18	10.52	11.49	11.39	12.22	10.87
Dec 06-90	0.21	0.20	0.37	0.09	0.42	0.29	0.33
2005_Q1	5.96	5.34	5.42	7.44	7.42	6.75	6.66
2006_Q2	10.38	9.39	9.53	10.78	10.31	11.27	9.84
2006_Q3	16.79	15.47	16.10	15.93	15.83	18.10	15.51
2006_Q4	11.41	10.37	10.81	11.71	11.82	12.58	11.34

6.3.6 Temperature threshold indicators

Model simulations (see 3.4) of daily temperatures between 1990 and 2006 provide a basis to compute a number of days per year (an average over 1000 simulation runs) when the water temperature is above or below a given threshold, or is within a set interval.

The review provided by Malcolm Elliott at the Expert Meeting (in Appendix) by Turnpenny and Liney (2006) and UKTAG 2007 informed our choice of threshold values as follows:

- below 10°C: 10°C is the existing Freshwater Fish Directive temperature standard for salmonid waters during the spawning season;
- Between 15°C and 17°C: a preferred range that covers feeding, growth, swimming and resistance to disease;
- Above 20°C or above 21°C: values that may constitute thermal barriers reducing the number of upstream migrating adults in the southern regions (Solomon and Sambrook, 2004).

Days below 10°C

Overall for all SAP sites, 88% have experienced a decrease in the number of days when the water temperature was less than 10°C. On average, the decrease is much higher for SW sites, with 12 days less per decade over the 1990-2006 period (Table 36).

The number of days when the water temperature is below 10°C decreases quasi linearly with the average daily temperature in 2006, as well as for the regional averages (Figure 40).

Table 36 Predicted number of days with t <10°C and 1990-2006 change

EA_REGION	Sites	Decadal change t°C 06-90	Avg t°C 2006	Avg 2006 days<10°C	Decadal change days 06-90
AN	1	0.50	12.32	148	-8
MD	57	0.21	11.18	167	-5
NE	36	0.20	10.18	187	-4
NW	57	0.37	10.52	181	-7
SO	14	0.09	11.49	153	-2
SW	96	0.42	11.39	157	-12
TH	65	0.29	12.22	148	-6
WA	111	0.33	10.87	171	-8
	437				

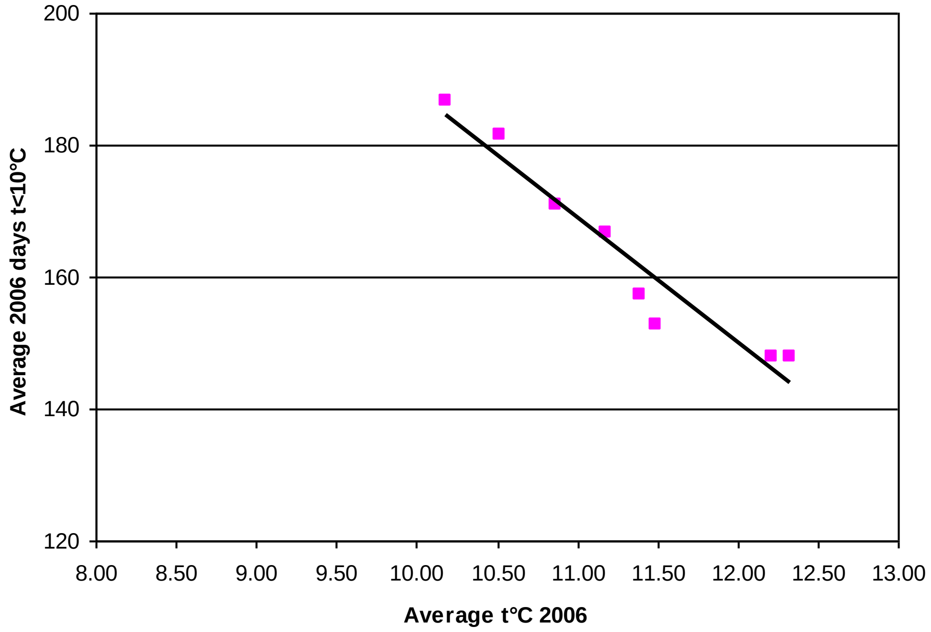

Figure 40 Average number of days with t<10°C per year and average annual daily temperature for 2006

The rate of decadal change in the number of coolest days is also related to the decadal rate of warming of the 1990 to 2006 period (Figure 41), although with additional variability due to the lone AN site on one side and the SW region with its different groups of sites (see 5.5.4) on the other.

