

# **Distinguishing the Relative Importance of Environmental Data Underpinning flow Pressure assessment (DRIED-UP)**

EMCAR Research Project EMC/WP05/086

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To establish priority areas for environmental monitoring for assessing the impact of abstraction. This will help define data collection for surface water hydro-morphology aspects of Environmental Monitoring Classification and Reporting (EMCAR).

**Keywords**

Monitoring, EMCAR, Water Framework Directive, Water Resource Standards, LIFE, Macroinvertebrate, Taxonomic Resolution, Habitat, River Habitat Survey, RHS, Habitat Modification, Hydraulic Modelling, Optimal Sampling, Multilevel Modelling.

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## EXECUTIVE SUMMARY

This project, funded by the Environment Agency's EMCAR programme, has examined various sources of uncertainty in the relationship between LIFE score (a flow-sensitive index of the macroinvertebrate community<sup>1</sup>) and historical river flow, with the aim of optimising monitoring investment. The focus has been on alternative derivations of the river flow and LIFE data (gauged vs modelled river flows; taxonomy at species, genus or family level), and on the potential benefit of using local habitat data to improve understanding of LIFE-flow relationships. The project used data already collected by the Agency, and throughout, a strong emphasis has been on the adequacy of the relationships for water resources purposes. The study has focused on a limited number of lowland sites in Northern Anglian Region, which have minor artificial influences to flows, and for which excellent quality flow and biology data are available. New RHS surveys were undertaken for most of the sites. The main analysis tool was linear regression modelling within a multilevel framework, which provides a powerful analysis tool when data are hierarchically structured (e.g. repeated observations at a set of sites). This allows the integrated analysis of the effects of sample-level (i.e. flow) and site-level (i.e. habitat) variables together.

The stated aim of the project was:

“To establish priority areas for environmental monitoring for assessing the impact of abstraction. This will help define data collection for surface water hydro-morphology aspects of Environmental Monitoring Classification and Reporting (EMCAR).”

In particular, the study has attempted to address the following questions for assessing water resource pressure:

- Can we replace gauged flows with modelled flows?
- Does biology need to be monitored to family, genus or species level?
- Do we need cross section data at biology or RHS sites?
- Do we need RHS data at biological sample sites?
- What spatial resolution of data collection is appropriate?

### **Taxonomic resolution**

Results were less clear than expected, with only slight trends for genus/species-level taxonomy to give tighter relationships than family-level. This could be due to the relatively family-rich lowland sites examined and results may be different in other river types. Some issues have been raised which relate to how the LIFE score is calculated for samples which include identifications at a mixture of taxonomic levels.

### **Effects of habitat on LIFE score**

The results clearly demonstrate the interaction between physical habitat, flow regime and biotic scores. Habitat modification appears to influence the relationship between LIFE score and flow, with more modified sites (higher RHS Habitat Modification Score, HMS) having lower LIFE scores and a steeper slope of response of LIFE score to flow. Neither HQA (RHS habitat quality score), nor HQA sub-scores related to LIFE in this study.

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<sup>1</sup> We use flow in the hydrological sense, to refer to river discharge, measured in volume/time (ie m<sup>3</sup>/s). The LIFE score flow group weightings relate to perceived sensitivity to high/low velocity and silt/coarse substrates. In-river velocity is a product of both flow (discharge) and channel structure/habitat.

Siltation has been shown to have an effect beyond that of the flow variables used, although this analysis is partly limited by the lack of silt fraction data for all samples. The response of individual LIFE flow groups can help explain the differences in the overall LIFE response of the more and less modified sites.

Some progress was made with including hydraulic data measured at biology sites. The results for the sites with true riffles indicated that the conveyance estimation system (CES) predicted water levels well from channel cross-section data and roughness estimates alone. However, water levels, and hence velocities at many of the sampled sites are influenced by downstream hydraulic controls, which would need to be included in any future monitoring.

These results have many implications for the use of LIFE and RHS in water resources management, and also in the use of RHS for other purposes in the Agency. At the moment, monitoring for macroinvertebrates occurs at sites selected at a time when assessment of water quality was the primary goal. River habitat surveys have been undertaken mainly under different sampling strategies, and have not generally been used in conjunction with any biological sampling. This study has shown the benefit of linking RHS and macroinvertebrate sampling, either from existing data or with new RHS surveys.

Habitat modification is not taken into account when setting flow objectives, these results suggest that perhaps it should. There are potential far-reaching implications of this study in terms of whether more modified channels should be granted more stringent flow standards than more natural channels. Given this potential link, it is strongly recommended to undertake some RHS surveys to be co-incident with macroinvertebrate monitoring sites considered to be of importance for water resources monitoring so that future analysis of such data can account for the potentially confounding effects of habitat.

Additionally, these results suggest that there is potential benefit in habitat rehabilitation works or reduction in sediment inputs in order to mitigate water resources pressure, and even climate change impacts on hydrology. However, comparison of sites with different levels of modification is not the same as showing the benefits of restoration, and more study is clearly needed in this area.

Similarly, historical changes in river flows will have led to variations in macroinvertebrate community structure; this should be taken into account in analyses of the relationships between habitat and macroinvertebrates. If analysing sites with small numbers of samples, temporal changes in flow could confound relationships between habitat and biota.

### **Reduction in flow corresponding to a set reduction in LIFE score**

An example is given of how water resources standards might be set, in terms of the proportional flow reduction at the long-term summer Q95 flow which would lead to an arbitrarily-set 0.1 unit reduction in LIFE-score. Three factors affect how this figure varies between sites: the magnitude of the long-term summer Q95 flow, the magnitude of the steepness of the LIFE-flow relationship, and the standard deviation of the time series of annual summer Q95 flows. Results suggest proportions of between 10 and 30%. This analysis is purely illustrative, but the figures do broadly agree with the results of other preliminary water resource standards work based on expert opinion – the SNIFFER WFD48 project. The results of this work emphasise the role of habitat conditions in determining sensitivity to flow, whereas the WFD48 project focused on catchment characteristics.

### **Replacing gauged flows with modelled flows**

In terms of the fit of the relationships at individual sites, there was little difference in results whether gauged or modelled flows were used as predictor variables. This is despite the fact that modelled flow time series were generated using a generalised rainfall-runoff model with predominantly automatic calibration (the CERF tool), and that the sites were in dry, eastern England, where it is difficult to describe the balance between summer rainfall and evapotranspiration and where there are often complex aquifer interactions with surface waters. The similarity of results is likely to be due in part to the nature of the LIFE index: it is highly aggregated and is likely to respond to broad temporal patterns of flow. However, there were differences when comparing the illustrative proportional flow changes developed using gauged vs CERF modelled flows. This highlights the importance of using an application-orientated measure of model performance rather than a simple model fit criterion.

These results may have important implications for water resource monitoring, and pave the way for the use of far more existing biological data in LIFE-flow analysis than is currently possible. This is because there is less need to consider only biological monitoring sites close to gauging stations.

Recent work as part of the RAM framework review by ENTEC has demonstrated the difficulty in relating abstraction pressures alone to LIFE scores. There are potentially many reasons for this, but of particular note are not including flow in the analysis, and concentrating on LIFE O/E. There is great potential for CERF natural flow time series to improve our understanding of the links between flow, abstraction and LIFE.

### **Effects of different amounts of data on the at-site LIFE-flow relationship**

In this study, the majority of the individual site specific relationships are good enough with which to make water resources judgements on the impact of flow changes on macroinvertebrates. However, these were chosen to be a “gold standard” in terms of data quantity and quality, in many other cases (other rivers, regions, CAMS), this is not the case, and the benefits of using a multilevel modelling approach, combined with flow and RHS predictors, to strengthen relationships at particular sites with limited data should be clearer.

Simulations were undertaken to examine the benefit of at-site habitat (i.e. RHS) data, and various combinations of at-site autumn biology data for a “new” site. The results reinforce the benefit of the habitat data, which is estimated to be between 1 and 5 years of autumn biology data. Unsurprisingly, at-site biology data is more useful when the LIFE-flow response of the new site does not fit the “more modified=steeper response” pattern of the other sites.

### **Future work**

Extension of the work to more upland sites is urgently required to achieve two objectives:

- Analysis at more taxon-poor sites could better demonstrate the benefits of taxonomy at genus or species level.
- The interaction between LIFE score, flow and habitat which is seen here for lowland sites needs to be tested on upland sites.

To this end, the positive results from the generalised rainfall-runoff modelling would allow the selection of upland sites, with good time series of macroinvertebrate data, along a gradient of habitat degradation, which do not necessarily need to be close to gauging stations. If co-incident RHS data were not available, it would not be too expensive to collect such data.

Other recommendations are given in the report.

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<b>CONTENTS</b>		<b>Page</b>
<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Aims and objectives	1
1.2	Project components	1
1.3	Data collation and fieldwork (Stage 1)	1
<b>2</b>	<b>Data analysis</b>	<b>6</b>
2.1	Methods	6
2.2	Baseline hydroecological behaviour (Stage 2)	6
2.3	Comparison of results from various taxonomic levels.	10
2.4	Predicting LIFE score variation with CERF-modelled flows	15
2.5	Reduction in flow corresponding to a set reduction in LIFE score	17
2.6	Modelling of between-site differences using habitat, indexed by RHS scores (Stage 3)	19
2.7	Influence of sample-level substrate data	28
2.8	Effects of different amounts of data on the at-site LIFE-flow relationship	29
2.8.1	Habitat Modification Score	29
2.8.2	A single year of biology data	31
2.8.3	Triennial sampling over the whole time period and continuously sampling for a portion of the time period	35
2.9	Channel hydraulics	38
2.10	Response of individual LIFE flow groups	41
2.11	Temporal trends in LIFE scores.	43
<b>3</b>	<b>Discussion</b>	<b>45</b>
3.1	Relationships at different taxonomic levels	45
3.2	RHS, habitat and LIFE	45
3.3	Reduction in flow corresponding to a set reduction in LIFE score	46
3.4	Flows modelled with generalised continuous rainfall-runoff model CERF	46
3.5	Benefits of different types and amounts of data	46
3.6	At-site hydraulics	47
3.7	Temporal trends	47
3.8	Relationship with results from the RAPHSA project	48
<b>4</b>	<b>Recommendations</b>	<b>49</b>
4.1	Monitoring and Management	49
4.2	Future Research	49
<b>5</b>	<b>References</b>	<b>51</b>
<b>A.</b>	<b>LIFE-FLOW Relationships for all sites</b>	<b>52</b>
<b>B.</b>	<b>Formulation of A multilevel linear regression model</b>	<b>54</b>
<b>C.</b>	<b>Site photographs</b>	<b>55</b>

## List of tables

Table 1. List of candidate sites for analysis.....	3
Table 2. Sites surveyed.....	4
Table 3. Model statistics for multilevel models at various taxonomic resolutions.....	12
Table 4. Data for converting a percentage change in LIFE score to a change in un-normalised summer Q95 (using gauged flows).....	18
Table 5. Data for converting a percentage change in LIFE score to a change in un-normalised summer Q95 (using CERF-modelled flows).....	18
Table 6. Summary of HMS scores and sub-scores for DRIED-UP core sites.....	22
Table 7. Summary of HQA and sub-scores for DRIED-UP core sites .....	23
Table 8. Coefficients for model with silt, season and HMS .....	29
Table 9. Table showing whether the model with HMS gives a closer or equal fit to the all-data at-site relationship.....	29
Table 10. Fixed effects for model of log abundance for flow groups 2 and 4 only .....	43
Table 11. Summary of relative benefits of RHS and biology data. ....	47

## List of figures

Figure 1. Time series of species+genus level LIFE scores (red) autumn samples and preceding summer flows (normalised Q95: green and Q10: blue). Some outlying points highlighted.....	8
Figure 2. LIFE-flow using autumn-only species+genus level data, using Q95 as the explanatory variable. A smooth nonparametric regression line (green) and a linear regression line (grey) are shown.....	9
Figure 3. LIFE-flow using autumn only species+genus level data, using Q10 as the explanatory variable. A smooth nonparametric regression line (green) and a linear regression line (grey) are shown.....	10
Figure 4. R <sup>2</sup> values for individual regressions with biological data at species+genus level, degraded to genus level, and degraded to family level.....	11
Figure 5. Taxonomic comparisons: SG & G .....	13
Figure 6. Taxonomic comparisons: SGF & GF .....	13
Figure 7. Taxonomic comparisons: SGF & SG .....	14
Figure 8. Taxonomic comparisons: SG & F.....	14
Figure 9. Relationship between time-varying Q95 flow statistics. ....	15
Figure 10. Relationship between time-varying Q10 flow statistics. ....	16
Figure 11. Comparison of proportions of Q95 for a 0.1 change in LIFE score, using both gauged and CERF-modelled flows.....	19
Figure 12. Mean relationship (red line) and predicted relationships for each site (grey lines) for multilevel model with Q95 as predictor. ....	21
Figure 13. Multilevel model with Q95 and HMS as predictors, including their interaction. Red line is mean relationship where HMS=0. Grey lines are the predicted site relationships assuming HMS=0. Blue line shows mean relationship where HMS=2000. Grey lines corresponding to variation around the blue line are not shown.....	21
Figure 14. Relationship between intercept and slope in multilevel model for 11 core sites. ....	24
Figure 15. Intercept terms for model with Q95 as predictor variable. ....	25
Figure 16. Intercept terms with HMS and Q95 including interaction.....	25
Figure 17. Slope of response for each site for model with Q95 as predictor variable. ....	26
Figure 18. Slope of response for each site for model with HMS and Q95 including interaction .....	26

Figure 19. Relationship between ELIFE and HMS score for sites in dataset.....	27
Figure 20. Relationship between ELIFE and mean LIFE score in dataset.....	28
Figure 21. Results for model with HMS, but no at-site biology data (green line). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge. ....	30
Figure 22. Effect of one data point on results for the Lud. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge. ....	32
Figure 23. Effect of one data point on results for the Chater. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge. ....	33
Figure 24. Effect of one data point on results for the Foston Beck. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge. ....	34
Figure 25. Foston Beck: illustration of the effect of three low flow points together on the predicted site LIFE-flow relationship (red line).....	35
Figure 26. At-site model using three different triennial sampling periods spanning approximately 18 years (green lines). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.....	36
Figure 27. At-site model using three different annual sampling periods of 5-6 years (green: 1987-1992, red: 1993-1998, blue: 1999-2004). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.....	37
Figure 28. Longitudinal water surface profiles for four sites. ....	39
Figure 29. Example hydraulic output from CES for River Witham. ....	40
Figure 30. Relationship between log of abundance and flow for individual flow groups 1-4 .	41
Figure 31. Relationship between number of taxa and flow for individual flow groups 1-4 ....	42
Figure 32. Temporal trends in residuals (model with Q95, Q10 and season as predictors).....	44



# 1 INTRODUCTION

## 1.1 Aims and objectives

To establish priority areas for environmental monitoring for assessing the impact of abstraction. This will help define data collection for surface water hydro-morphology aspects of Environmental Monitoring Classification and Reporting (EMCAR).

In particular, the study has attempted to address the following questions for assessing water resource pressure by modelling the relationship between historical river flow and the LIFE (Lotic Invertebrate Index for Flow Evaluation) score:

- Can we replace gauged flows with modelled flows?
- Does biology need to be monitored to family, genus or species level?
- Do we need cross section data at biology or RHS sites?
- Do we need RHS data at biological sample sites?
- What spatial resolution of data collection is appropriate?

## 1.2 Project components

The project was planned as a series of stages:

Stage 1: Select sites and collect any additional data

Stage 2: Investigate the Relative Importance of Flow and Biology Data

2.1: Create a baseline

2.1a: Develop a hydrological – hydro-ecological model for each core site

2.1b: Simulate hydro-ecological Behaviour

Stage 2.2: Investigate the loss in accuracy of using genus and family data

Stage 2.3: Investigate the loss in accuracy of using modelled flow data

Stage 3 Investigate the marginal gain from using morphology data

In practice, there was considerable overlap in the work on stages 2.2, 2.3 and 3.

The following stages were originally conceived, but it was not possible to undertake detailed analysis as part of this project:

Stage 4: Investigate the decay in relationships away from paired sample sites

Stage 5: Investigate whether local data is useful in impacted sites

## 1.3 Data collation and fieldwork (Stage 1)

The criteria for site selection were agreed as:

- Good quality biological data, with majority of identifications at species level,
- Data going back until at least 1990, preferably earlier, preferably with supporting physical data taken during sampling,
- Some sites without any significant abstractions upstream,
- Biology sites with a range of levels of physical modification,
- Biology sites from more than one underlying geology type,
- Biology sites close to flow gauging stations,
- Biology sites either very close to existing RHS sites, or in an area where existing manpower could be used to fill in with new RHS surveys,

- If new RHS surveys required, sites within a reasonable distance of each other.

In the time available for the project, this effectively restricted the work to sites from Northern Area of Anglian Region. Although there is some geological and topographical diversity in this area, sites are all of relatively lowland character, and with low rainfall. These issues are considered further in the discussion.

A set of candidate sites was selected by the project board members. Core sites were identified that were not perceived to suffer from any significant impacts, while Impact sites had likely suffered from abstraction, water quality or other impacts. The subsequent analysis was focused on the core sites only.

**Table 1. List of candidate sites for analysis**

Site ID	Easting	Northing	Waterbody	Site Name	Core/ Impact	Impact Type*	Primary geology	Secondary geology	Gauge ID	Catch Area Gauge	Distance of Site from Gauge (m)
55020	523500	374300	Bain	Hemingby	C		Chalk	Sandstone	30011	62.5	6700
55088	492000	328700	Cringle Brook	Thunder Bridge	C		Limestone		30015	50.5	1400
55117	487700	341700	Foston Beck	A1 (Behind Q.K. Cold Stores)	C		Clay		30031	37.4	2000
55123	538800	375700	Great Eau	Calceby	C		Chalk		29002	77.4	4600
55184	540100	385400	Long Eau	Little Carlton	C		Clay	Chalk	29014	21.3	100
55206	540200	367500	Lymn	Partney	C		Chalk	Sandstone	30004	61.6	0
55287	532100	387200	Lud	Louth Trout Farm	C		Chalk		29003	55.2	1900
55395	525300	401700	Waithe Beck	Brigsley	C		Chalk		29001	108.3	0
55417	492700	326900	Upper Witham	Easton Park	C		Clay	Limestone	30017	51.3	2700
55501	498300	304300	Chater	Station Road Bridge, Ketton	C		Clay		31010	68.9	3300
55714	495700	308900	North Brook	Empingham	C		Limestone		31016	36.5	0
55740	484000	282600	Ise	Rushton	C		Clay		32004	194.0	18000
55172	522300	405000	Laceby Beck	Track To Manor Top Farm	I	M	?		29021	?	2700
55279	503300	391100	Rase	Bishopbridge	I	Q	Chalk	Clay	29005	66.6	2000
55299	502100	367300	Sandhill/ Branston Beck	Branston	I	M	Limestone		30013	21.2	4500
55305	508500	357800	Scopwick Beck	Kirkby Green	I	?	Limestone		30020	?	1200
55339	508400	347100	Slea	Bonemill Bridge	I	F	Limestone		30006	48.4	1200
55425	484200	348900	Upper Witham	Claypole	I	R	?		30001	297.9	1000
55564	510600	314900	Glen	Kate's Bridge	I	F	Limestone		31002	341.9	0
55582	486800	305100	Gwash (South)	Gunthorpe	I	B	Clay		31025	24.5	1000
55598	498400	279800	Harpers Brook	A6116	I	Q	Clay		32003	74.3	100
55645	480100	292600	Medbourne Brook	Medbourne	I	Q	Clay		31019	?	1500
55824	498600	300900	Welland	Duddington	I	Q	Clay		31007	411.6	7000
55826	500800	306200	Welland	Tinwell Mill	I	F	?		31031	?	1400
55854	506300	293500	Willow Brook	Fotheringhay	I	F	Clay		32002	89.6	500
79571	502400	343300	Ancaster Beck (Slea)	Wilsford Warren	I		Limestone		30032	29.2	2000

\* Key M: morphology, Q: quality, F: flow, B: biology.

Two sites were initially designated as core sites but were late re-designated as impacted, firstly the Ancaster Beck site (which also only has very limited biology data) and Harpers Brook.

Biology sites were matched to gauges by Chris Extence, Dan Cadman and John East. Biology sites were manually matched to RHS sites by Mike Dunbar.