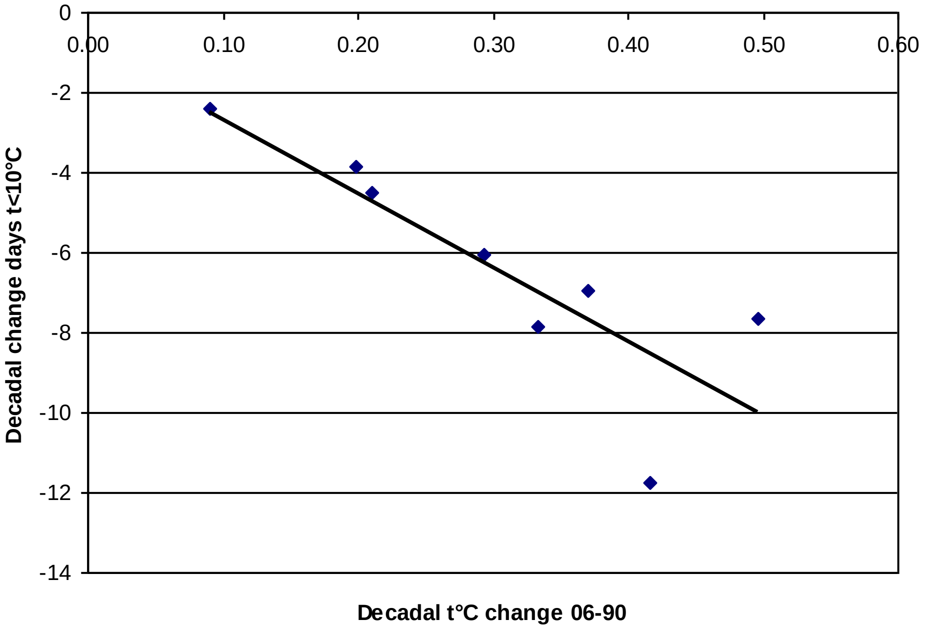

Figure 41 Average decadal change in days t<10°C with decadal change in average annual daily temperatures by EA region

Days between 15°C and 17°C

There is no trend or no average clear picture for the number of days when water temperatures may be optimal. Table 37 shows no obvious link between number of days or their decadal change, which ranges between 10 and -2, with no apparent link to annual mean temperatures or their decadal rate of change over the 1990-2006 period.

Table 37 Predicted number of days when temperatures 15-17°C and 1990-2006 change

EA_REGION	Sites	Decadal change t°C 06-90	Avg t°C 2006	Avg 2006 days15-17°C	Decadal change days 06-90
AN	1	0.50	12.32	43	-1
MD	57	0.21	11.18	53	-1
NE	36	0.20	10.18	52	3
NW	57	0.37	10.52	55	0
SO	14	0.09	11.49	71	-1
SW	96	0.42	11.39	63	10
TH	65	0.29	12.22	44	-2
WA	111	0.33	10.87	54	8

With hindsight this may have been expected, as a narrow range of temperatures on one side of the annual daily temperature distribution is not a statistically well-defined quantity. Any changes are therefore even less defined. Another problem possibly lies in the fact that the range is too narrow, and that any intermediate temperatures in the 15-17°C range may arise at different times of the year, and therefore not correspond to any clear climate signal. This is suggested by the fact that there is no clear relationship between number of days and either the 2006 annual temperature at the site, or its decadal change in the table below or at site level (not shown here).