All biology data were received except from a candidate site on the West Glen where there was a mix up over sites. As this is an impact site, we decided not to request further data here.

Flow data were extracted, either from NRFA (National River Flow Archive) held at CEH, or non-NRFA gauges, supplied directly by the Agency. Catchment areas were received for non-NRFA gauges but no independently-derived catchment boundaries exist for those sites (i.e. not from an automated DTM climb).

Flow indices were calculated following the procedures in the Generalised LIFE Response Curves (GRC) project (Dunbar and Clarke, 2004), standard periods for flows of summer period (April to September) and winter (October to March) were used. In each year that a biology sample existed, the Q10 and Q95 were extracted from the flow record in the ~180 day period: April and September for Autumn data and October to March for Spring data. The flow statistics were normalised by subtracting the mean and dividing by the standard deviation of the relevant statistic, calculated from a long-term record of 1970-2005 (or whenever the gauged record started).

Species-level and family LIFE scores were provided with the data. However, we re-calculated scores at various nominal taxonomic levels, this is further detailed in Section 2.3. When comparing CEH and Agency-calculated scores, there were some minor discrepancies between the raw species data and recoded family data, however we felt this could be time-consuming to resolve in its entirety. The discrepancies are extremely unlikely to affect the overall conclusions of the study (Pearson product-moment correlation between CEH and Agency species-level scores 0.99).

Fieldwork was undertaken on 28<sup>th</sup> February to 2<sup>nd</sup> March: Mike Dunbar undertook hydraulic surveys (cross-section geometry, water level, velocities/discharge), whilst Andrew Constable from the Agency Spalding Office undertook RHS surveys. Eight sites could be visited in the 2½ days available, these were chosen based on distance to nearest RHS site and distance to gauge. Table 2 gives details of the sites, survey dates and notes on the character of the sites.

**Table 2. Sites surveyed**

Site	Date	Geology	Notes
Waithe Beck at Brigsley	28/2/2006	Chalk	Resectioned straight channel with high banks. Quite fast velocities in centre of channel but slow velocities in margins, dormant marginal vegetation. Fairly low longitudinal depth variation, but variation in velocity caused by width variation. May be backwater from gauge.
Lud at Louth	28/2/2006	Chalk	Overhanging trees, low banks, superficially natural, although in parkland. May be backwater from downstream bridge
Long Eau at Little	28/2/2006	Clay/Chalk	Resectioned straight channel with high

Site	Date	Geology	Notes
Carlton			banks. Quite fast velocities in centre of channel, superficially little refuge habitat in margins.
Lymn at Partney	28/2/2006	Chalk/Sandstone	Ran out of time to survey but did take some velocity measurements. Site is very steep with coarse substrates and velocities > 1m/s.
Foston Beck at behind cold store on the A1	1/3/2006	Clay	Resectioned straight channel with high banks. Pool-riffle development, site is downstream of big pool downstream of culvert.
Cringle Brook	1/3/2006	Limestone	Low banks and considerable instream and marginal vegetation. Wide wet marginal areas with little flow.
Witham at Easton Park	1/3/2006	Clay/Limestone	Relatively low banktop height. Pools and riffles, coarse substrate possibly from previous bridge upstream.
Chater at Ketton	2/3/2006	Clay	Overhanging trees, gardens on both sides, relatively low banktop. Pool/riffle, coarse substrate, bridge close upstream.
North Brook at Empingham	2/3/2006	Limestone	Superficially "natural", low banks but grazed and poached. Considerable instream vegetation. Gauge immediately downstream.

Having visited these sites, it was clear that they are very different in their physical character. The Waithe Beck, Long Eau and Foston Beck (and also the Lymn at Partney) are heavily resectioned with banktop heights of around 2m. All sites are immediately downstream of road bridges apart from the Lud at Louth, which is immediately upstream. This undoubtedly affects their physical character, in some circumstances the river will have been re-aligned to go underneath the road. Some of the sites, e.g. Witham, Chater seem to have an excess of coarse substrate arising from previous bridge structures. The North Brook and Cringle Brook are notable for their instream vegetation, although the former has suffered from poaching.

## 2 DATA ANALYSIS

### 2.1 Methods

The response variable (LIFE score) is an aggregate index of the taxa collected in a sample of macroinvertebrates from a river. It is a weighted average, where the weights reflect the perceived sensitivity of each taxon to higher water velocities and clean gravel/cobble substrates vs lower velocities and silty substrates. It is described in more detail in Extence et al. 1999.

Initial analyses used linear regression between LIFE score and historical flow, on a site by site basis. Later analyses used the multilevel linear modelling framework to allow integrated analyses of all core sites in one model. Multilevel models allow consideration of a nested hierarchy of explanatory variables, while retaining correct degrees of freedom, they can also handle situations such as this with unequal numbers of observations within the higher-level grouping variable (site in this case). A nested hierarchy occurs in this case because the same sites are sampled repeatedly through time, hence samples are nested within sites. Considering potential explanatory variables, site characteristics act at the higher level, whereas flow indices act at the lower sample level. The results of a multilevel are initially more difficult to interpret, but they do give significantly more information, and allow more questions to be answered than more simplistic site by site regressions or lumped models which do not consider the nested nature of the data. In this context, the results take the form of fixed effects, giving the overall response in terms of intercept and slope, and random effects, expressed as standard deviations (or variances), giving the variation around the overall response.

In a multilevel model of LIFE vs flow for a set of sites, regression lines for individual sites may still be predicted, despite being a random variable rather than a parameter: the results of a regression for a site do not just depend on the data from that site, but also on the data from other sites. The extent to which these two factors interact depends on the quality of fit and the numbers of data points at the site. Thus the line reflecting the relationship between LIFE and flow at a site with relatively fewer data points or with a weak relationship will be more strongly pulled towards the overall relationship for all sites. It should also be noted that the ability of the models to detect differences between sites (e.g. due to habitat factors described in RHS) will be dependent on the number of sites, and on the within site variance not explained by flow. A brief formulation of a simple multilevel model is given in the Appendix.

### 2.2 Baseline hydroecological behaviour (Stage 2)

Time series of autumn LIFE scores and preceding summer flows (Figure 1) for core sites illustrate the controlling effects of flow on LIFE<sup>2</sup>. For example the Waithe Beck (already documented), Foston Beck, Lud, Bain.

Both the Bain and Cringle Brook seem to show some lag in response which is not being accounted. In the GRC project (Dunbar and Clarke 2004) no evidence of autocorrelation in

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<sup>2</sup> The Harpers Brook was also plotted in this way but showed poor or non-existent relationship. Also replicate samples in 1990 gave quite different scores. This site was removed from subsequent analysis.

LIFE scores once flow taken into account, but that project had much less complete time series.

On the Cringle Brook, the flow indices were low in 1992-1997, but LIFE scores recovered, this could mean that the chosen flow indices are not picking up the salient features of the flow regime. This is also seen on the Foston Beck. This project has not considered alternative flow indices, but this is a useful follow-up area.

In general, once Q95 was included as a term in the model, adding Q10 did not significantly improve the fit. Experience on the previous LIFE GRC project suggested that Q10 could add some explanatory power on flashy catchments, but not on baseflow catchments where high and low flows are generally highly correlated anyway. The sample size in this study was not really large enough to test several flow variables.

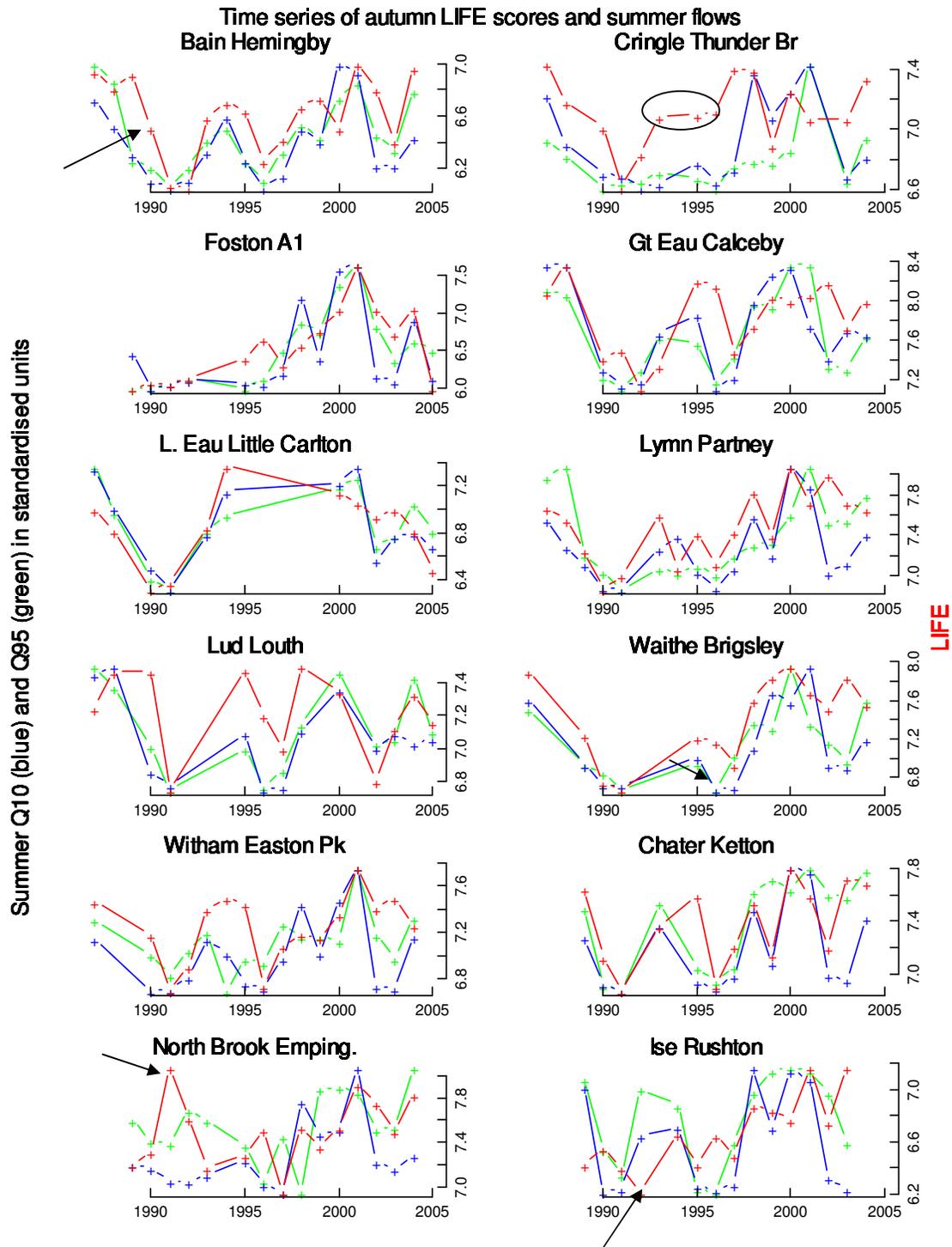
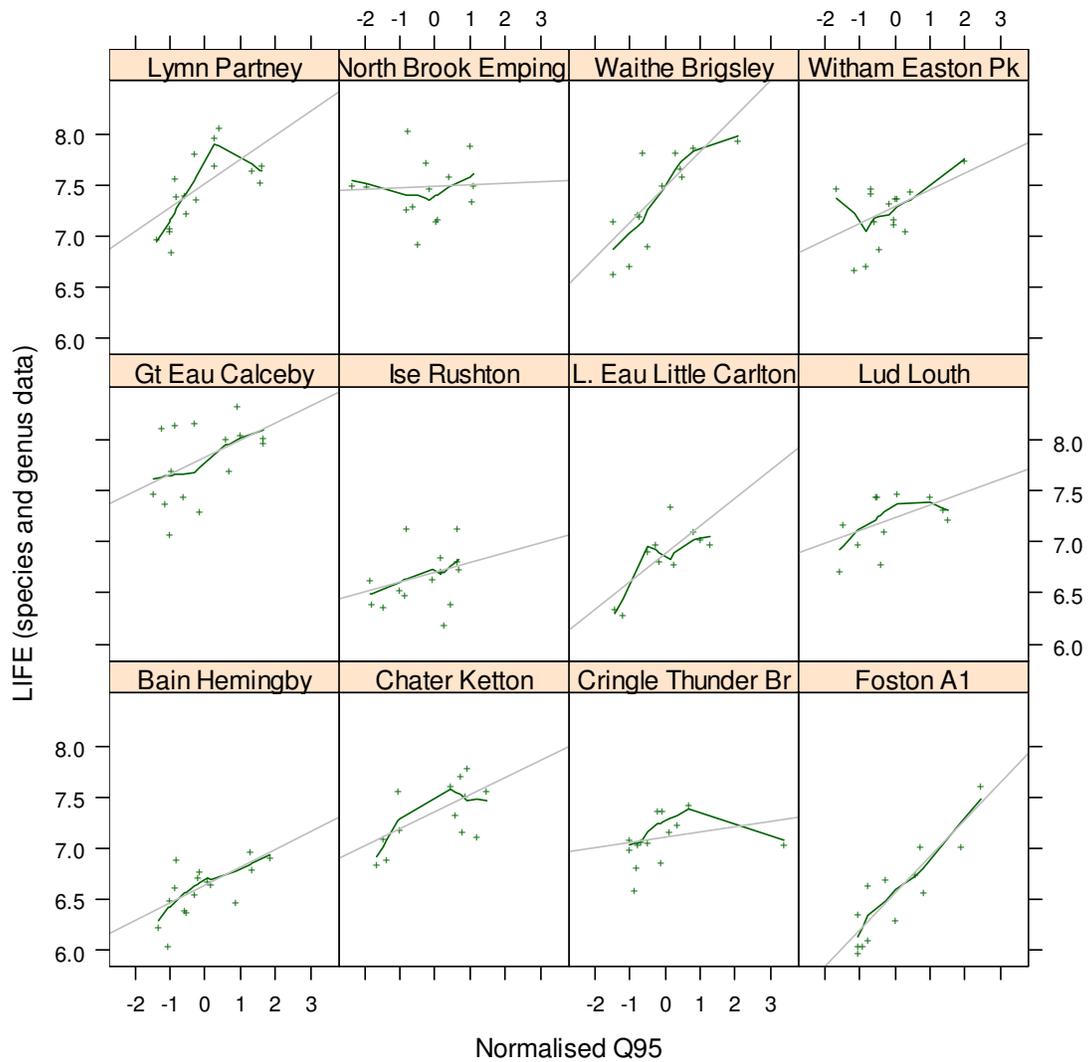


Figure 1. Time series of species+genus level LIFE scores (red) autumn samples and preceding summer flows (normalised Q95: green and Q10: blue). Some outlying points highlighted.

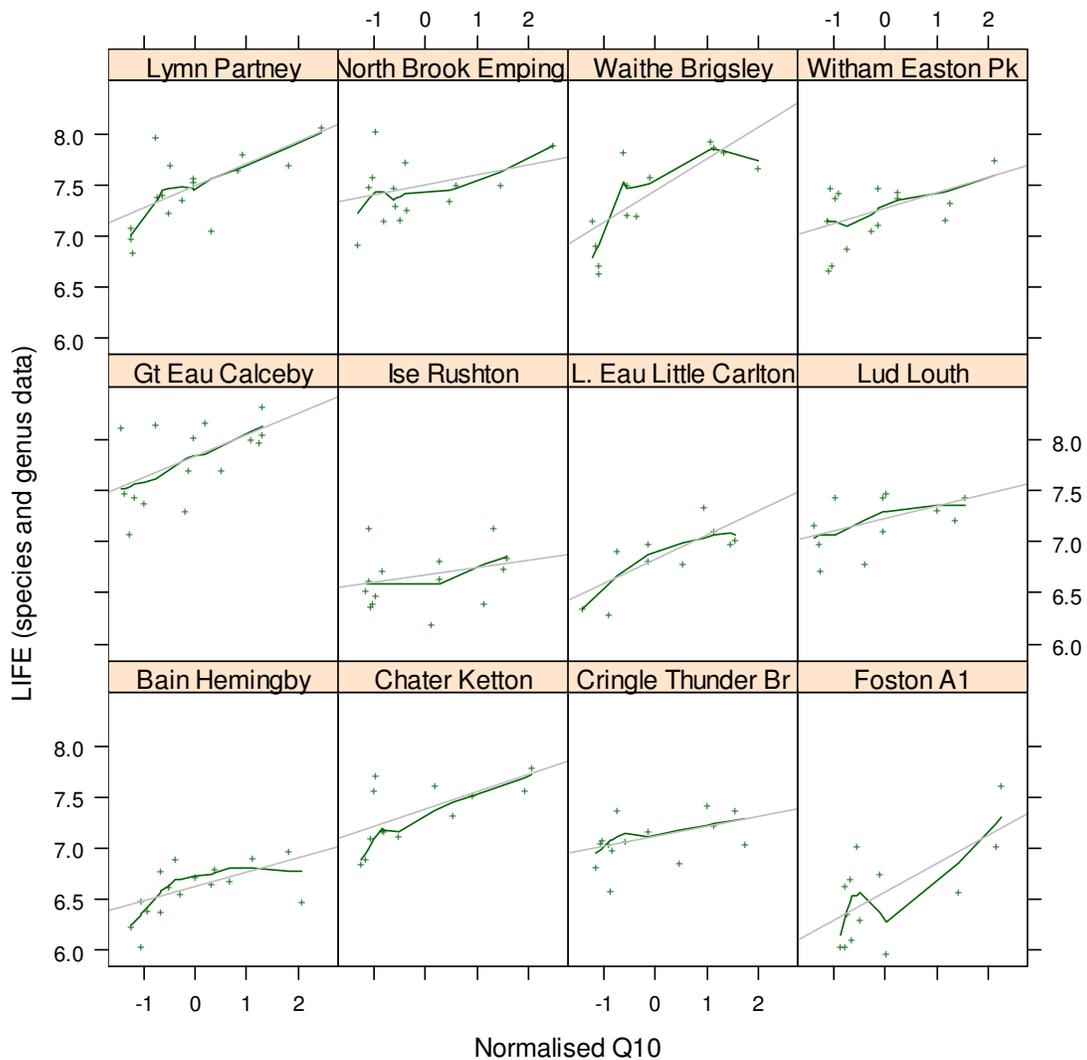
Figure 2 and Figure 3 illustrate the general non-temporal relationships between flow and LIFE for the core sites, using the autumn samples only. In general there are clear positive relationships, and there is little evidence that the relationships are non-linear. Some sites give

relatively poor relationships. Two of these: Cringle Brook and North Brook are high quality sites with wide banks and macrophyte growth<sup>3</sup>.



**Figure 2.** LIFE-flow using autumn-only species+genus level data, using Q95 as the explanatory variable. A smooth nonparametric regression line (green) and a linear regression line (grey) are shown.

<sup>3</sup> There is an outlying point on the Cringle Brook, this has been investigated and linked to a pollution incident.



**Figure 3. LIFE-flow using autumn only species+genus level data, using Q10 as the explanatory variable. A smooth nonparametric regression line (green) and a linear regression line (grey) are shown.**

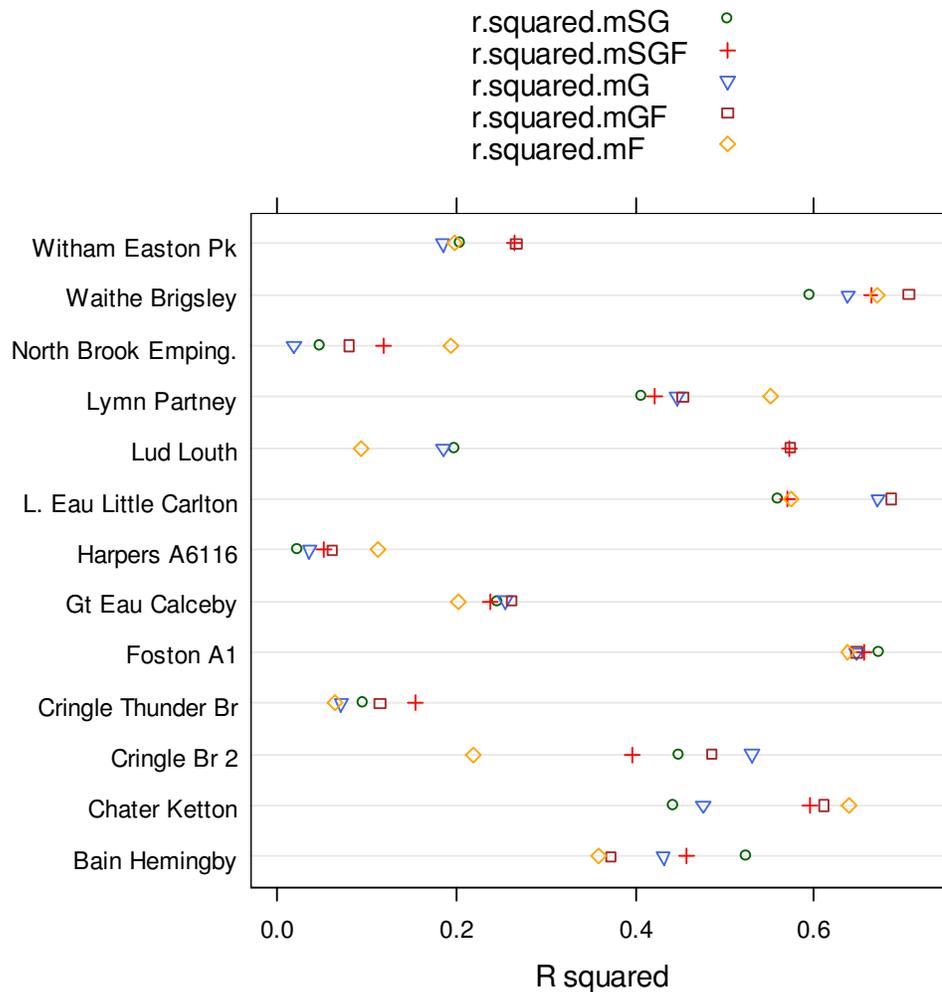
### 2.3 Comparison of results from various taxonomic levels.

Individual linear regression models were developed between autumn LIFE score and summer Q95 flow for the LIFE response calculated using the:

- raw species and genus level data (following current Agency policy)
- raw species and genus level data, plus family level scores where families were surveyed
- harmonised genus-level LIFE score calculated from raw species and genus level data
- harmonised genus-level LIFE, plus family level scores where families were surveyed
- harmonised family-level LIFE, calculated from all LIFE scoring taxa

R<sup>2</sup> values for these individual models are shown in Figure 4 (Results for Cringle Brook are shown with and without outlying point). The pattern is not entirely clear, there are sites where

the “best” relationship is any of the three main taxonomic levels<sup>4</sup>. There are some general trends. In particular, degrading species data to genus level makes very little difference to the overall score.



**Figure 4. R<sup>2</sup> values for individual regressions with biological data at species+genus level, degraded to genus level, and degraded to family level.**

Table 3 illustrates some model statistics for multilevel models (i.e. using data from all sites together) for the most important taxonomic resolutions. Although model comparison using alternate predictor variables is a well-established field, it is more difficult to make meaningful comparisons in terms of what is a “better” model when the response variable is different. The AIC and residual standard deviation terms might indicate that actually the family-level model is “best”. In addition the family level gives a lower correlation between intercept and slope random effects, which is desirable from a modelling perspective. However, the overall mean slope term is slightly more precise for the species-based models.

<sup>4</sup> It should be noted that visual comparison of R<sup>2</sup> values is mainly illustrative, seemingly large differences in their magnitude may not themselves be statistically significant.

**Table 3. Model statistics for multilevel models at various taxonomic resolutions**

	Species+Genus	Species+Genus+ Family	Genus	Family
AIC (Akaike Information Criterion)	90.1	53.4	76.5	33.7
<i>Random effects</i> (expressed as standard deviations)				
Intercept	0.388	0.315	0.364	0.275
Slope	0.069	0.049	0.073	0.074
Correlation	-0.66	-0.59	-0.59	-0.18
Residual	0.262	0.238	0.251	0.222
<i>Fixed effects</i>				
Intercept	7.218 (0.119)	7.105 (0.097)	7.191 (0.111)	6.960 (0.084)
Slope	0.212 (0.030)	0.210 (0.024)	0.205 (0.030)	0.187 (0.029)

In general it seems that whether the maximum resolution of data is species or genus level makes little difference. What is more important is

- how many family level ids are in the sample
- whether these families are a “single” or “most common” flow group

Certainly when there are family level ids then it appears its best to include them.

The North Brook is the main outlier, where for some reason the family-level score gives the best relationship. In the dataset, on the North Brook taxa identified at family level occur frequently, ignoring these significantly degrades the relationship. Furthermore, in some cases, there is a single species on a single occasion which when degraded to family level gives a different flow group and hence overall LIFE score, and it happens that the family level data fit the pattern better. This is compounded for species with high abundances, where a switch from a flow group abundance combination of say 2C to 4C will change the flowscore from 10 to 4: a large change. This issue is discussed further in Monk (2006), who illustrates how formulations of the LIFE score restricted to specific orders (e.g. trichoptera - caddis flies), can minimise this effect.

A similar effect appears with the Long Eau data, in this case a single species (*Sphaerium rivicola*: FG3) when degraded to genus level (FG4) for a single sample affects the R<sup>2</sup> considerably.

Figure 5 to Figure 8 show the data and regression relationships for various taxonomic calculations which would be useful to compare.

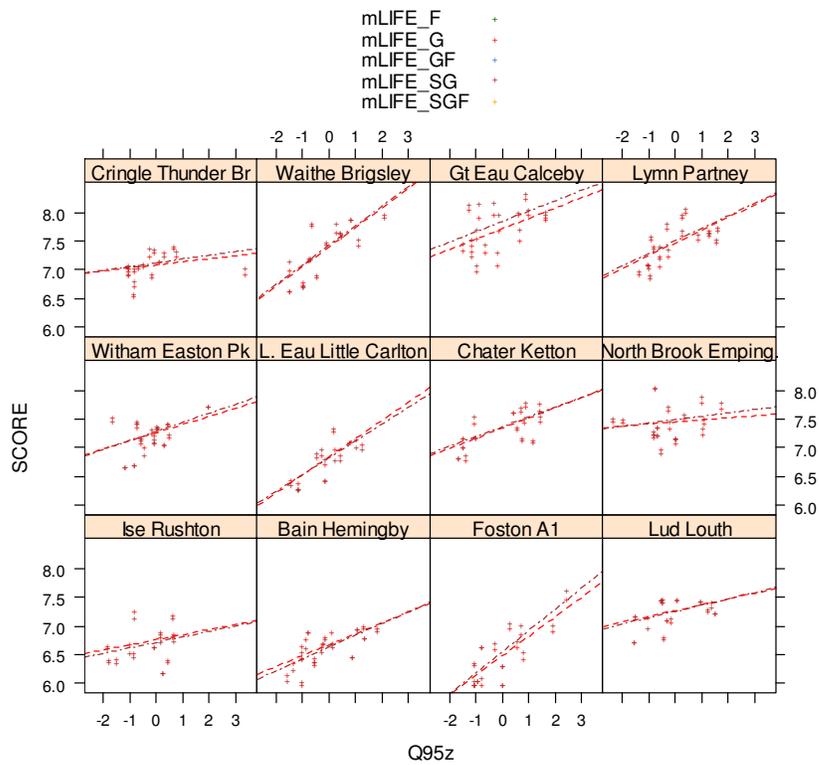


Figure 5. Taxonomic comparisons: SG & G

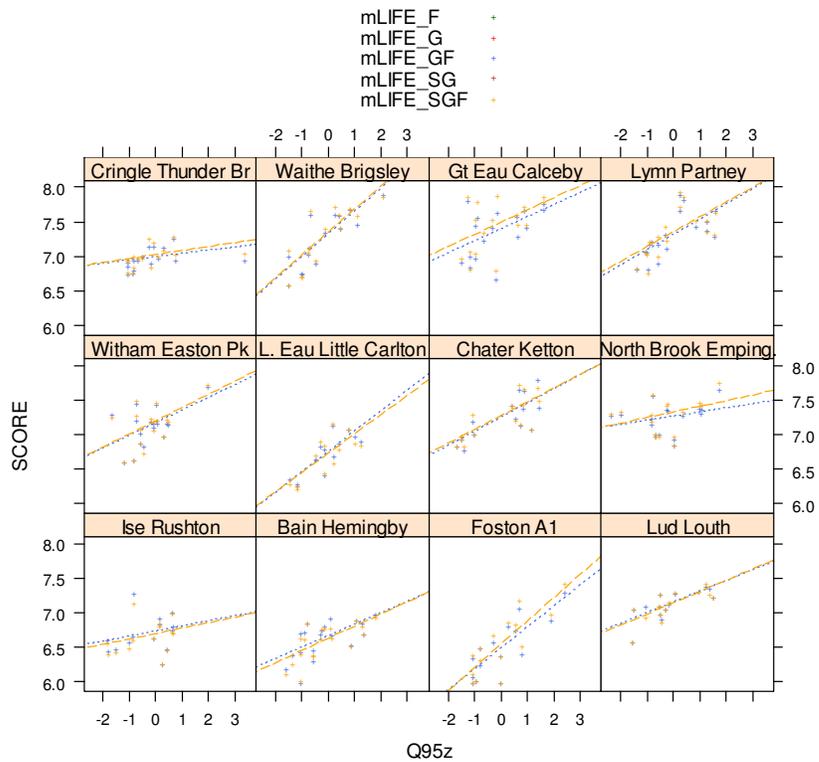


Figure 6. Taxonomic comparisons: SGF & GF

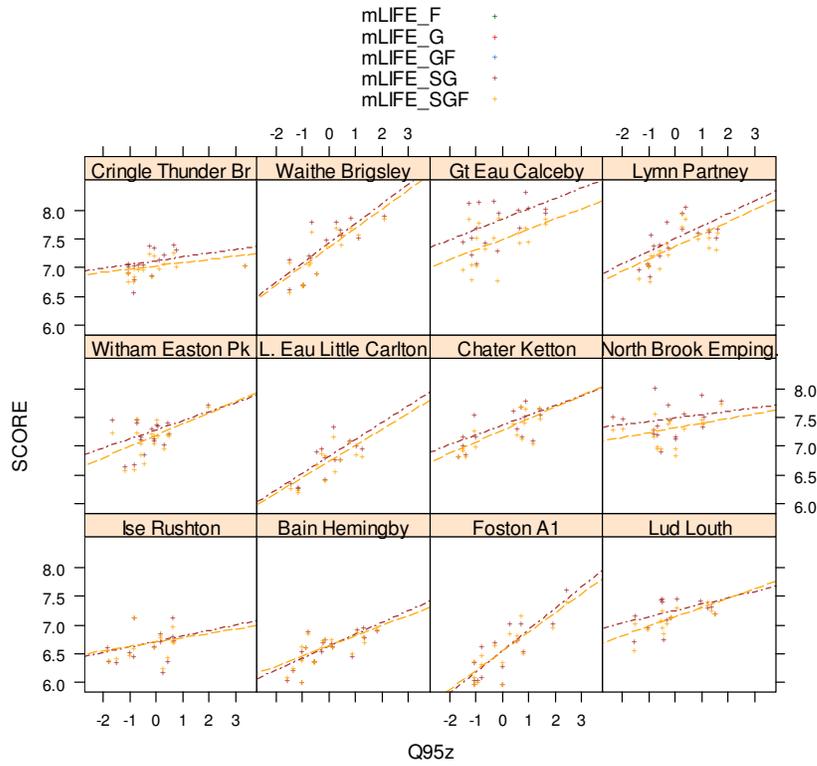


Figure 7. Taxonomic comparisons: SGF & SG

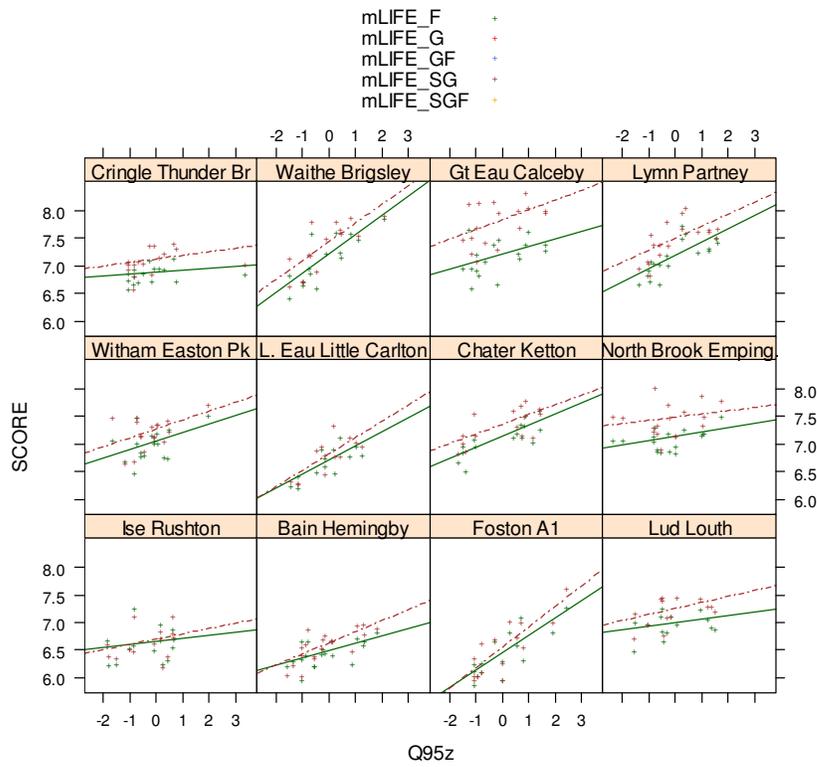


Figure 8. Taxonomic comparisons: SG & F

## 2.4 Predicting LIFE score variation with CERF-modelled flows

The CERF (Continuous Estimation of River Flows) system is the product of a joint R&D project by CEH and the Environment Agency (Project W6-001). A forerunner of CERF is described in Young (2006), the current version will be written up as an Agency R&D Report by Autumn 2006. CERF was configured and run to predict daily mean flows at the gauges corresponding to the core sites. No detailed comparisons of CERF vs gauged flows have been undertaken, it should be noted that the area chosen for the study is somewhat challenging to model flows, being in the drier eastern part of the country, furthermore modelling flows on sites on permeable geologies may be additionally uncertain because of uncertainties in defining catchment boundaries. CERF predictions are available up until end of 2001, whereas the gauged flow data used in the rest of the study exist up until the end of 2004 or 2005. So, the analysis in this section compares only the data common to both sets of flow time series, i.e. until the end of 2001.

Figure 9 and Figure 10 illustrate the relationships between gauged and CERF-modelled flows for the flow statistics used in this study.

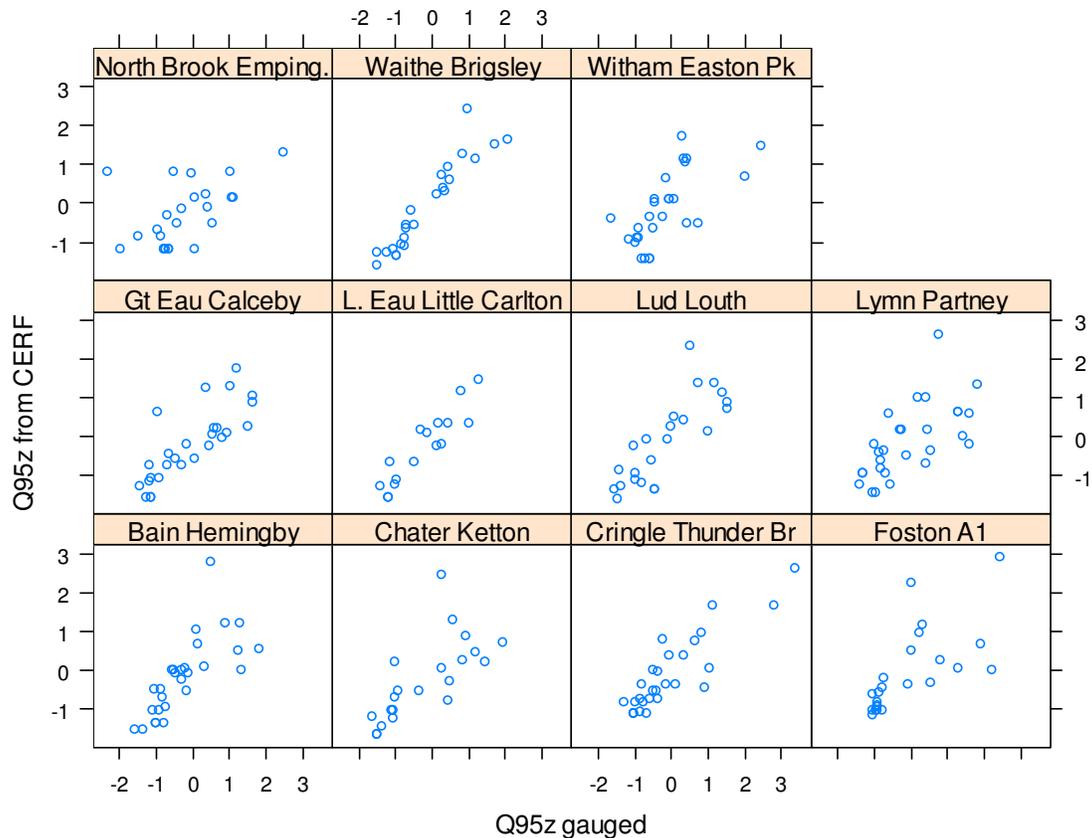
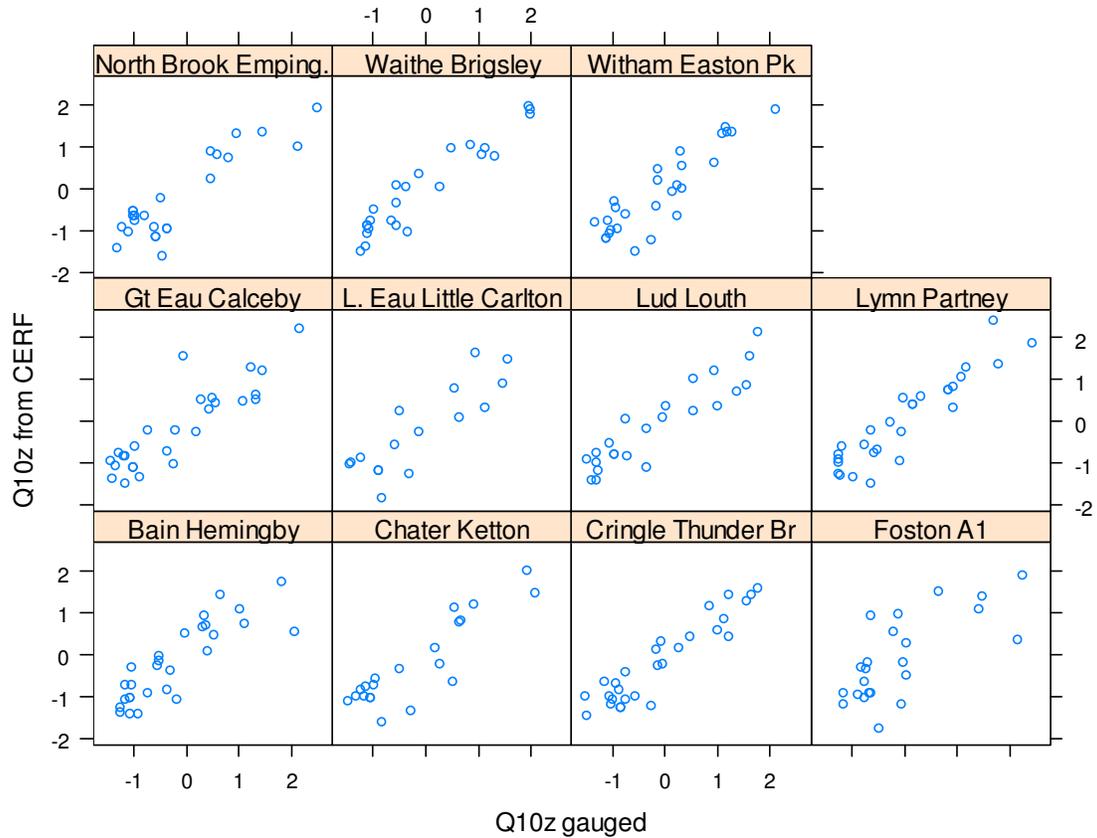


Figure 9. Relationship between time-varying Q95 flow statistics.