Days above 21°C

Among all 437 SAP sites, only one – the THAMES AT NSWC INTAKE, CHERTSEY (siteID PTHR0096) - has a predicted non-zero number of days in 2006 when daily temperature is greater than the 21°C threshold. The progression starts from zero up to and including 2003, 4 days in 2004, 7 days in 2005 and 14 days in 2006.

Days above 20°C

Seventeen sites exceeded the 20°C threshold by 2006, 16 in the TH region and one in WA. The list in Table 38 and Table 39 gives site names, the average daily 2006 temperature and decadal increases, as well as the detailed number of days for each year over the 17-year period. The TH region sites are all on the river Thames, apart from the twelfth in the list on the Blackwater.

Table 38 List of sites with days >20°C, 2006 annual temperature and 1990-2006 decadal change in days and temperature

N	2006 days	2006 t°C	dec days	Avg 0690	WFD	siteID	siteName
1	48	13.31	19	0.58	8	PTHR0096	THAMES NSWC INTAKE, CHERTSEY
2	47	13.11	2	-0.01	8	PTHR0076	THAMES AT RAVENS AIT, SURBITON
3	45	13.15	26	0.54	8	PTHR0094	THAMES AT MWD INTAKE, WALTON
4	42	13.16	25	0.52	8	PTHR0075	THAMES ABOVE NSWC INT, EGHAM
5	41	12.69	24	0.38	8	PTHR0081	THAMES AT CLIFTON HAMPDEN BR
6	39	13.00	23	0.47	8	PTHR0079	THAMES AT BOVENEY WEIR
7	37	12.76	19	0.35	8	PTHR0083	THAMES AT DAYS LOCK
8	32	12.93	19	0.43	8	PTHR0108	THAMES AT THREE VALLEYS WATER
9	30	12.65	18	0.56	8	PTHR0098	THAMES AT RADLEY COLLEGE BOAT
10	28	12.92	16	0.37	8	PTHR0082	THAMES AT COOKHAM BRIDGE
11	22	12.37	13	0.18	8	PTHR0111	THAMES AT WALLINGFORD BRIDGE
12	22	13.53	13	0.51	5	PLDR0012	BLACKWATER BELOW SANDHURST S
13	21	12.27	12	0.30	8	PTHR0105	THAMES SUTTON BRIDGE, CULHAM
14	18	12.53	9	0.08	8	PTHR0080	THAMES AT CAVERSHAM WEIR
15	10	12.29	6	0.25	8	PTHR0085	THAMES AT FOLLY BRIDGE, OXFORD
16	8	12.68	5	0.34	8	PTHR0088	THAMES AT HENLEY BRIDGE
17	2	12.14	1	0.63	17	50032	R WYE AT REDBROOK RAILWAY BR.

In Table 38, the sites are arranged in decreasing number of days above the threshold for 2006 (2nd column). It is therefore no surprise that the site at the top of the list is the Thames at Chertsey, which also exceeded the 21°C threshold.

The fourth column (dec days) gives the decadal change in number of days between 1990 and 2006[6], which gives some indication as to how fast the site is warming up .

It is interesting to note that the increase in number of days above the threshold in 2006 is not always simply related to the decadal change over the 1990-2006 period. The second site in the list, for example, (PTHR0076 Thames at Surbiton), changed very little, while the sites immediately further down the list are estimated to have experienced a much higher increase over the same period.

The rate of increase in number of days above 20°C generally increases with the decadal temperature change for the TH region sites (Figure 42) . The site in Wales (50032, R WYE AT REDBROOK RAILWAY BR.) is the obvious outlier.