**Figure 10. Relationship between time-varying Q10 flow statistics.**

## Results

Models were constructed predicting LIFE score using the same flow statistics, firstly calculated from gauged flow data, secondly calculated from CERF. As the models are fitted using numerical optimisation and maximum likelihood rather than analytically using least squares, model comparison is not quite as straightforward as it is with linear regression. Akaike's Information Criterion (AIC) was used to compare models. In order to provide an alternative view, a version of  $R^2$  can also be calculated. As the models are hierarchical (two level in this case), there is no overall  $R^2$ , rather there is one for each level in the model. In this case the  $R^2$  at the lowest level in the hierarchy is presented, which reflects the change in error variance associated by going from a null model (no explanatory flow variables) to a model with Q95z as a predictor.

Predictor variables	Residual $\sigma$	AIC	$R^2$ (1)	$R^2$ (2)
Gauged	0.235	40.7	0.26	0.72
CERF	0.247	53.4	0.23	0.69
Gauged, with HMS*	0.232	66.4	0.60	0.73
CERF, with HMS*	0.245	80.3	0.57	0.70

\* see next section for more details

(1) reflects prediction error for an unknown site (between and within site LIFE variation)

(2) reflects prediction error for an known site (within site LIFE variation only)

Change in precision of the regression coefficient of Q95z could also be used as an alternative predictor variable, however for all the above models, they are highly significant ( $t > 8$ ,  $p \gg 0.0001$ ).

Whichever approach to model assessment is used, it is clear that the results using CERF modelled flows are only slightly less good than the results using gauged data.

## **2.5 Reduction in flow corresponding to a set reduction in LIFE score**

It is interesting to compare the results for different rivers in terms of the reduction in flows that gives a consistent reduction in LIFE score. This illustrates one way in which the results of the study may eventually feed into ecologically-based water resource standards.

Any judgement on what would be an acceptable reduction in LIFE score is arbitrary, so in this case an arbitrary 0.1 unit reduction in LIFE score was chosen. This compares to a residual standard deviation in most of the models of between 0.2 and 0.25 LIFE score units.

The ideal way of making this calculation would be to set up a “reverse model”, predicting normalised flow from LIFE score and covariates. Unfortunately the data were not set-up to construct this sort of model, rather they are set up to predict LIFE score from flow, and it is not possible to reformat the data in a simple way. So, the existing relationships were used, in interpreting these results it should be borne in mind that they are based on the use of a regression equation in the “wrong” direction.

The regression lines in this work have constant slopes, so it is possible to calculate the change in normalised flow corresponding to a 0.1 unit change in LIFE score. This can then be un-transformed into an un-normalised flow value in  $\text{m}^3\text{s}^{-1}$  by multiplying by the standard deviation of the flow statistic distribution. Assuming the explanatory variable is summer Q95, the number obtained would be the change in summer Q95 in  $\text{m}^3\text{s}^{-1}$ , corresponding to a 0.1 unit change in LIFE score. Table 4 illustrates the results obtained using summer Q95 calculated from gauged flow as the predictor variable, whereas Table 5 illustrates the results using CERF-modelled flows. Figure 11 gives a comparison of the proportions using gauged and CERF-modelled flows. In some cases (e.g. Lymn, Witham, Bain), the results are only very slightly different, in other cases (e.g. North Brook, Cringle Brook, Lud, Great Eau), the results are quite different.

**Table 4. Data for converting a percentage change in LIFE score to a change in un-normalised summer Q95 (using gauged flows).**

Site	Slope	Q95sd	Q95mean	Q95 cv	Flow change	Proportion
Bain Hemingby	0.201	0.044	0.093	0.47	0.022	0.24
Chater Ketton	0.186	0.04	0.119	0.34	0.021	0.18
Cringle Thunder Br	0.211	0.045	0.097	0.46	0.021	0.22
Foston A1	0.289	0.007	0.01	0.70	0.002	0.24
Gt Eau Calceby	0.202	0.098	0.374	0.26	0.049	0.13
L. Eau Little Carlton	0.261	0.028	0.053	0.53	0.011	0.20
Lud Louth	0.175	0.064	0.189	0.34	0.037	0.19
Lymn Partney	0.195	0.059	0.158	0.37	0.030	0.19
North Brook Emping.	0.103	0.037	0.111	0.33	0.036	0.33
Waithe Brigsley	0.280	0.046	0.082	0.56	0.016	0.20
Witham Easton Pk	0.207	0.017	0.031	0.55	0.008	0.27

Key:

Slope: regression slope when predicting LIFE score from flow

Q95sd: standard deviation of series of summer Q95s

Q95mean: mean of series of summer Q95s

Q95cv: coefficient of variation, i.e. Q95sd/Q95mean

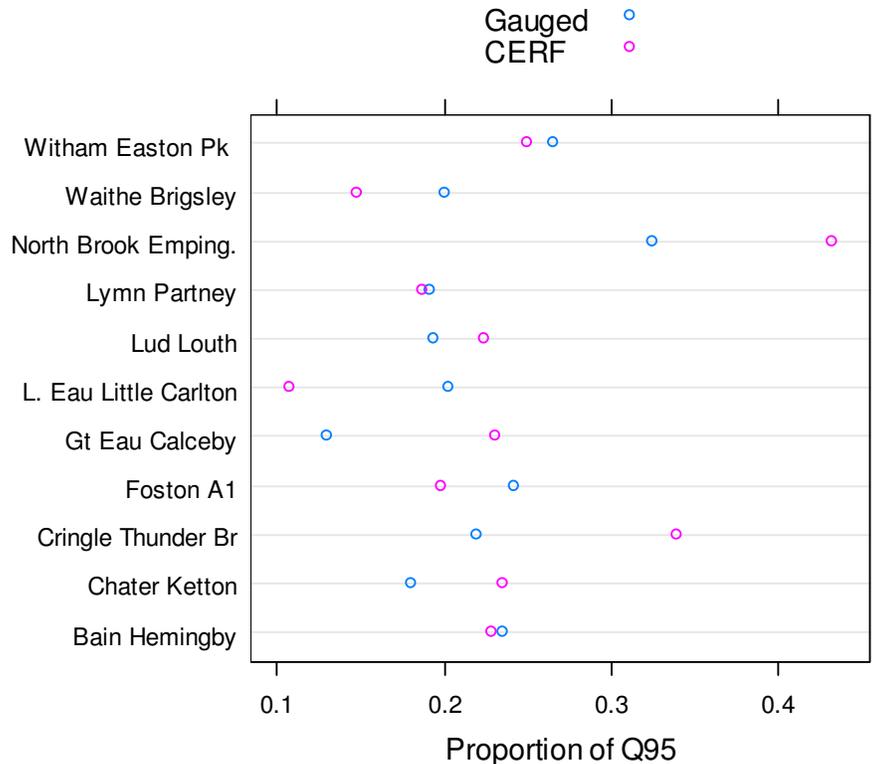
Flow change: of summer Q95, measured in  $\text{m}^3\text{s}^{-1}$ , for a 0.1 unit change in LIFE score: i.e.  $\text{Q95sd} \times 0.1 / \text{Slope}$

Proportion: flow change as a proportion of mean summer Q95.

**Table 5. Data for converting a percentage change in LIFE score to a change in un-normalised summer Q95 (using CERF-modelled flows).**

Site	Slope	Q95sd	Q95mean	Q95 cv	Flow change	Proportion
Bain Hemingby	0.172	0.059	0.150	0.39	0.034	0.23
Chater Ketton	0.169	0.048	0.120	0.40	0.028	0.24
Cringle Thunder Br	0.197	0.027	0.040	0.67	0.014	0.34
Foston A1	0.267	0.071	0.134	0.53	0.027	0.20
Gt Eau Calceby	0.163	0.073	0.194	0.38	0.045	0.23
L. Eau Little Carlton	0.247	0.036	0.137	0.26	0.015	0.11
Lud Louth	0.162	0.080	0.221	0.36	0.049	0.22
Lymn Partney	0.235	0.049	0.111	0.44	0.021	0.19
North Brook Emping.	0.124	0.015	0.028	0.53	0.012	0.43
Waithe Brigsley	0.272	0.114	0.284	0.40	0.042	0.15
Witham Easton Pk	0.162	0.019	0.048	0.41	0.012	0.25

Key: as for Table 4.



**Figure 11. Comparison of proportions of Q95 for a 0.1 change in LIFE score, using both gauged and CERF-modelled flows**

### 2.6 Modelling of between-site differences using habitat, indexed by RHS scores (Stage 3)

Eight core sites were visited and surveyed as part of the project, thus these have at-site spring RHS surveys. There are also several RHS surveys near the sites, including each of the three core sites not visited as part of the project. Relevant summary data are shown in Table 6 and Table 7. These tables present some interesting features:

- All the sites have plenty of modification, the least modified according to RHS is the Lymn, where the RHS site does not coincide with the DRIED-UP site.
- There are large differences between the HQA scores and classes for nearby sites on the same river. Part of this difference may be due to the timing of the surveys, however it also leads us to question whether RHS surveys even a kilometre or two away from a biology sample site are representative.

RHS HQA (habitat quality assessment) and HMS (habitat modification score) scores were tested for their ability to explain some of the differences in LIFE scores between sites, both in terms of overall mean LIFE score and in terms of the LIFE-flow relationship. In order to keep the process manageable, a single base model was used: relating autumn LIFE scores to normalised summer Q95 flow.

HQA and HMS the main two indices commonly derived from RHS data. Each consists of the sum of a number of sub-scores as follows:

HQA sub-scores are:

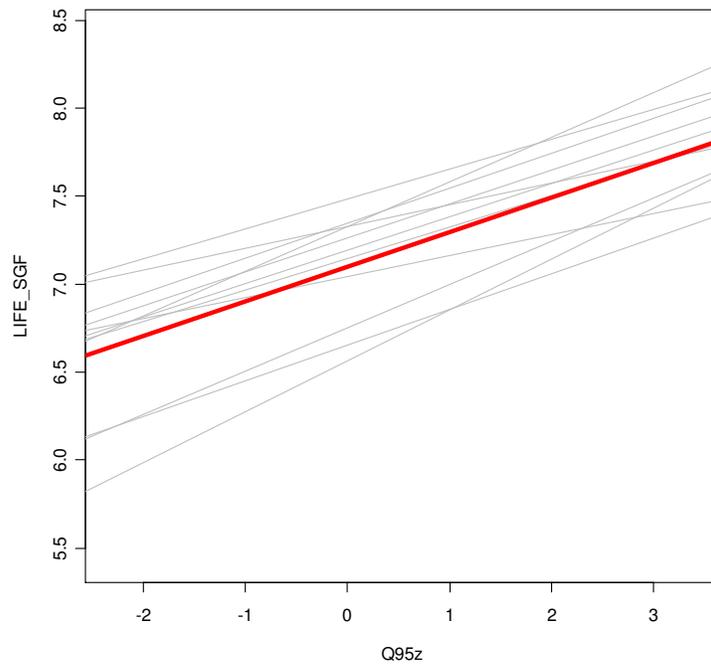
- Bank Features
- Bank Vegetation
- Channel Features
- Channel Substrates
- Surface Flow Types
- In Stream Channel Vegetation
- Land Use
- Special Features
- Trees and associated Features

HMS sub-scores are:

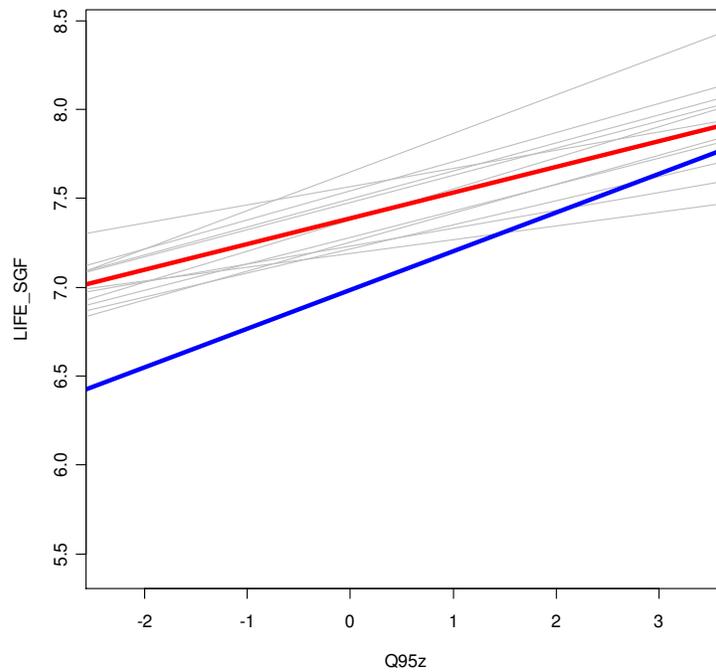
- Fords
- Outfall and Deflector
- Poaching
- Reinforced Bank and Bed
- Resectioned Bank and Bed
- Weirs, Dams and Sluices
- Berms and Embankments
- Bridges
- Culverts

HQA was not a significant explanatory variable (Wald t-test,  $p=0.41$ , 8 df), however HMS was, both as a main effect (parameter value:  $-0.0002$ ,  $p=0.0027$ , 8 df) and as an interaction with flow ( $0.00005$ ,  $p=0.0246$ ,  $df=163$ ). The significance of these effects was confirmed using a likelihood ratio test and maximum likelihood estimation (ratio 15.8 on 2df,  $p=0.00004$ ).

So, compared to a HMS of 0, a HMS score of 2000 will reduce mean LIFE score by 0.4 units, but it will increase the slope of the LIFE-flow relationship by 0.1 units per normalised Q95 unit. This effect is illustrated in Figure 12 and Figure 13. Figure 12 shows the multilevel model with just Q95z as predictor. There is considerable scatter in overall mean LIFE score about the mean line (no O/E standardisation has been used). There is some difference in slopes between the sites as well. Figure 13 illustrates results where the HMS score for the site is included as a main effect covariate able to influence mean LIFE score, and an interaction, able to influence the slope of response to Q95. The first thing to note is that all the lines are conditional on a value for the HMS score. The red and grey lines relate to a hypothetical HMS score of zero, of particular note is the lower degree of scatter compared with Figure 12. The blue line is the mean line with a hypothetical HMS score of 2000 (within the range of the observed data). This line has a lower mean LIFE score and a steeper slope, indicating that at the lowest flows, the more modified sites are proportionately more affected.



**Figure 12. Mean relationship (red line) and predicted relationships for each site (grey lines) for multilevel model with Q95 as predictor.**



**Figure 13. Multilevel model with Q95 and HMS as predictors, including their interaction. Red line is mean relationship where HMS=0. Grey lines are the predicted site relationships assuming HMS=0. Blue line shows mean relationship where HMS=2000. Grey lines corresponding to variation around the blue line are not shown.**

**Table 6. Summary of HMS scores and sub-scores for DRIED-UP core sites**

River	Survey Date	New	HMS score	Fords	Ofall Dflector	Poaching	Rforced Bnk Bed	Rsctned Bnk Bed	Wds	Berms Embnk	Bridges	Culverts
BAIN	09/05/1994	N	2880	0	0	0	0	2800	0	80	0	0
CHATER	04/07/1995	N	2340	0	0	20	0	2320	0	0	0	0
CHATER	02/03/2006	Y	1195	0	200	0	100	40	255	0	600	0
CRINGLE BROOK	01/03/2006	Y	705	0	0	0	80	0	375	0	250	0
FOSTON BECK	12/06/1995	N	2860	0	0	0	0	2760	0	0	100	0
FOSTON BECK	01/03/2006	Y	3385	0	25	0	100	2440	0	20	0	800
GREAT EAU	14/06/1995	N	300	0	0	0	0	0	300	0	0	0
LONG EAU	11/05/1994	N	1665	0	25	0	40	800	300	0	500	0
LONG EAU	28/02/2006	Y	3705	0	50	0	0	2800	555	200	100	0
LUD	24/05/1996	N	2210	0	0	0	80	1480	0	0	250	400
LUD	28/02/2006	Y	245	0	25	0	0	0	0	20	200	0
LYMN	14/06/1995	N	80	0	0	0	0	80	0	0	0	0
NORTH BROOK	06/06/1996	N	1280	0	0	0	80	800	0	0	0	400
NORTH BROOK	02/03/2006	Y	625	0	100	50	20	0	375	0	0	80
WAITHE BECK	07/06/1995	N	400	400	0	0	0	0	0	0	0	0
WAITHE BECK	28/02/2006	Y	1610	0	125	0	340	280	375	140	350	0
WITHAM	01/03/2006	Y	390	0	0	40	0	0	0	0	350	0
WITHAM	18/05/1996	N	985	0	0	20	150	600	75	40	100	0
WITHAM	30/05/1994	N	2145	0	25	0	0	2120	0	0	0	0

**Table 7. Summary of HQA and sub-scores for DRIED-UP core sites**

Survey Id	River	Survey Date	New	HQA Class	HQA Score	HQA Bank Features	HQA Bank Veg	HQA Chnl Features	HQA Chnl Substrates	HQA Flow Types	HQA In Str Chnl Veg	HQA Land Use	HQA Special Features	HQA Trees Assoc Ftes
423	BAIN	09/05/1994	N	5	24	7	6	0	3	3	3	0	0	2
10061	CHATER	04/07/1995	N	5	33	1	4	2	8	7	9	0	0	2
31271	CHATER	02/03/2006	Y	1	49	4	12	2	8	9	1	2	1	10
31265	CRINGLE BROOK	01/03/2006	Y	1	60	0	11	7	6	11	8	3	3	11
3549	FOSTON BECK	12/06/1995	N	5	27	3	12	1	3	3	3	0	0	2
31266	FOSTON BECK	01/03/2006	Y	1	38	6	9	3	4	9	4	0	0	3
3424	GREAT EAU	14/06/1995	N	2	47	4	12	1	3	8	4	3	3	9
393	LONG EAU	11/05/1994	N	2	40	8	6	3	5	6	1	0	0	11
31270	LONG EAU	28/02/2006	Y	1	35	2	11	2	6	8	1	1	0	4
6393	LUD	24/05/1996	N	4	31	3	6	0	5	5	5	0	2	5
31268	LUD	28/02/2006	Y	1	47	2	12	3	7	8	3	1	1	10
3456	LYMN	14/06/1995	N	3	40	8	12	0	4	8	5	1	0	2
6623	NORTH BROOK	06/06/1996	N	5	25	0	3	1	5	8	5	0	0	3
31264	NORTH BROOK	02/03/2006	Y	1	53	4	11	1	8	9	6	2	1	11
3345	WAITHE BECK	07/06/1995	N	3	40	4	9	4	4	8	7	0	0	4
31269	WAITHE BECK	28/02/2006	Y	1	41	1	11	2	4	8	4	1	0	10
31267	WITHAM	01/03/2006	Y	1	47	5	7	3	9	7	4	2	1	9
6550	WITHAM	18/05/1996	N	4	33	2	3	4	5	11	4	0	0	4
584	WITHAM	30/05/1994	N	4	37	4	5	5	4	6	0	8	0	5

Figure 14 shows the relationship between intercept and slope for the model with just Q95 as a predictor variable. The following groups stand out:

- Foston Beck, Long Eau and Bain, all modified sites with lower mean scores and steeper slopes
- Cringle Brook and North Brook: sites with high in-channel and marginal macrophyte cover, low banktop height
- Lud, Witham and Chater: all sites with some structural complexity but overhanging trees and little macrophyte growth, relatively low banktop height
- Waithe Beck: this stands out on its own as high LIFE score and high slope of response. It has summer marginal macrophyte cover (contributing to slope), it also has the gauging station close downstream which acts as a hydraulic control, possibly maintaining overall mean LIFE score.