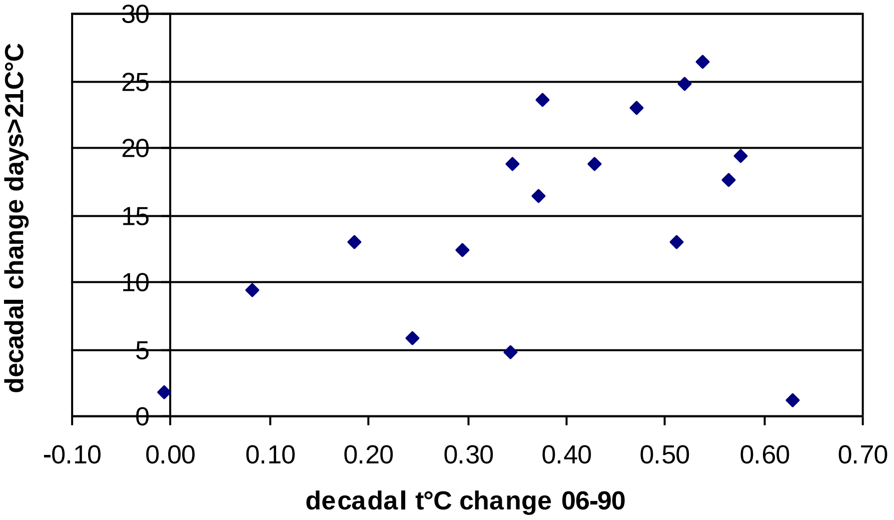

Figure 42 Average decadal change in days t>20°C with decadal change in average annual daily temperatures for 2006 for 17 sites concerned

Leaving aside the WA site, the decadal change in number of days above 20°C to 2006 is even more clearly related to the average temperature for 2006 for each TH site (Figure 43).

---

[6] Just as for the temperature decadal change, calculated as 10*(days06-days90)/17

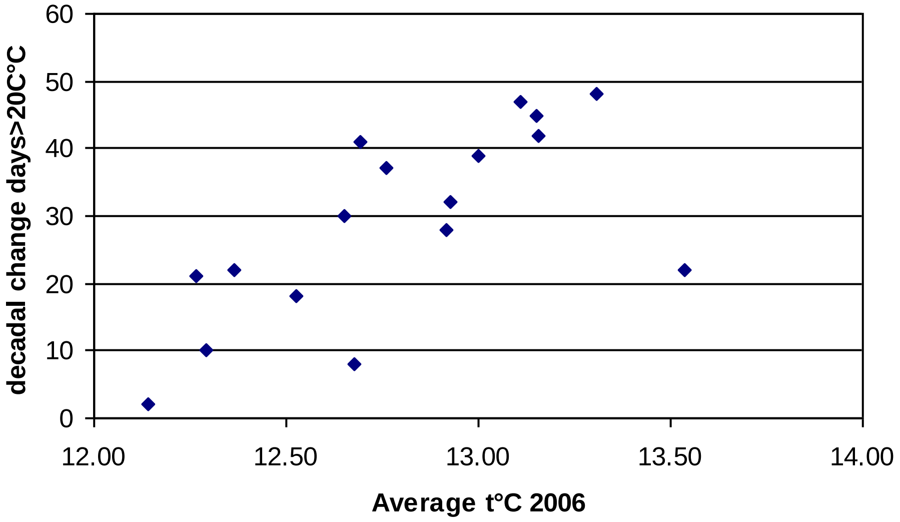

Figure 43 Average decadal change in days t>20°C with the average annual temperature for 2006 for 17 sites concerned

Table 39 Number of days per year >20°C between 1990 and 2006 and 2006 annual temperature

N		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2002	2001	2003	2004	2005	2006	2006 t°C
1	TH	15	21	21	22	28	29	30	33	35	37	40	41	41	42	45	47	48	13.31
2	TH	44	26	0	0	9	40	52	58	41	25	20	38	23	39	36	41	47	13.11
3	TH	0	0	1	8	17	20	21	26	27	30	32	37	36	38	41	43	45	13.15
4	TH	0	0	0	0	0	2	6	13	17	24	28	33	30	36	38	39	42	13.16
5	TH	1	5	12	12	17	21	21	24	27	26	30	34	33	34	35	41	41	12.69
6	TH	0	0	4	10	10	19	19	22	24	25	30	32	32	34	38	39	39	13.00
7	TH	5	7	11	15	17	17	22	24	26	28	30	30	30	33	37	39	37	12.76
8	TH	0	0	0	0	3	3	9	14	15	18	22	27	24	25	29	30	32	12.93
9	TH	0	0	0	0	0	0	0	0	0	7	10	19	15	22	25	29	30	12.65
10	TH	0	0	0	0	0	0	0	0	0	2	7	16	7	17	22	25	28	12.92
11	TH	0	5	9	11	13	11	14	17	16	19	20	20	19	19	23	24	22	12.37
12	TH	0	0	0	0	0	0	0	0	0	0	0	2	0	4	9	14	22	13.53
13	TH	0	0	0	0	0	0	0	0	2	2	3	11	6	14	18	19	21	12.27
14	TH	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	7	18	12.53
15	TH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	6	10	12.29
16	TH	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	8	12.68
17	WA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	12.14

6.3.7 Discussion

The Atlantic Salmon case study provides a rich illustration of the key features of the Archive and its potential to inform topical management questions.

GIS information on the location of Salmon Action Plan (SAP) rivers selected 437 sites among the 2,772 with modelled water temperature times series between 1990 and 2006. It will be possible to improve the site selection process in the future, once more precise elevation data are available, and some data quality control process is in place.

There is little information in the Archive that links directly to the site local scale, and catchment-scale data from the WFD typology or BFI do not explain much of the variability observed. However, general trends with site altitude, easting and northing are apparent.

The most promising use of the Archive for this case study is the use of temperature thresholds to compute the number of days below and above the thresholds from the simulation models.

The Archive gives clear location of sites above a threshold and makes it possible to reconstruct the site thermal history. Even the first results presented here suggest some good predictive value per site, as extreme thresholds have clear links with average annual temperatures and decadal rates of temperature change. The Archive can be used to further our understanding of where such water temperature thresholds are reached and when they are likely to be crossed, and therefore help develop national strategic adaptation strategies.

7 Surface water temperature monitoring network

7.1 Introduction

The Archive can be a useful resource to inform the choice of sites for the purpose of monitoring climate change.

The emphasis of this project has been placed on long-term trends, and both geographical coverage and the duration of time series have guided the selection of sites and analyses presented in this report. High frequency sub-daily time series generated by Automatic Water Quality Monitoring Stations (AWQM) are mostly very recent, and the number of records per site also put them beyond the computing capacity of our models. However, these times series will soon be long enough to inform long-term trends, and their site locations are also given.

7.2 Data holdings

Bearing in mind the need for data quality assurance and for more precise GIS information, the Archive's exhaustive sites coverage for temperature records up to June 2007 can easily be queried for record numbers per sites, records start, end date and duration, within each region and using WFD typology attributes.

The Archive data holdings are described in chapter 2, but only time series longer than 17 years or more are analysed in detail. Thus, for the purpose of monitoring specific ecological aspects, local questions or links between sites, it is important to emphasize that the Archive is very much richer than this report can show.

7.2.1 Record length and frequency

A precise assessment of recording frequency is not easy to query from the Archive mostly because for any given site, frequency changes over time and the total number of records listed per site may be influenced by a switch between daily, monthly or occasional records within and between years.

In our analyses, we have filtered out long-term records with interruptions of a year or more in two steps. We first counted the number of records per year, and then used this query to leave out sites with one or more missing years with zero records.

For the purpose of monitoring long-term temperature changes, the most even regional coverage in the Archive is undoubtedly given by the 2,772 sites for which the analyses are presented in detail in chapter 5.

7.3 WFD typology

The number of sub-catchments in the current WFD typology can be used to assess the typology coverage provided by the 2,772. Table 40 gives the number of river catchments (WBs) with at least one site currently monitored. The % column refers to the total number of river catchments in each type and region, and can be readily compared with those in Table 9.

The current level of temperature monitoring is about one catchment in five (21%, Table 41) with differences between regions. The percentage sub-catchment monitored varies widely between water body types, with more than half of the catchments covered for types 4, 5, 8, 13, 14, 16 and 17 (Table 42), and even a percentage greater than 100 for type 7 resulting from a site assigned to the wrong catchment type.