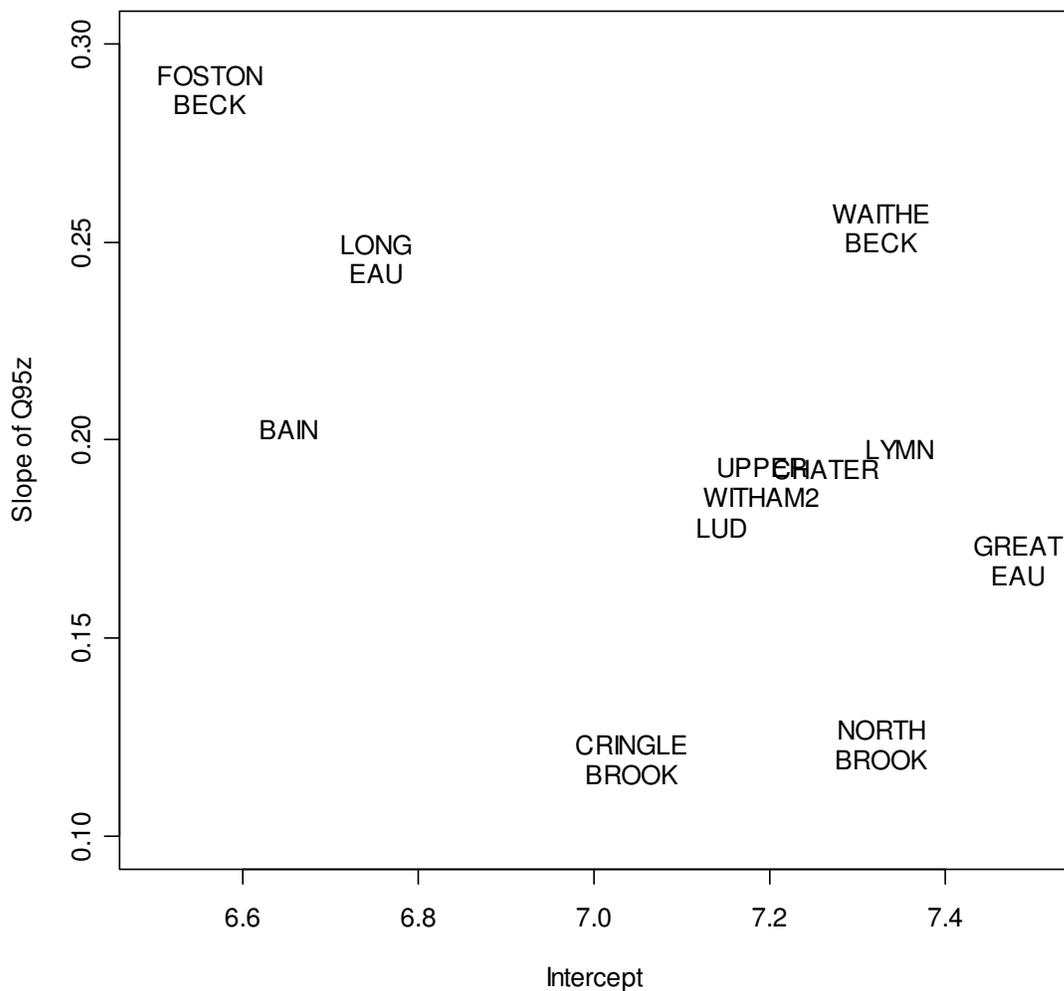


Figure 14. Relationship between intercept and slope in multilevel model for 11 core sites.

Figure 15 and Figure 16 show intercept terms (i.e. mean LIFE score) for models with and without HMS as a predictor variable. The dots in Figure 16 indicate mean LIFE score for a hypothetical HMS of 0 at the site, so are higher than in the previous figure. Figure 17 and Figure 18 illustrate the slopes of response of LIFE score to flow.

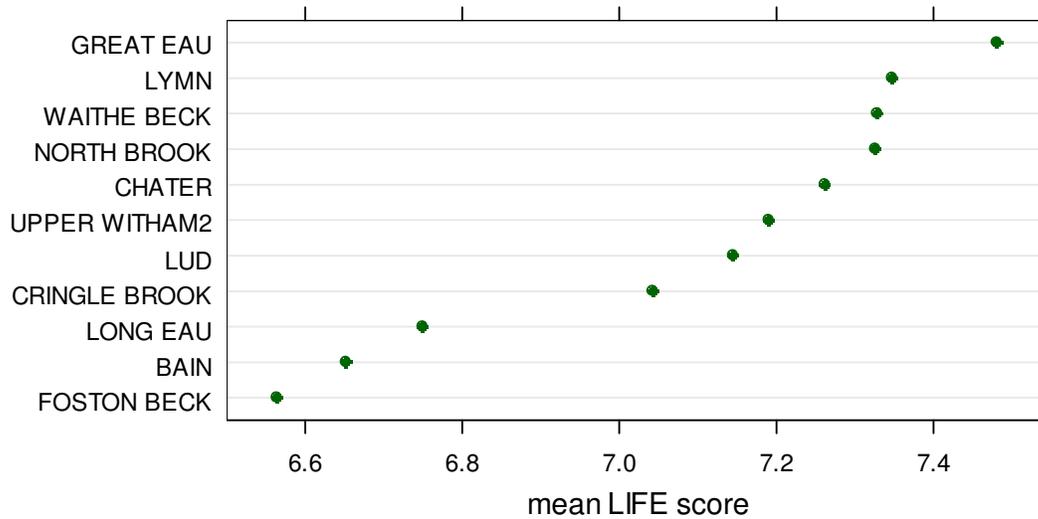


Figure 15. Intercept terms for model with Q95 as predictor variable.

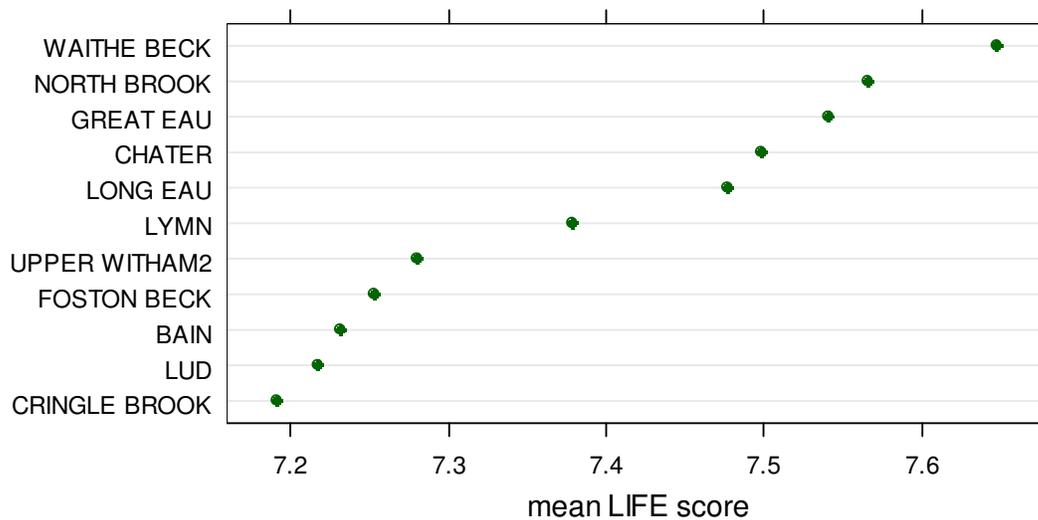


Figure 16. Intercept terms with HMS and Q95 including interaction.

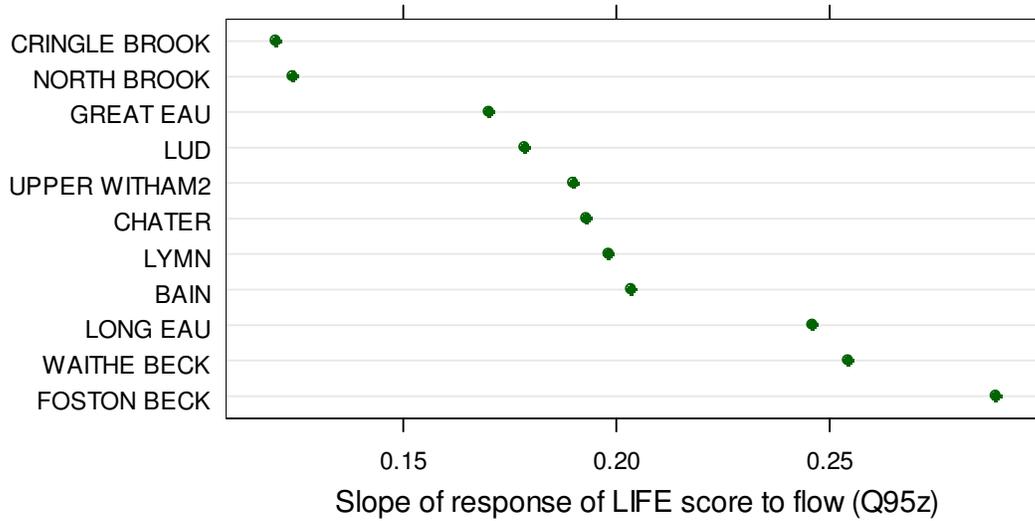


Figure 17. Slope of response for each site for model with Q95 as predictor variable.

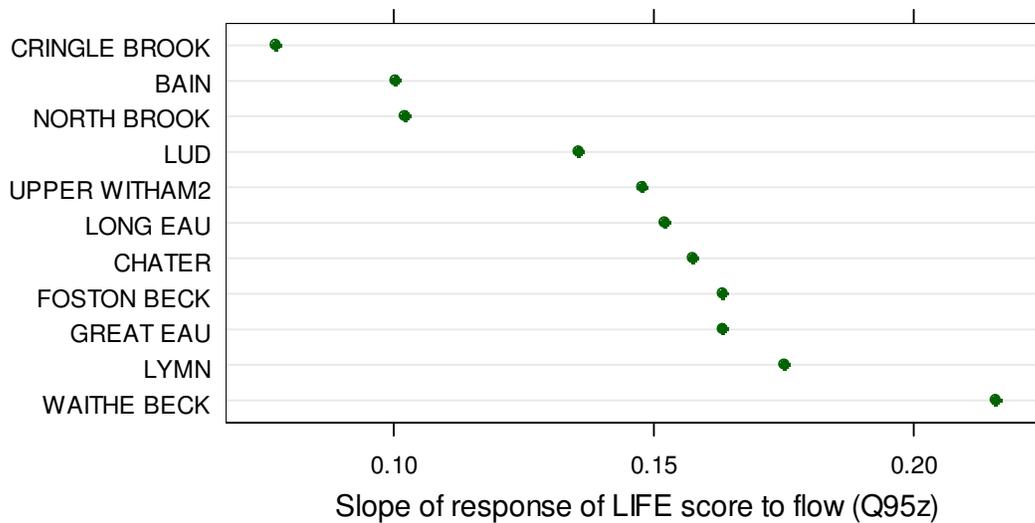


Figure 18. Slope of response for each site for model with HMS and Q95 including interaction

### Use of expected LIFE scores

Expected LIFE score is an alternative or additional covariate, which is known to be able to explain variation in LIFE score between sites, or variation in slope of the LIFE-flow relationship.

It could be brought in by transforming LIFE into an O/E ratio or to maintain comparability with the above analysis, tested as a predictor variable in the same way as HMS.

When an initial analysis was undertaken using gauged flows and data up to 2001, but ignoring the three sites which correspond to non-NRFA gauges (Long Eau, Lud, Foston Beck), it seemed that calculating a LIFE O/E ratio negated the effects of HMS on LIFE and LIFE-flow. This was probably because of a slight negative relationship between ELIFE and HMS in this

dataset (Figure 19) when the non-NRFA sites are ignored. This does highlight the relatively small number of sites used in the analysis, which is sensitive to period of record and exactly which sites are included.

However, re-analysis of the more complete dataset indicates that this is not the case. In fact, for the sites in this analysis, it appears to be HMS, rather than ELIFE which is the better predictor of mean LIFE score. Figure 20 illustrates how the three most modified sites lie below the 1:1 line, while the other sites (which do also some variation in modification) lie above the line.

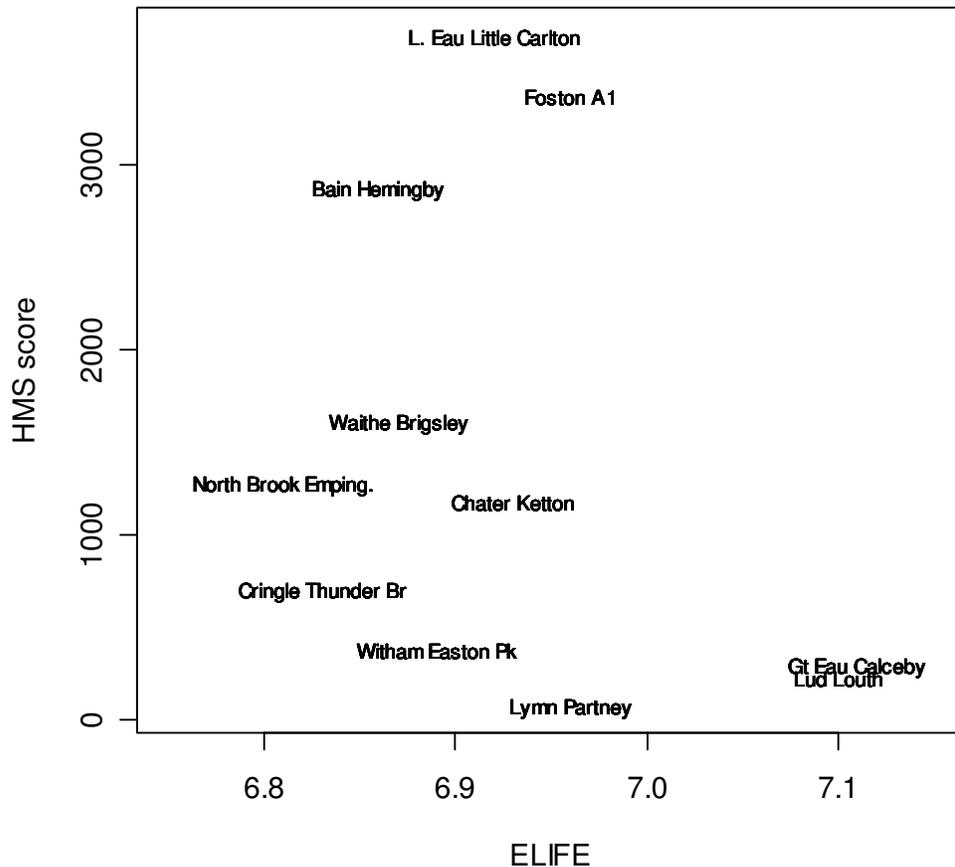
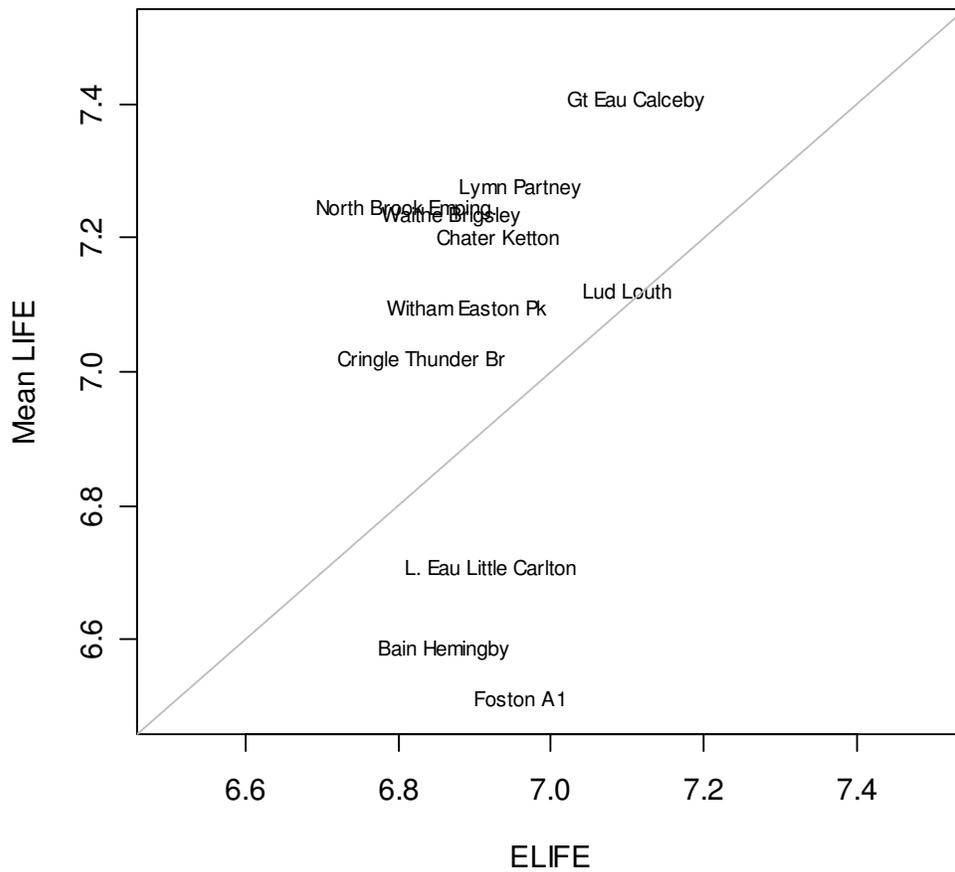


Figure 19. Relationship between ELIFE and HMS score for sites in dataset



**Figure 20. Relationship between ELIFE and mean LIFE score in dataset**

## 2.7 Influence of sample-level substrate data

Some physical data are collected every time a biological sample is taken. Some of these data, e.g. depth, width, substrate composition, are directly required if RIVPACS is to be used, other data, e.g. habitat types, vegetation is of more general interest. The extent of sampling of these variables has changed (increased) over time, so the decision was taken to concentrate on a single consistently-collected and relevant variable, substrate and particularly % silt.

Silt is indeed an important predictor if included in an analysis which includes season and HMS as covariates. In this model there are not interactions between HMS or season with flow, but silt does interact with flow. The silt main effect is negative, indicating that not surprisingly, more silt corresponds to a lower LIFE score, but it is interesting that this is the case, even correcting for flow. In addition the positive Q95zG interaction with silt suggests that the difference between LIFE vs flow is lower at high silt than it is at low silt levels. It is not immediately obvious why this should be.

**Table 8. Coefficients for model with silt, season and HMS**

Coefficient	Value	Std.Error	DF	t-value	p-value
Intercept	7.4	0.11	157	66	0.0000
Q95zG	0.11	0.04	157	2.7	0.0071
Silt	-0.0041	0.0012	157	-3.3	0.0012
Season Spring	0.074	0.034	157	2.2	0.033
HMS	-0.00014	0.000059	9	-2.5	0.035
Q95zG:Silt	0.0027	0.0012	157	2.2	0.028

## 2.8 Effects of different amounts of data on the at-site LIFE-flow relationship

Firstly the effects of the HMS term were investigated by comparing the results for a “new” site with and without the HMS term, with results for the full model with all data for all sites.

Secondly, the effects of at-site biological data on at-site LIFE-flow relationship were investigated through a series of simulations, in each case comparing with a model using all data, and a model using no at-site data:

- effect of a single biology sample
- effect of triennial sampling for approximately 18 years
- effect of annual sampling for 5-6 years

### 2.8.1 Habitat Modification Score

The results demonstrate that for the majority of the sites, the HMS score clearly improves the intercept component of the at-site model (Figure 21 and Table 9), but for the slope component, the improvement is less clear. The effects of HMS on slope are strongly affected by the more extreme values of the Cringle (lower score), and Long Eau and Foston Beck (high score).

**Table 9. Table showing whether the model with HMS gives a closer or equal fit to the all-data at-site relationship.**

	Intercept	Slope
Bain	Yes	No
Great Eau	Yes	No
Upper Witham	(Yes)	(No)
Waithe Beck	No	No
Chater	Yes	(Yes)
Lymn	Yes	(No)
North Brook	No	No
Cringle Brook	No	Yes
Foston Beck	Yes	Yes
Lud	No	No
Long Eau	Yes	Yes

Brackets around Yes indicate an equal (no worse) fit, brackets around no indicate a fit which is visually not much worse.

For the Waithe Beck and North Brook, the effect of HMS is minimal. For the Waithe Beck this is because it does not fit the pattern of lower score + steeper slope, it has a higher score and steeper slope. For the North Brook the result may be due to the scatter in the data for that

site and that the overall RHS HMS score is higher than one might expect from the HMS-LIFE relationships at the other sites.

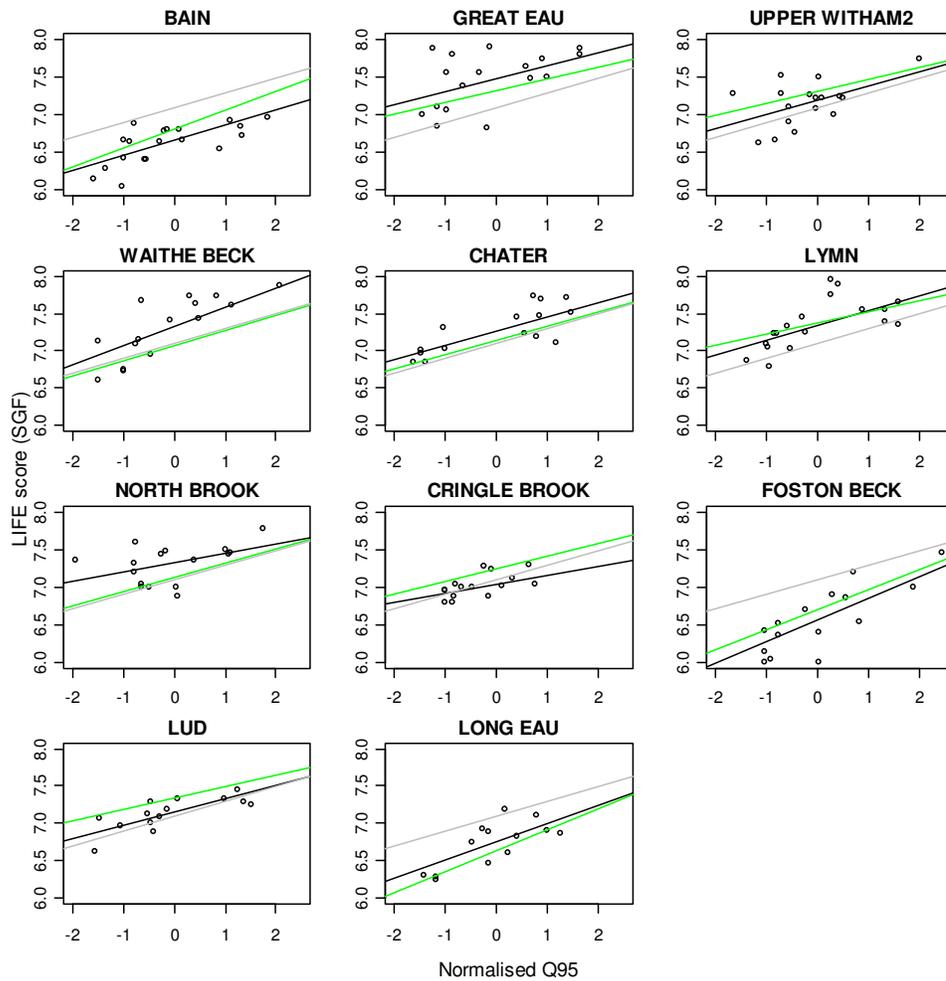
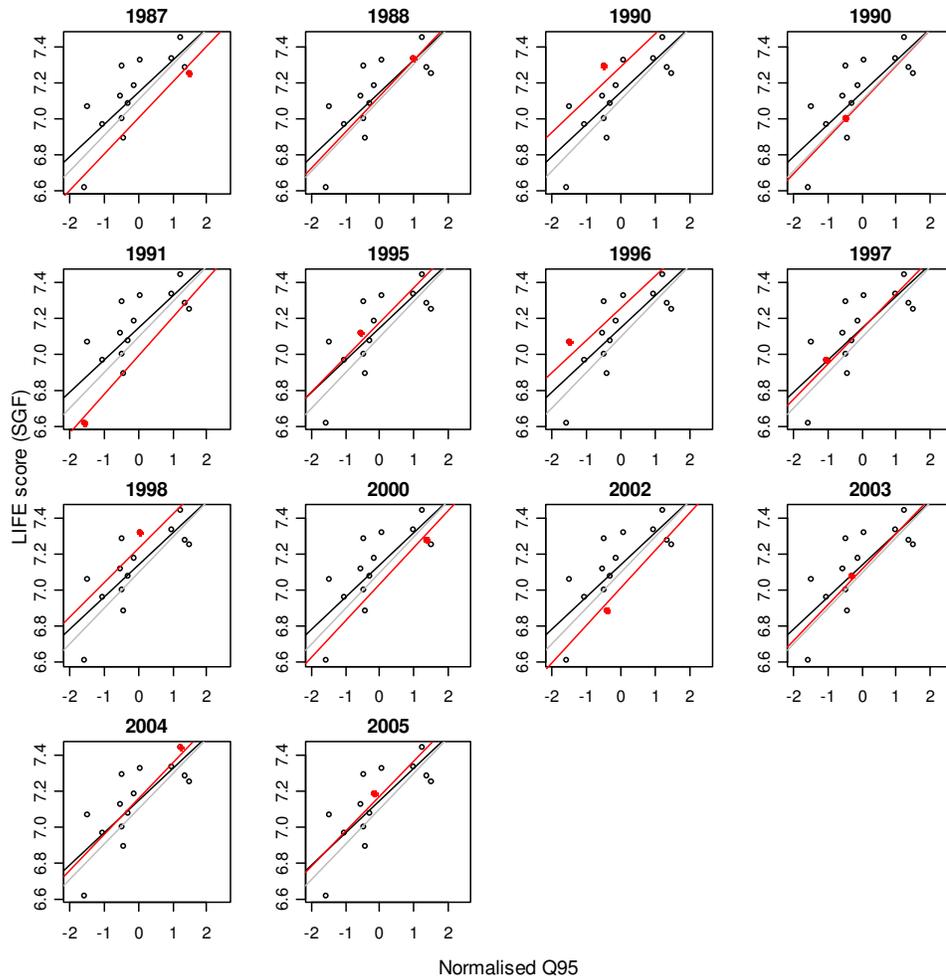


Figure 21. Results for model with HMS, but no at-site biology data (green line). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.

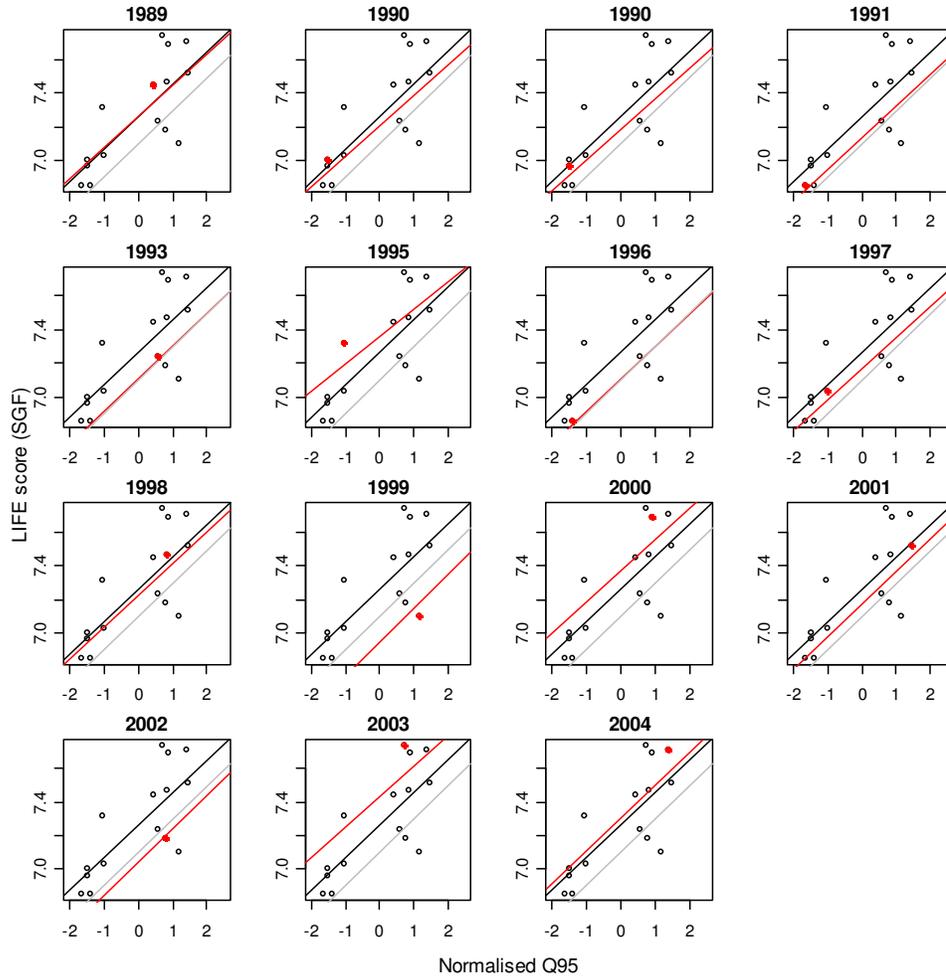
### 2.8.2 A single year of biology data

This was investigated for three of the sites, chosen to reflect close to the average relationship (Lud), higher than average scores (Chater), and lower than average scores with a steeper response (Foston Beck). The following figures make use of a red line, which indicates the at-site relationship using all non-at-site data, plus a single at-site biology sample. The black line represents the “best” relationship using all data from the dataset (including all data from the site). The grey line represents a “worst” case, with no at-site data at all. In general terms, the red line represents an adjustment to the grey line, which hopefully brings it closer to the black line.

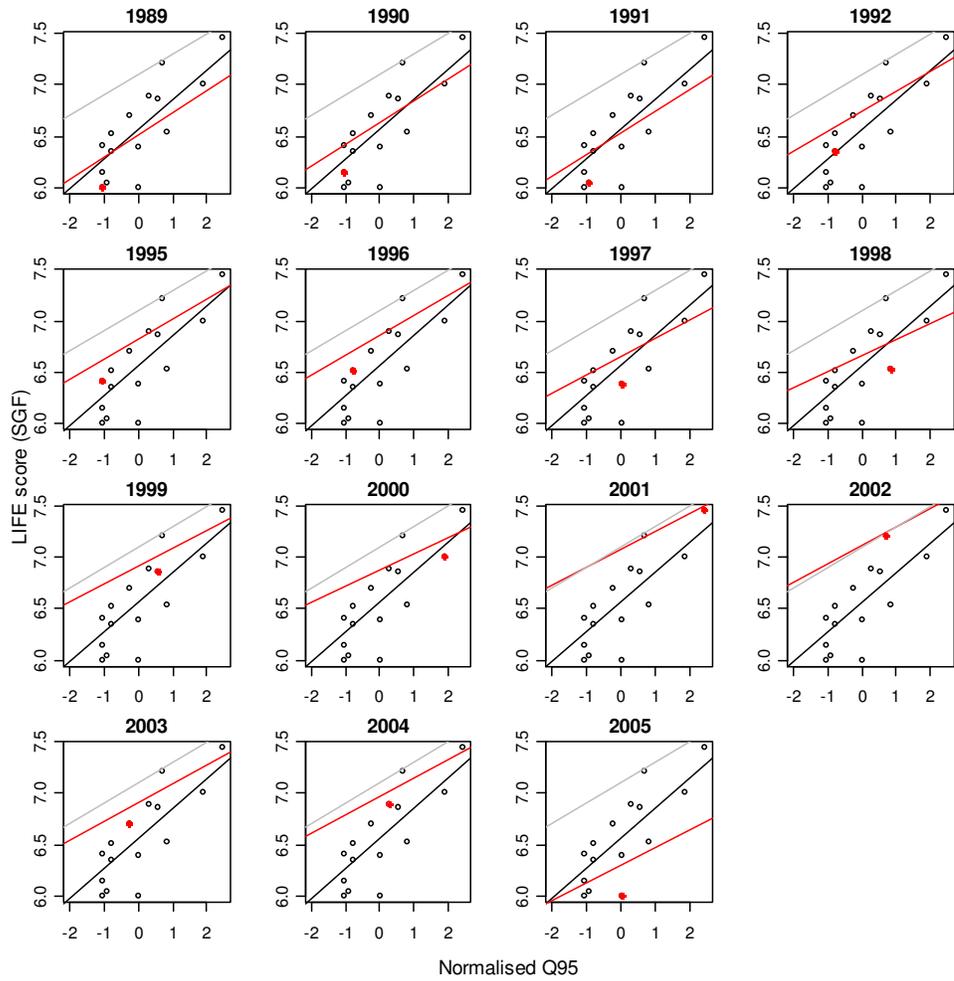
The results indicate that for the Lud, the at-site relationship is close to the mean overall relationship, hence a single sample does not improve the mean overall relationship, and can actually make it worse. For the Chater, in general, an at-site sample does improve the mean overall relationship (or have no effect), except in one of the years (1999), when an outlying point degrades the relationship. On the Foston Beck, a single sample is able to drag the red line down closer to the black line, but is not able to affect the slope to bring it much closer to the black line. To investigate this further, a simulation was undertaken with three at-site biology samples from 1989, 1990 and 1991. Together, these samples bring the red line lower than any one sample along, but again, they do not affect the slope sufficiently.



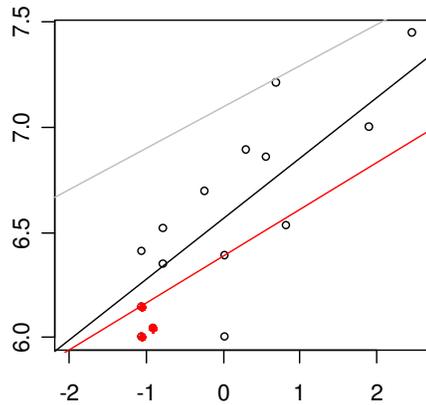
**Figure 22. Effect of one data point on results for the Lud. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.**



**Figure 23. Effect of one data point on results for the Chater. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.**



**Figure 24. Effect of one data point on results for the Foston Beck. Red line is at-site relationship using a single biology sample for the site, plus all data from other sites. Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.**



**Figure 25. Foston Beck: illustration of the effect of three low flow points together on the predicted site LIFE-flow relationship (red line).**

### **2.8.3 Triennial sampling over the whole time period and continuously sampling for a portion of the time period**

Results are presented in Figure 26 and Figure 27. They indicate that in most cases, six samples, taken once every three years, are able to reproduce the at-site behaviour much better than a single sample. The exception to this is the Cringle Brook. This is probably because there is an outlying sample on the Cringle Brook which gives a low score at high flows<sup>5</sup>.

Sampling every year for six years works well in some cases (Bain, Chater), whereas for many other sites, the results are not as good as for the triennial sampling. Clearly these results could have been different if different six-year periods had been chosen.

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<sup>5</sup> As noted previously, this is probably due to a confirmed pollution incident. However, omitting the outlying sample caused convergence problems in the model as a whole. This problem could have been overcome with time.

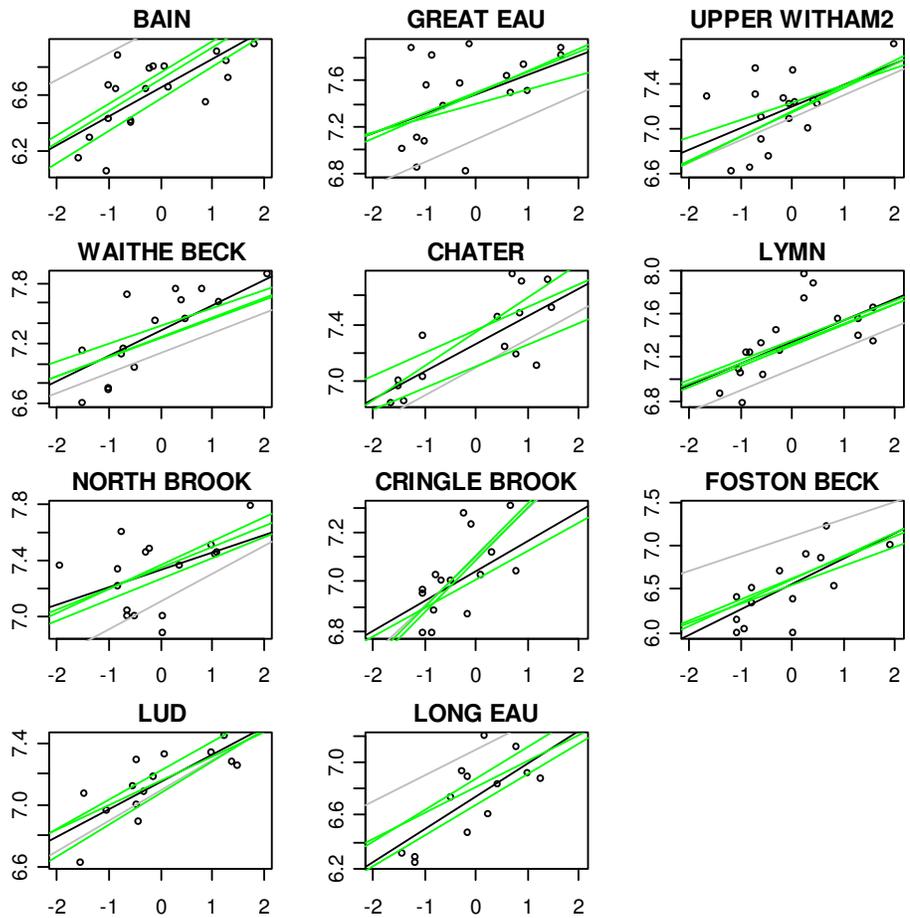


Figure 26. At-site model using three different triennial sampling periods spanning approximately 18 years (green lines). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.

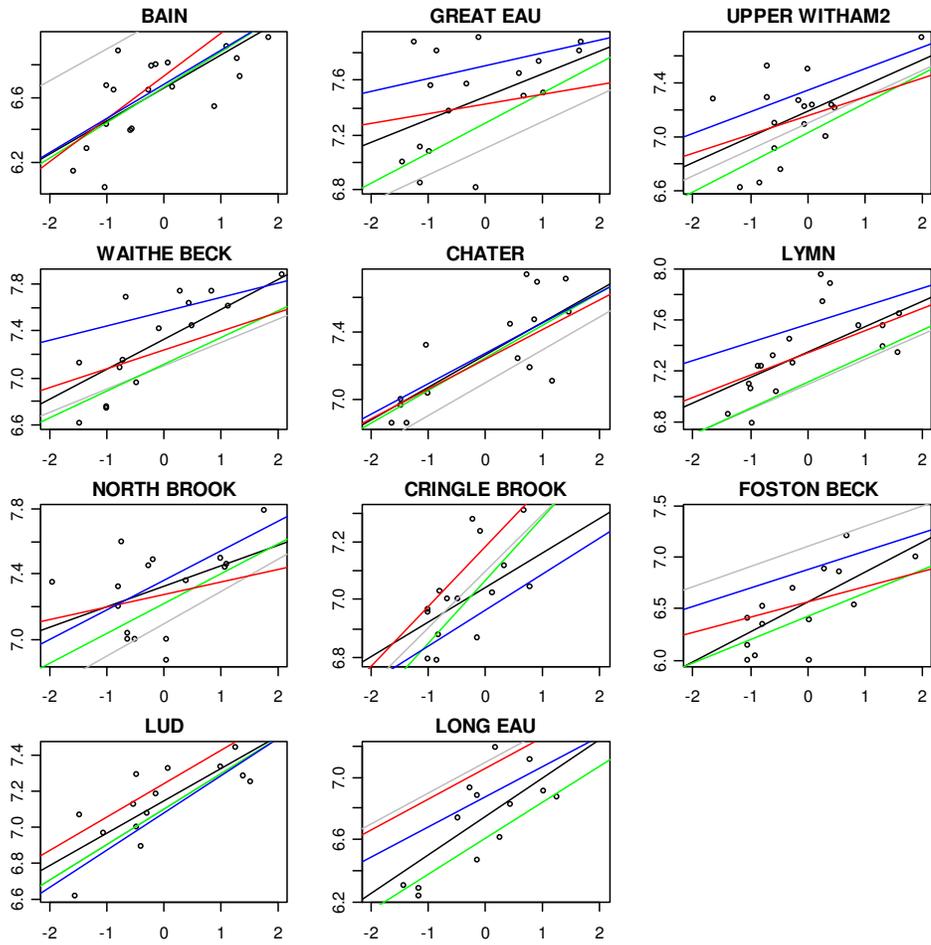
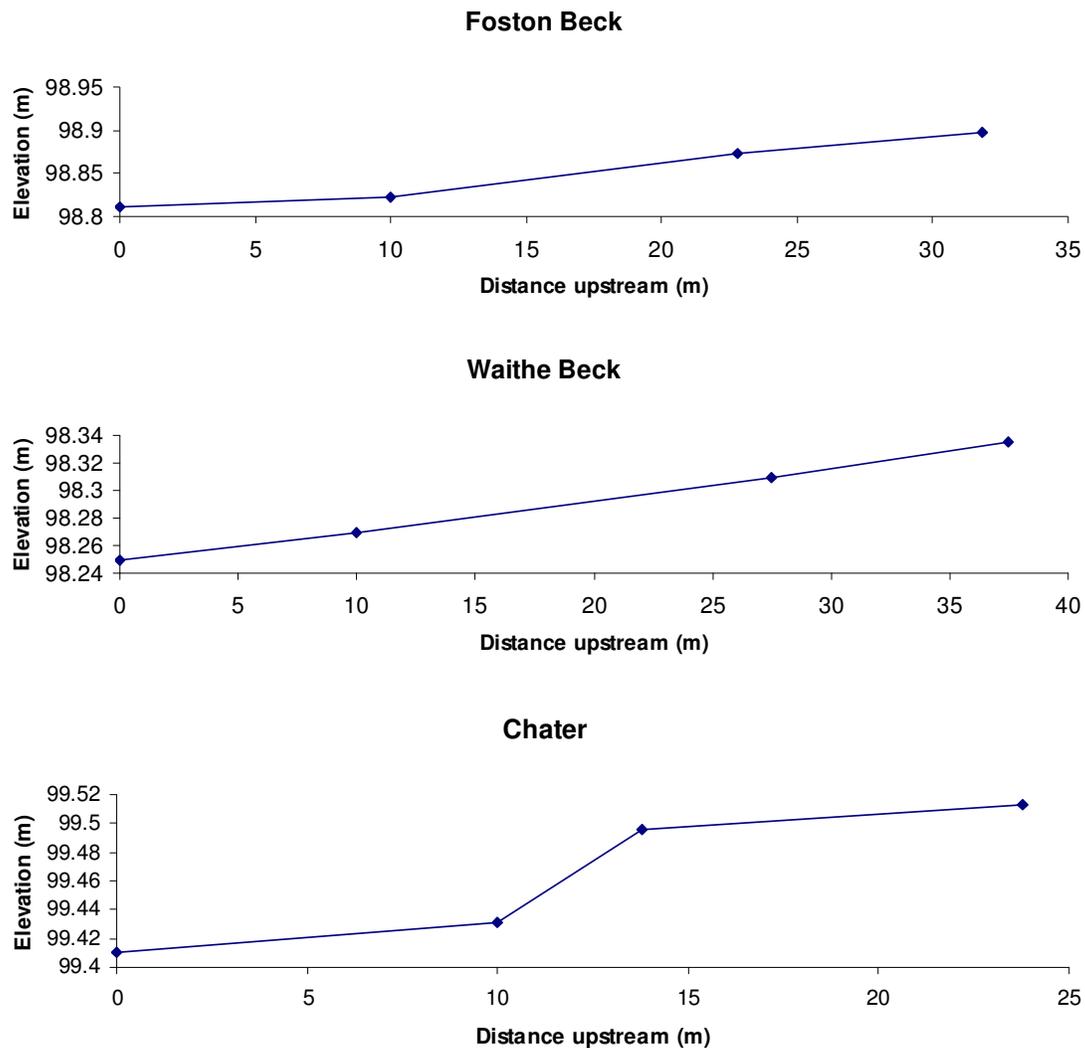