Table 40 WFD River Water Bodies with at least one 1990-2006 site

TYPE	AN	MD	NE	NW	SO	SW	TH	WA	WBs	%rep	ALT	GEOL	SIZE
0 or null	8	3	4	3	9	4	3	2	36		U	U	U
1	1	3	6	11	69	82	15	30	217	14%	LOW	SI	S
2	162	63	42	68	79	95	82	27	618	39%	LOW	CA	S
3	1								1	0%	LOW	OR	S
4			6	3	7	21	3	5	45	3%	LOW	SI	M
5	71	49	27	18	25	40	56	6	292	18%	LOW	CA	M
6	1								1	0%	LOW	OR	M
7		5				2		1	8	1%	LOW	SI	L
8	11	12	6	2	6	5	11		53	3%	LOW	CA	L
10		7	14	21		36		67	145	9%	MID	SI	S
11		7	12	20		2	5	20	66	4%	MID	CA	S
12		1	2	3		1			7	0%	MID	OR	S
13		6	7	17		16		25	71	4%	MID	SI	M
14		3	17	11				11	42	3%	MID	CA	M
15				1					1	0%	MID	OR	M
16				1				2	3	0%	MID	SI	L
17		3	3	5				3	14	1%	MID	CA	L
28				1					1	0%	LOW	SA	S
37					3	3			6	0%	LOW	SI	XS
40	2				3		1		6	0%	LOW	CA	XS
	257	162	146	185	201	307	176	199	1633				
	16%	10%	9%	11%	12%	19%	11%	12%					

Table 41 WFD River sub-catchments (WBs) by region and level of on-going monitoring (WBs with at least one 1990-2006 site)

Region	AN	MD	NE	NW	SO	SW	TH	WA	WBs
WBs	1,134	832	1,031	736	684	1,473	467	1,375	7,732
monit'd	257	162	146	185	201	307	176	199	1633
	23%	19%	14%	25%	29%	21%	38%	14%	21%

Table 42 River sub-catchments (WBs) by WFD type and level of on-going monitoring (WBs with at least one 1990-2006 site)

WFD Type	WBs	monit'd	
1	684	217	32%
2	2779	618	22%
3	13	1	8%
4	59	45	76%
5	386	292	76%
6	2	1	50%
7	7	8	114%
8	55	53	96%
10	692	145	21%
11	483	66	14%
12	120	7	6%
13	100	71	71%
14	64	42	66%
15	3	1	33%
16	4	3	75%
17	20	14	70%
28	13	1	8%
37	441	6	1%
40	368	6	2%
WBs	6293	1597	25%

7.4 Longest times series

The ten longest time series for WIMS sites in the Archive for each of the eight EA regions are mapped in Figure 44, with an indication of the number of years for each site. End dates for each site with current records vary according to the time the data were transferred to us between October 2007 and April 2008. Thus we have used an end-date greater than 1st June 2007 to indicate on-going monitoring.

The map also shows the location of high frequency monitoring sites from TIMS and WISKI, which complement the spot sampling coverage particularly in the MD and NE regions.

Five of the eight benchmark sites proposed by the Scoping study (Hammond and Pryce, 2007) are among the 80 selected sites, their AN and WA sites were set aside because of low sampling frequency in recent years, and their MD site is one of the WISKI sites.

Twenty four of the sites among the 80 longest on-going time series analysed are on Salmon Action Plan rivers (see 6.3). Table 43 shows the predicted 2006 temperature and decadal warming over the period 1990 to 2006 for each of these sites.