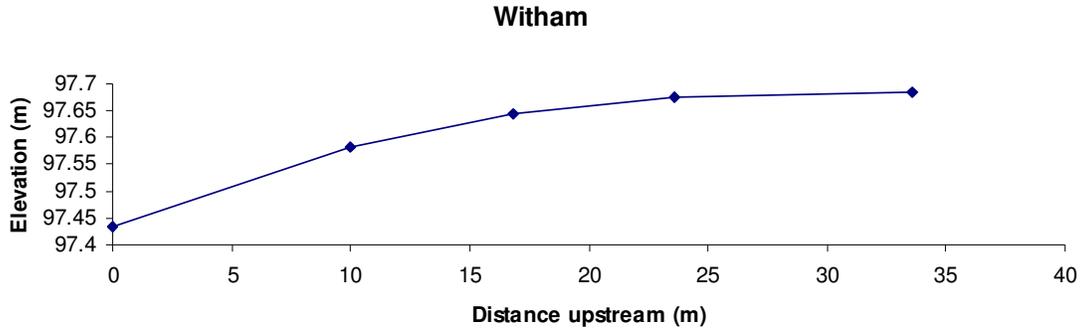
Figure 27. At-site model using three different annual sampling periods of 5-6 years (green: 1987-1992, red: 1993-1998, blue: 1999-2004). Black line is at-site relationship using all data, and grey line is overall relationship but with no at-site knowledge.

## 2.9 Channel hydraulics

Hydraulic models were set up for a single cross-section on the Waithe Beck, Foston Beck, Chater and Witham sites, using the Agency's Conveyance Estimation System.

The analysis in previous sections has shown that in general the sites are not showing curvilinear relationships with flow, in which case using modelled velocity instead of flow would not make the models fit any better. However, given the suggested effect of HMS on LIFE, it could be that some aggregate site hydraulic properties relate to LIFE score.





**Figure 28. Longitudinal water surface profiles for four sites.**

Default roughness values within the Roughness Advisor (part of the CES) were used. In some cases for vegetation, no obvious attributes were available, e.g. “brambles” on the Waithe Beck, so roughness values for height-varying grass were used. No calibration is needed, modelled water levels can be compared with those measured.

Water levels at the measured flow for the riffle cross-sections: on the Witham and Chater, were modelled extremely well by the CES: to within 1cm. This gives us some confidence that the CES is working for single cross-sections when there is no downstream hydraulic control. It is unfortunate that time constraints mean that we were unable to collect hydraulic data on the Lymn, which is the other site with obvious “riffle” characteristics.

On the other sites (Waithe Beck and Foston), water levels were consistently modelled too low. This is likely to be due to backwater effects in the channel: i.e. the water level at the sample site is affected by what is going on downstream. Without a measurement of the channel dimensions at the relevant downstream hydraulic control, it would not be possible to calibrate these models adequately, but if the data were collected, there is no reason why calibration should not be good.

Although the CES does have procedures for accounting for time-varying vegetation roughness changes, it is probably not worth undertaking any hydraulic modelling on the North and Cringle Brooks because of their extensive macrophyte growth. In addition, the effects of seasonal macrophyte growth on other sites such as the Waithe Beck would need careful consideration.

Because of these issues, it was decided not to continue further with the hydraulic modelling at this time.

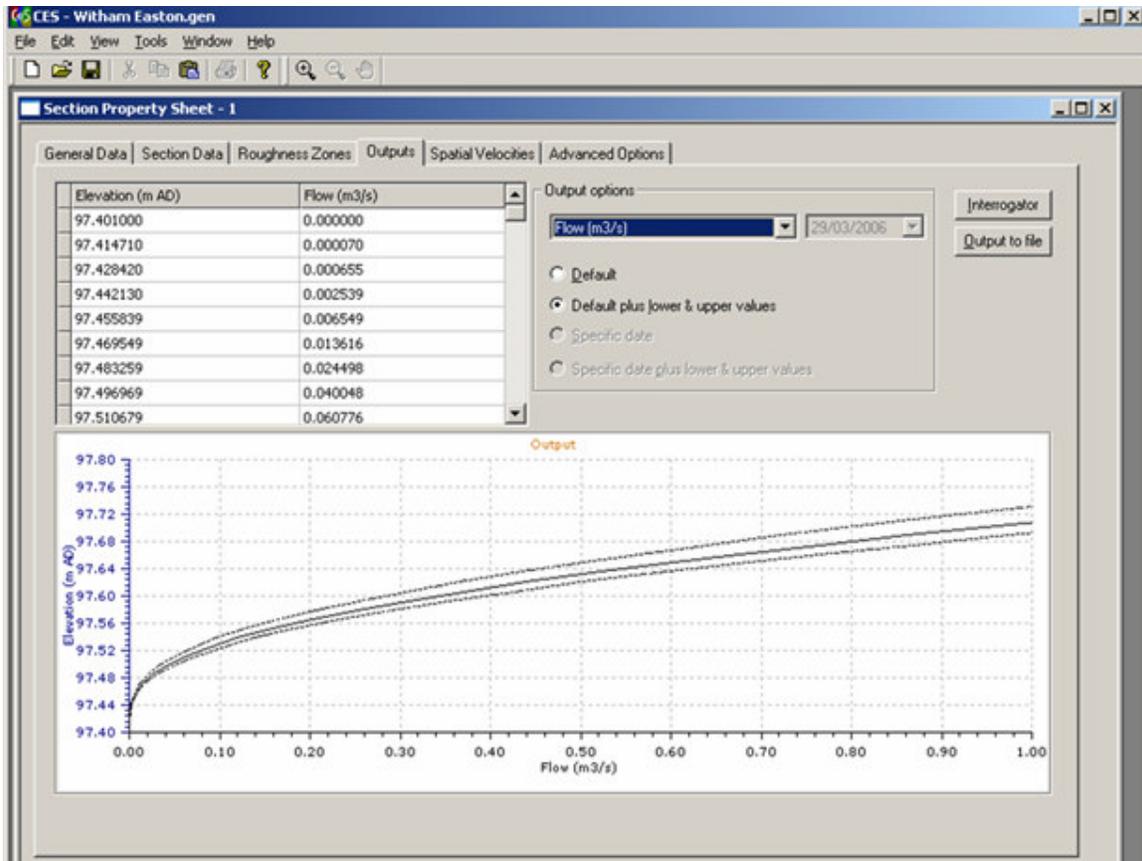


Figure 29. Example hydraulic output from CES for River Withham.

## 2.10 Response of individual LIFE flow groups

This brief graphical analysis was undertaken in order to understand better the differing responses at the sites, for which aggregate LIFE on its own could be too coarse a measure. In particular, it could help understand the mechanisms by which the HMS score is affecting LIFE. Figure 30 and Figure 31 illustrate the site-by-site responses of the individual LIFE flow groups to flow, expressed in terms of total abundance, and number of taxa.

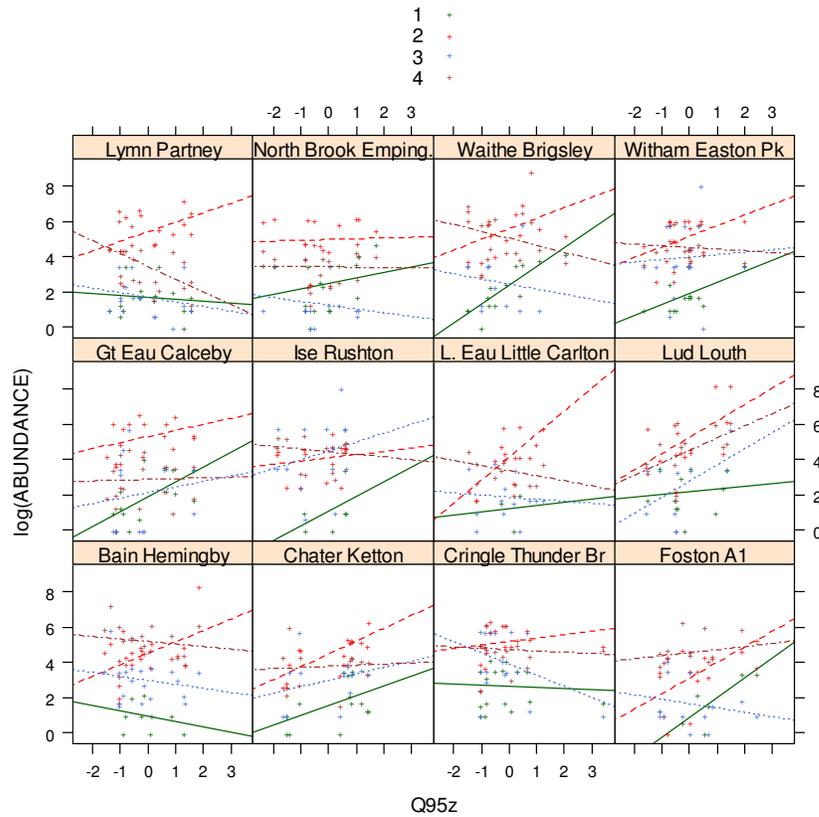
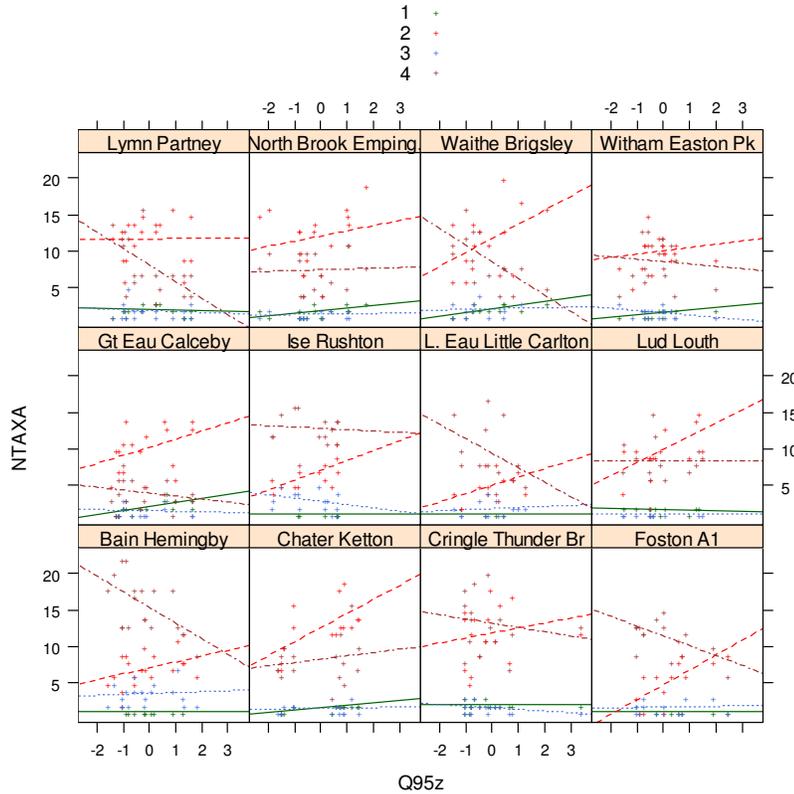


Figure 30. Relationship between log of abundance and flow for individual flow groups 1-4



**Figure 31. Relationship between number of taxa and flow for individual flow groups 1-4**

For both total abundance and ntaxa, overall, FG2 tends to respond more clearly than FG1. Clearly there are generally few FG1 taxa present, but FG1 total abundance does in some cases respond well, such as on the Waithe and Foston.

The number of FG4 taxa is a very good indicator at some sites (Lymn, Waithe, L.Eau, Bain, Foston). These are all “drain” sites with less habitat diversity except that arising from ingress of marginal macrophytes. Interestingly at the more natural sites, FG4 ntaxa has less indicator value. On the Lud, FG4 total abundance increases with flow (this is the exception rather than the rule). On the other sites there is a marginal decline (of course it could be more strongly related to another flow variable).

Table 10 illustrates the magnitude of the fixed effects for a model with flow groups 2 and 4 only. There is probably more in the data than is described in this simple model, for example it appears from the graphs that there is more variance in the slopes of the FG4 response than the FG2 response: this is not explicitly modelled. The results do show the overall negative relationship between Q95 and FG4 ( $0.5554-0.6127=-0.0573$ ). They also show that the relationship between HMS and FG2 is negative ( $-0.0004$ ), but the relationship between FG4 and HMS is positive ( $-0.0004+0.0006=0.0002$ ). This is not obvious from the above figures, but provides an explanation as to how increased HMS has a negative influence on overall LIFE score.

**Table 10. Fixed effects for model of log abundance for flow groups 2 and 4 only**

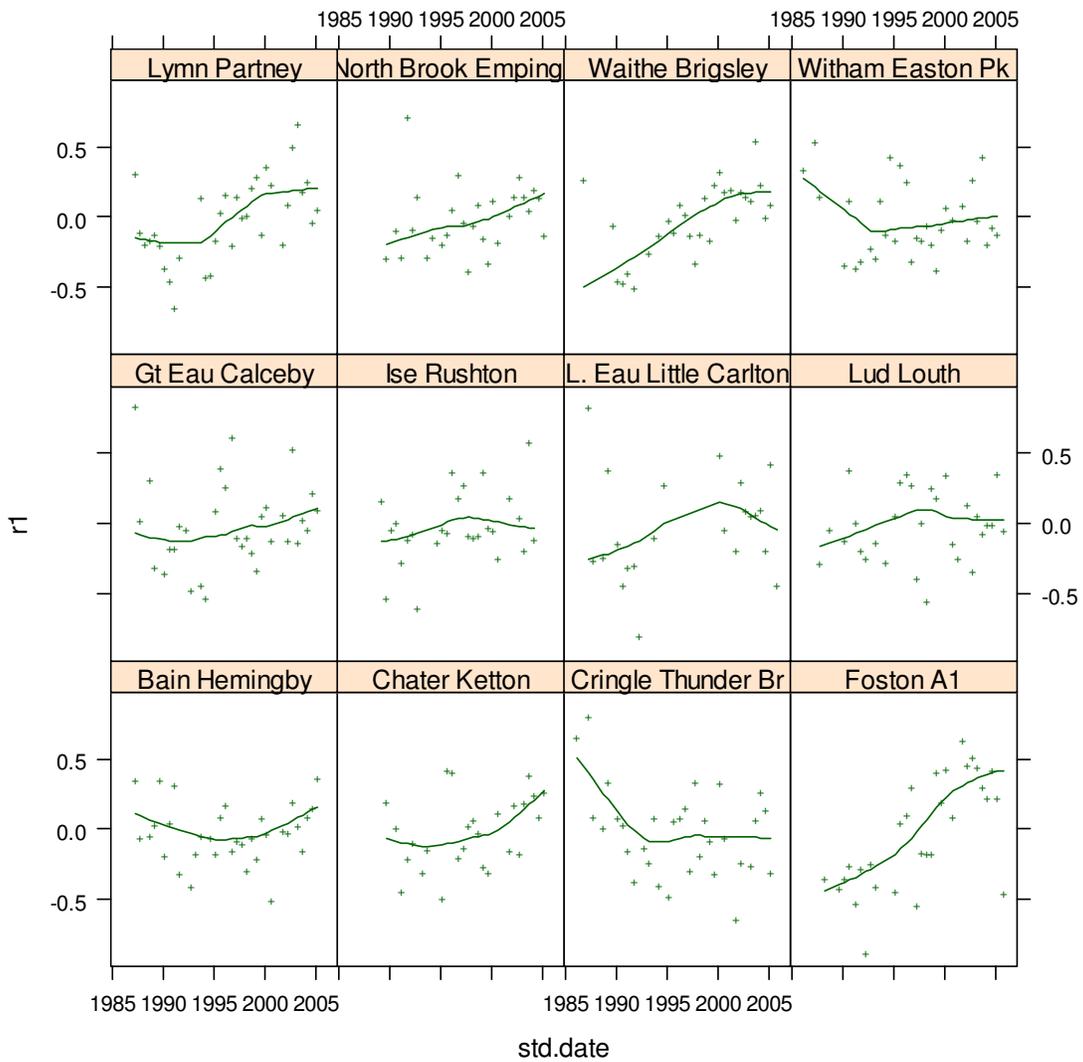
	Value	Std.Error	DF	t-value	p-value
(Intercept)	5.4867	0.2428	335	22.6	<0.0001
Q95zG	0.5554	0.0998	335	5.567	<0.0001
FG4	-1.5743	0.1922	335	-8.19	<0.0001
HMS	-0.0004	0.0001	9	-3.426	0.0076
Q95zG:FG4	-0.6127	0.1281	335	-4.784	<0.0001
FG4:HMS	0.0006	0.0001	335	5.786	<0.0001

Results of an analysis including flow groups 1 and 2 (not shown) illustrated that while there is a clear significant difference between overall mean log(abundance) – with flow group 1 being of lower abundance, there is no interaction between FG1&2 and flow, indicating that it was not possible with the current data to detect a significant difference between the slope of response of FG1 and 2 to flow.

### 2.11 Temporal trends in LIFE scores.

Figure 32 illustrates temporal trends in residuals of the model with Q95zG as a covariate.

- The strong trend on the Foston Beck may be indicative of pre 1995 water quality issues.
- The “outlying” points on the Cringle Brook are at the beginning of the dataset, this may be indicative of something.
- The Waithe Beck also has increasing scores: it is unclear why.
- At the other sites, the trends are probably not significant.



**Figure 32. Temporal trends in residuals (model with Q95, Q10 and season as predictors)**

### **3 DISCUSSION**

The results from this pilot study should help to inform future river monitoring for water resources purposes, and could also help inform other river monitoring. The results clearly demonstrate the interaction between physical habitat, flow regime and biotic scores. It appears from this analysis with a limited number of sites, that habitat modification can influence the relationship between LIFE score and flow, with more modified sites having lower LIFE scores and a steeper slope of response of LIFE score to flow.