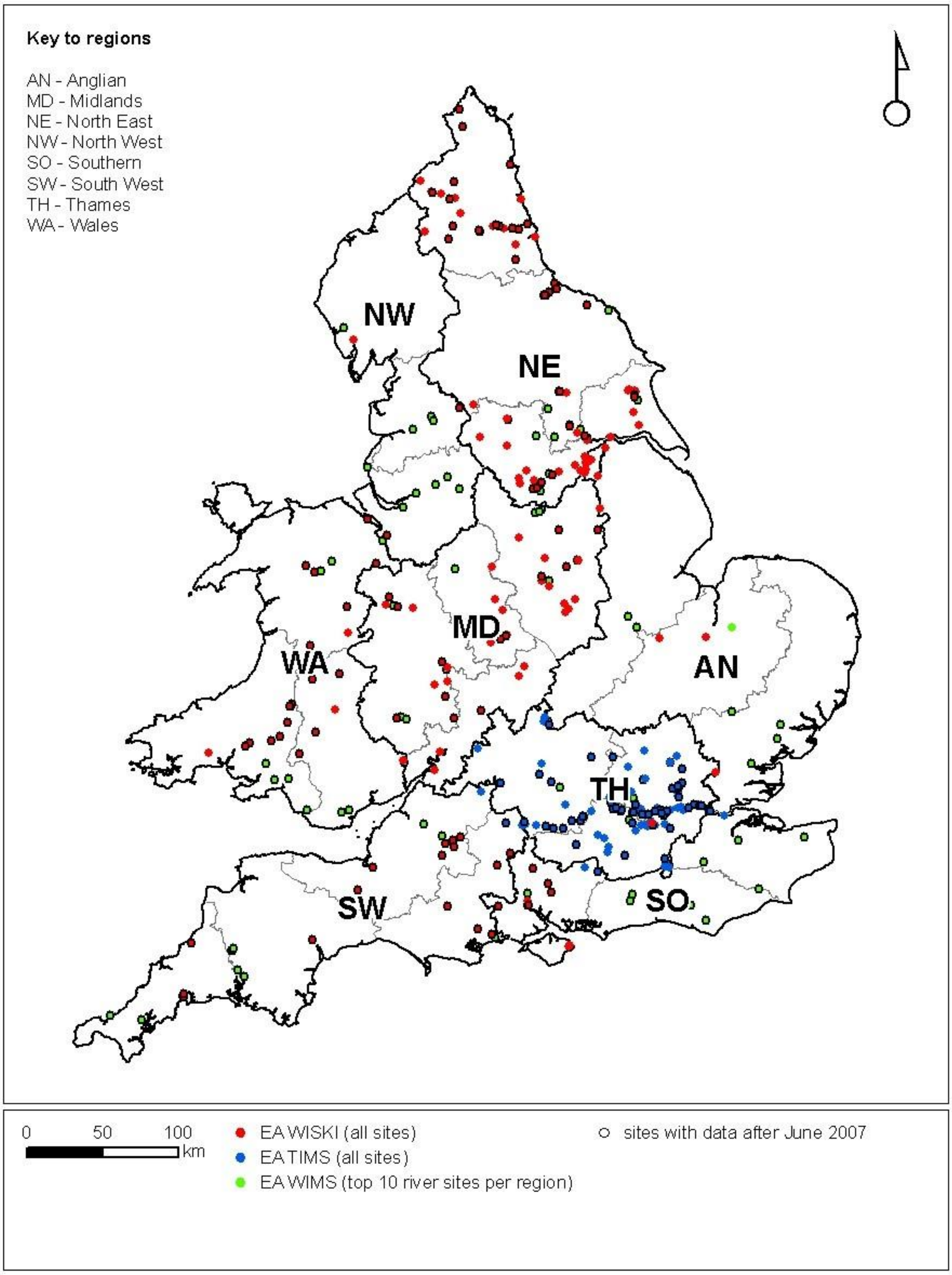

Figure 44 Ten "best sites" in each region

Table 43 SAP river sites (24) in 10 best records by region

EA-Region	2006	Avg0690	siteName
AN	12.32	0.50	CHERWELL AT ROADBRIDGE, TWYFORD
MD	12.05	0.42	R.STOUR AT STOURPORT
MD	11.59	0.39	HOLT FLEET MEADOWS HOLT FLEET
NW*	11.10	0.77	RIVER RIBBLE AT MITTON BRIDGE
NW*	11.37	0.83	RIVER CALDER AT WHALLEY
NW	11.21	0.71	RIVER RIBBLE AT SAMLESBURY PGS
NW	9.56	-0.01	RIVER ESK AT CROPPLE HOW GAUGING STATION
SO	11.26	-0.12	R TEST GREATBRIDGE
SW	12.53	0.30	RIVER STOUR AT IFORD BRIDGE
SW	11.81	0.70	RIVER TAVY AT DENHAM BRIDGE
SW	11.80	0.37	RIVER TAMAR AT GUNNISLAKE BRIDGE
SW	11.26	0.26	RIVER LYD AT LIFTON BRIDGE
SW	11.43	0.39	RIVER THRUSHEL AT TINHAY BRIDGE
TH	13.59	0.36	COLNE AT GAUGING STATION, DENHAM
TH	13.16	0.52	THAMES ABOVE NSWC INTAKE, EGHAM
TH	12.53	0.08	THAMES AT CAVERSHAM WEIR
TH	12.76	0.35	THAMES AT DAYS LOCK
WA	10.70	0.51	R DEE @ LLANDDERFEL
WA	11.41	0.15	R OGMORE AT DIPPING BRIDGE
WA	12.01	0.55	R ELY AT ST FAGANS GS
WA	11.81	0.30	RIVER TAWE @ MORRISTON RD.BR.
WA	11.91	0.63	RIVER LOUGHOR AT H.M POINT
WA	12.14	0.63	R WYE AT REDBROOK RAILWAY BR.
WA	10.80	0.40	R ALYN AT ITHELS BRIDGE

7.5 Hot spots

Another important group of sites to be monitored is those with the most rapid change. Form our analyses we see that a predicted decadal rate of 0.76°C over the 1990-2006 period is exceeded by a little more than 5% of the 2776 sites analysed. On this basis the Archive holds 146 sites 'hot spots' across 11 WFD types and all eight regions (Table 44).

There are four hot spots among the ten best records per region, including two SAP sites from in the NW region (NW*).

Table 44 Hotspot river sites by WFD type and region

TYPE	AN	MD	NE	NW	SO	SW	TH	WA	Sites
0 and null	2			2		4		2	10
1			1		5	10	1	5	22
2	2	4	3	11	4	17	3		44
4			1	2	1	2			6
5	1	14		2	1	8	1		27
8	2	2				5	2		11
10		2				3		11	16
11			1					2	3
13				2					2
14				3					3
17		2							2
Total sites	7	24	6	22	11	49	7	20	146

Table 45 Hotspots among the 10 best records by region

EA_REGION	Avg0690	2006	20063	siteName
MD	0.94	13.01	20.32	RIVER TRENT AT NOTTINGHAM TRENT BRIDGE
NW*	0.83	11.37	17.91	RIVER CALDER AT WHALLEY
NW*	0.77	11.10	18.26	RIVER RIBBLE AT MITTON BRIDGE
SW	0.90	12.70	19.93	BRISTOL AVON AT LIMPLEY STOKE

7.6 Discussion

In this chapter we have identified ten WIMS sites per region as ‘best’ sites for long-term temperature change monitoring, on the basis of the record numbers and recording integrity, and length.

Ultimately, the choice of key monitoring sites may include other dimensions pertinent to environmental change monitoring such as the presence of hydrological, water quality, invertebrate or fish monitoring, but the Archive now makes it possible for each region to have its historical temperature records organised in one place for the first time.

The Archive also holds elevation, WFD typology and BFI information devised from GIS layers. In its final form, the Archive can be used in conjunction with other spatially structured information data systems, such as for land use or reconstructed air temperatures that may be relevant to further inform the choice of temperature monitoring sites.

One dimension currently lacking in the Archive is that of the river confluence and hierarchy within river basins so that sites can be linked together along a river system from source to estuary. This would allow, for example, a test for a possible cumulative warming of downstream sites that may be the reason for the more rapid warming of lowland sites in the AN region (section 5.5.4).

Finally, much of the work presented here has been aimed at the estimation of long-term trends in river water temperatures. If the purpose of monitoring is to help develop mitigation or adaptation measures the Archive holds a large volume of information for more recently monitored sites and should be equally resourceful.