#### **3.1 Relationships at different taxonomic levels**

The results are less clear cut than expected. This is likely in part to be due to the relatively small number of sites used in the analysis: a few erroneous taxa may be artificially increasing the apparent quality of the models at certain sites.

This could be because sub-optimal flow variables have been used. It could also be because the precision is in part related to who collects and sorts the samples. The data used here are still essentially species-level, a sample collected by an experienced biologist, identified to the highest resolution and then degraded to family level may not be the same as a family-level sample by a less experienced biologist.

It seems fairly clear that any reduction in precision involved with going from species to genus level is minimal.

The question remains what to do with family-level identifications in a sample nominally identified to species or genus level. The results here seem to indicate that including them has some value, however this could also be an artefact of the data and would ideally need further confirmation.

#### **3.2 RHS, habitat and LIFE**

The association between higher Habitat Modification Scores (HMS) and lower overall LIFE scores is particularly clear. The interaction between HMS and flow which suggests that more modified sites are more sensitive is noteworthy and statistically significant.

It is interesting that HMS, not Habitat Quality Score (HQA) score shows a relationship to LIFE. Although the HMS is made up of several elements, indexing different aspects of habitat modification, in this dataset, there is one overall gradient which dominates the overall HMS, that of the resectioned bed and banks sub-score. This suggests that it could be the degree of resectioning which is controlling the LIFE-flow relationship. More highly resectioned sites would probably have fewer low-velocity niches which would provide refuge for flow group 4 taxa. Equally, the less resectioned sites could have areas of higher velocity at low flows, which would provide refuge for flow group 1 and 2 taxa. This on its own does not explain why it is HMS and not HQA which provides a relationship. The lack of a clear pattern nationally between HMS and HQA (which superficially might be negatively correlated) has already been documented. In this case, it could be that HQA is too generic and aggregated to be useful, but that no one sub-score of HQA relates to LIFE on its own. Other explanations could be that HQA is more difficult to score repeatably than HMS, that HQA exhibits greater

seasonality than HMS, or that HMS reflects habitat quality at a broader scale, beyond the 500m RHS reach, this could better relate to the macroinvertebrate community through time.

Siltation has been shown to have an effect beyond that of the flow variables used, although this analysis is partly limited by the lack of silt fraction data for all samples.

The response of individual LIFE flow groups further demonstrates the differences between the more and less modified sites, with the flow group 4 taxa at less modified sites not showing the expected decreases with increasing flows. The analysis with expected LIFE score highlights that expected LIFE score includes some site variables which are also indirectly in HMS scores.

Some sites do not follow the general pattern of the other sites with regard to the relationship to local habitat conditions (e.g. Lymn at Partney has higher LIFE scores than expected, the Waithe Beck at Brigsley exhibits a steeper slope of response than might be expected). This may be related to habitat conditions other than those immediately local to the biology sampling site. However, although there are indications of this, there are too few sites overall to make any firm conclusions.

### **3.3 Reduction in flow corresponding to a set reduction in LIFE score**

This has been a useful illustration of how water resource environmental standards could be set using LIFE and flow data. However, it is very important to note that these results are entirely illustrative, being based on relatively few sample sites, an arbitrarily-selected reduction in LIFE score, and a regression model used in the reverse direction. Results suggest figures of between 10 and 30% of mean summer Q95. Although illustrative, the figures do broadly agree with the results of other preliminary water resource standards work based on expert opinion – the SNIFFER WFD48 project. This is perhaps surprising as the figures are directly linked to the choice of a 0.1 unit drop in LIFE score, which was chosen arbitrarily in advance. The results of this work emphasise the role of habitat conditions in determining sensitivity to flow, whereas the WFD48 project focused on catchment characteristics.

The techniques applied in this project could be used to test whether there is a relationship between any combination of catchment characteristics and the slope of the LIFE score – flow relationship. With the current dataset, there is not really a broad enough gradient in catchment characteristics to test the typology used in WFD48.

The differences, for some sites, between the figures obtained using gauged flows and CERF-modelled flows highlight the importance of using an application-orientated measure of model performance, rather than a simple  $R^2$  fit measure.

### **3.4 Flows modelled with generalised continuous rainfall-runoff model CERF**

The results of the analysis have been very encouraging, especially given the potentially challenging nature of these relatively dry catchments.

### **3.5 Benefits of different types and amounts of data**

For all the sites in this analysis, the relationships using all the biology data are relatively good, being based on plenty of data points. Hence they are good enough with which to make water

resources judgements on the impact of flow changes on macroinvertebrates. In other situations this may not be the case, with fewer data points per site the benefits of using a multilevel modelling approach to strengthen relationships at particular sites would be clearer. Likewise, the value of the RHS data lies in the situations where fewer biology data are available.

From a visual inspection of the results, it appears that an RHS survey, when combined with a model that uses RHS as a predictor, is more beneficial than a single year of autumn biology data, it is probably worth between 1 and 5 years of autumn biology data. An RHS survey on its own is clearly not a substitute for a long term record of biology samples. Biology data would of course be more useful if a particular site did not fit the HMS-LIFE pattern of the other sites in the model, but of course one never knows in advance if this is the case. Biology data is of less use the more scatter there is in the LIFE-flow relationship for a site (again this would not be known in advance), as any single point could give a more incorrect impression than no at-site data. It may be that a combination of RHS and some biology data would give the best results. The general pattern is summarised in Table 11. Further work could quantify these relative benefits in more detail, but this is probably only worth doing on a larger dataset.

**Table 11. Summary of relative benefits of RHS and biology data.**

	Is beneficial	Is not beneficial
RHS data	When site fits the HMS-LIFE pattern of other sites	When site does not fit pattern
Small amount of biology data	When scatter in LIFE flow relationship is less. When HMS-LIFE relationship does not fit pattern of other sites.	When scatter in LIFE-flow relationship is more.

These results are particularly relevant when setting up new monitoring sites under CAMS, under these circumstances, an improved LIFE-HMS+flow model could help avoid potentially erroneous conclusions from short periods of biology data.

### 3.6 At-site hydraulics

In the time available, only limited progress was made with including the site hydraulic data. The results for the sites with true riffles indicated that the conveyance estimation system predicted water levels well from channel cross-section data and roughness estimates alone. Water levels, and hence velocities at many of the sampled sites are influenced by downstream hydraulic controls, which would need to be included in any future monitoring.

One way in which the existing data could be used could be an index of the discrepancy between CES-predicted water level and measured water level, as a descriptor of the riffle-like nature of the site.

### 3.7 Temporal trends

There were temporal trends in LIFE score at some of the sites which did not appear to relate to flow. These trends could illustrate changing water quality but could also indicate where the currently-used flow variables are not sufficient and longer term flow patterns could affect LIFE score.

### **3.8 Relationship with results from the RAPHSA project**

The joint CEH-Environment Agency project RAPHSA (Rapid Assessment of the Physical Sensitivity to Abstraction) is also concerned with hydroecological relationships which could be used by the Agency Water Resources function. The overall aim of RAPHSA is to produce a suite of tools that can give a rapid indication of physical sensitivity to abstraction. The focus is on how water depth, width and velocity change with flow, and there is an implicit focus on fish species for which physical habitat suitability criteria exist. The data used in RAPHSA consist of physical data at 64 PHABSIM sites in England, Wales and Scotland: 5-15 topographic cross sections with water levels and water velocities measured at three separate flows.

There are both similarities and differences between the RAPHSA and DRIED-UP results. RAPHSA has used data from sites throughout Great Britain, although coverage is biased towards the types of rivers where PHABSIM has been undertaken. DRIED-UP has been a pilot study, focused on a particular area of England. In addition, the relationships seen in RAPHSA between physical habitat and flow are generally curvilinear, whereas in DRIED-UP, the relationships between LIFE and flow are straight lines.

One key similarity is that both projects have highlighted the controlling influences of relatively local habitat conditions on their respective hydroecological relationships. In RAPHSA, a key aim was to relate physical habitat-flow relationships to catchment characteristics, however this was relatively unsuccessful. Similarly with the DRIED-UP dataset, habitat has proved a better predictor of LIFE score than RIVPACS expected LIFE score. A second similarity is that both projects have emphasised incremental benefits of data collection, allowing the use of minimal data leading to relatively uncertain relationships, but also allowing the improvement of these relationships with additional data. A further similarity is that both projects are ultimately limited by the data available, in particular in spatial coverage. What is required for a range of management purposes (CAMS, WFD etc.) is relationships that are valid at the water body scale. However, all existing data, whether biological or physical, is for much shorter lengths of river, and within-water body replicates are rarely, if ever available. Hence it is in some ways not surprising that the best relationships are found with local physical data.

## **4 RECOMMENDATIONS**

### **4.1 Monitoring and Management**

At the moment, monitoring for macroinvertebrates occurs at sites selected at a time when assessment of water quality was the primary goal. River habitat surveys have been undertaken mainly under different sampling strategies, and have not generally been used in conjunction with any biological sampling. This study has shown there is a potential benefit of linking RHS and macroinvertebrate sampling, either from existing data or with new RHS surveys.

Habitat modification is not taken into account when setting flow objectives, these results suggest that perhaps it should. There are far-reaching implications of this study in terms of whether more modified channels should be granted more stringent flow standards than more natural channels. Given this potential link, it is strongly recommended to undertake some RHS surveys to be co-incident with macroinvertebrate monitoring sites considered to be of importance for water resources monitoring so that future analysis of such data can account for the potentially confounding effects of habitat. This would be in addition to RHS surveys undertaken for other purposes.

Additionally, these results suggest that there is potential benefit in habitat rehabilitation works in order to mitigate water resources pressure, and even climate change impacts on hydrological regime. However, comparison of sites with different levels of modification is not the same as showing the benefits of restoration, and more study is clearly needed in this area.

Similarly, temporal changes in flow will lead to alterations in the macroinvertebrate community differently in different sites: this should be taken into account in analyses of the relationships between habitat and macroinvertebrates. If analysing sites with small numbers of samples, it is easy to see how temporal changes in flow could confound relationships between habitat and biota.

Recent work as part of the RAM framework review by ENTEC has demonstrated the difficulty in relating abstraction pressures alone to LIFE scores. There are potentially many reasons for this, but not including flow in the analysis, and concentrating on LIFE O/E should be highlighted. There is great potential for CERF natural flow time series to improve our understanding of the links between abstraction and LIFE.

### **4.2 Future Research**

The results of the linking of CERF and LIFE are encouraging, and it would be beneficial to extend the current analysis to a wider range of sites, especially more upland sites where CERF is known to work better. Extension of the work to more naturally taxon-poor sites could better demonstrate the benefits of a higher degree of taxonomy.

Extending the analysis to some targeted ungauged sites would allow the relationship between habitat modification, LIFE and flow to be evaluated in more detail, without the restriction of having to use sites close to gauging stations. Such sites could either have existing nearby RHS data or new RHS data could be collected as in this study.

In this context, it would be extremely useful to extend the time series of rainfall grids used in CERF, from 2001 to the present. At the time of writing (mid 2006) this would allow the utilisation of four more years of biology data an increase of 25% for a time series starting in 1986, 35% for a time series starting in 1990, and 66% for a time series starting in 1995.

This study has not focused on the selection of optimal flow indices, neither has it focused on temporal sequencing of LIFE scores, in particular whether there is incremental damage associated with multiple years of drought. Both these topics need further investigation.

This study has used existing sampling locations and has consequently concentrated on temporal as opposed to spatial variation in LIFE scores. Questions remain to be answered as to the extent to which the current sampling network represents the river network, and what is the balance between local and broader-scale habitat in structuring river communities. These can only be answered with spatial replication (ideally within waterbodies). The flexibility of multilevel models, which do not require balanced data, mean they are an ideal tool to examine both spatial and temporal variation together.

The CERF vs gauged flow differences in the proportions of summer Q95 corresponding to a 0.1 unit change in LIFE score need further investigation, so that the causes of the differences can be understood.

There are obvious links between the aims of RAPHSA and DRIED-UP, once the RAPHSA tools are complete, some of them could be tested for their utility in predicting LIFE-flow relationships.

The work undertaken for this study is highly publishable, and could form the basis of several articles in peer-reviewed journals. The most obvious topic for a single paper would be the relationship between the HMS score and the LIFE-flow relationship.

## 5 REFERENCES

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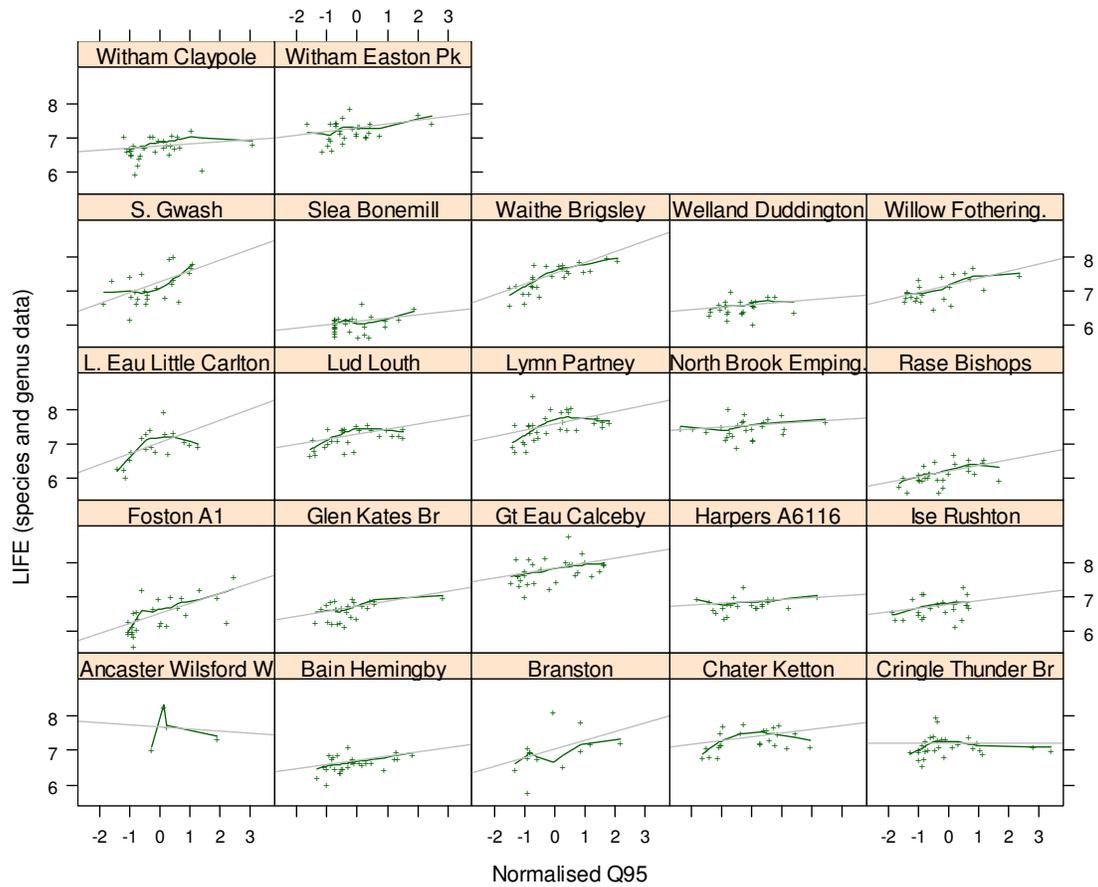
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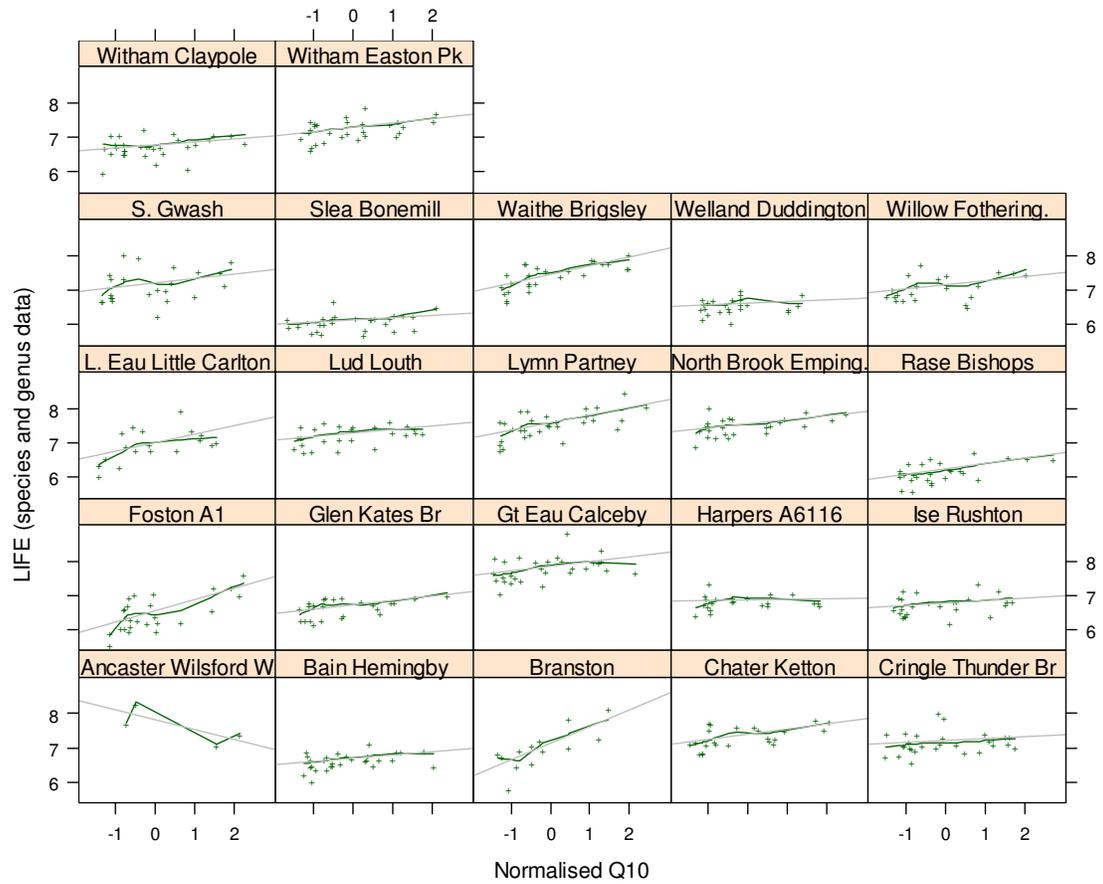
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# Appendices

## A. LIFE-FLOW RELATIONSHIPS FOR ALL SITES





## B. FORMULATION OF A MULTILEVEL LINEAR REGRESSION MODEL

$$\begin{aligned}Y_{ij} &= \beta_{0j} + \beta_{1j}x_{ij} + R_{ij} \\ \beta_{0j} &\sim N(\gamma_{00}, \tau^2_{00}) \\ \beta_{1j} &\sim N(\gamma_{10}, \tau^2_{10}) \\ \text{cov}(\beta_{0j}, \beta_{1j}) &= \tau_{01} \\ R_{ij} &\sim N(0, \sigma^2)\end{aligned}$$

Equation 1

$$\begin{aligned}Y_{ij} &= \beta_{0j} + \beta_{1j}x_{ij} + R_{ij} \\ \beta_{0j} &= \gamma_{00} + \gamma_{01}z_j + U_{0j} \\ \beta_{1j} &= \gamma_{10} + \gamma_{11}z_j + U_{1j} \\ U_{0j} &\sim N(0, \tau^2_{00}) \\ U_{1j} &\sim N(0, \tau^2_{10}) \\ \text{cov}(\tau^2_{00}, \tau^2_{10}) &= \tau_{01} \\ R_{ij} &\sim N(0, \sigma^2)\end{aligned}$$

Equation 2

$i = 1 \dots n_j$  where  $n_j$  is number of observations for site  $j$   
 $j = 1 \dots N$  where  $N$ =number of sites

$Y_{ij}$  is always LIFE score

$x_{ij}$  is a level 1 (innermost) explanatory variable such as flow for a specific year and site

$z_j$  is a level 2 explanatory variable such as habitat modification score

## C. SITE PHOTOGRAPHS



BAIN.JPG



Chater.JPG



Cungle Brook.JPG



Foston Beck.JPG



Great East.JPG



Long East.JPG



Lud.JPG



Lynn.JPG



North Brook.JPG



Wathe.JPG



Wotton.JPG