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Preparing for climate change impacts on freshwater ecosystems (PRINCE)

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Steve Killeen

Head of Science

Executive Summary

This study was commissioned to review current understanding of the implications of climate change for freshwater ecosystems, improve predictions of future change; communicate this information effectively; and inform relevant policies.

It builds on the earlier literature review and scoping study (Conlan *et al*. 2005), which discussed the available options for modelling climate change impacts on freshwater ecosystems. The scoping study indicated that upland headwaters and middle river reaches may be particularly sensitive to climate modification. Impacts could manifest themselves in a number of ways, including as a direct response to temperature-mediated impacts and through indirect effects of changes in river flows. The study also highlighted the potential shift in balance in the ecosystem in response to altered competition within aquatic communities and their species, although these effects would be far less certain and harder to predict.

This study had two aims: to identify the best way to model freshwater ecological change in selected water bodies and thereafter to provide preliminary findings concerning the potential impacts of climate modification on specified aquatic ecosystems. The assessment has applied some existing approaches and contrasted them with novel ways of modelling climate, river flow and ecological impact. The simpler approach uses future river flows and temperatures linked to statistical ecological models developed from field survey data (empirical modelling). The more complex approach uses a downscaling climate model, together with continuous catchment and reach-scale simulation models, to provide input data for a fish habitat ('fuzzy') assessment model. Both approaches require field data (the complex methods requiring significantly more), which can severely constrain their application in data poor catchments. A technique for extending the modelling to other sites in a climatically similar region was also undertaken.

The report considered three main locations: the upper River Wharfe; the middle reaches of Yorkshire rivers more generally; and headwater streams of the upper Afon Tywi in mid-Wales. The more complex continuous simulation method was applied to the River Wharfe, where a suitable hydrological model has been developed, and the empirical method was applied to the remaining sites. The River Wharfe was chosen because of the good availability of data, its familiarity to the project team and its ecological importance. The Afon Tywi study area was chosen as it has one of the longest and best macroinvertebrate (small river animal) datasets for upland rivers in the UK.

In the case of the River Wharfe, the analysis concentrated on the impact of climate change on river flows and the consequent implications for salmon and brown trout habitats. At the other Yorkshire river sites, the analysis concentrated predominantly on the effects on macroinvertebrates of changes to temperature and river flows.

The key finding when considering the assessment methods was that long-term good quality records are vital such as species level macroinvertebrate data. Extreme conditions are important drivers of ecological change (such as floods and droughts), sub-daily and daily information – rather than bundled statistics (mean river flow over a month) are required to improve ecological response models. Many of the methods employed at present cannot provide this information and more complex approaches, such as the one used for this study, may be more appropriate. The challenge is to be able to broaden the findings to larger areas, as the methods are very time-consuming and data intensive.

The results for the ecological impact assessments are of interest. Generally, there was a significant link between macroinvertebrate communities and river temperature. Projecting these findings into the future, where average temperatures could be 2–3^{o}C higher by the 2080s, the

studies suggest that such increases would exceed the current range occupied by some macroinvertebrate species (mid-Wales) and families (Yorkshire) by 2020. The number of species or families affected changes with different models for future climate however, trend is consistent. The consequence would be a change in the macroinvertebrate assemblages at the various streams and rivers investigated, including a significant reduction in abundance and/or richness. This may, in turn, influence the communities and species that use these macroinvertebrates as a food source, such as fish.

Results for the upper River Wharfe suggest that by the 2050s there may be differential displacement of salmon and brown trout from upland streams and rivers due to changes in the availability of their preferred habitats. Increasingly, low flows will have a corresponding impact on river velocities and water depths and affect different species in different ways. In the reach studied, this effect would have a greater impact on salmon than it would on the brown trout population, resulting in a general pressure for movement downstream. The study looked at annual changes in low flows, seasonal analysis could indicate which times of the year habitat would be most restricted. Water temperature and the consequent effects on dissolved oxygen saturation may be an even greater factor affecting habitat suitability, but was not modelled in this study.

There is a cascade of uncertainty through each analytical stage. No quantification of the level of uncertainty in the study output has been undertaken and the results from the modelling approaches used in this study should therefore be viewed as exploratory. However, the study has shown that upland streams are particularly sensitive to predicted future climates. Macroinvertebrate communities are likely to change which needs to be reflected in biological monitoring systems designed to support regulation and delivery of conservation objectives. Suitable habitat for economically important salmonid species is likely to be reduced in headwater areas.

Adaptation strategies could involve management of upland streams to increase shade cover and potential reduce temperature extremes. Other pressures on upland habitats such as water abstractions, effluent discharge or diffuse pollution could also be reduced to enhance ecosystem resilience.

Further research is required to assess the climate sensitivity of other water body types, in different regions and also to determine the climate sensitivity of key freshwater species nationally

Crynodeb Gweithredol

Comisiynwyd yr astudiaeth hon er mwyn arolygu'r ddealltwriaeth bresennol o oblygiadau newid hinsawdd i ecosystemau dŵr croyw, cynyddu rhagfynegiadau am newid yn y dyfodol; rhannu'r wybodaeth hon yn effeithiol; a hysbysu polisïau perthnasol.

Ychwanega at yr arolwg llenyddol blaenorol ac astudiaeth terfynau (Conlan *et al.* 2005), a drafododd yr opsiynau posibl ar gyfer modelu effaith newid hinsawdd ar ecosystemau dŵr croyw. Awgrymodd yr astudiaeth terfynau bod blaenddyfroedd ucheldir ac estyniadau afon ganol o bosibl yn sensitif i addasiad hinsawdd. Gall effeithiau amlygu eu hunain mewn amrywiol ffyrdd, gan gynnwys ymateb uniongyrchol i effeithiau a gyfryngir gan dymheredd a thrwy effeithiau anuniongyrchol yn y newid mewn llif afonydd. Amlyga'r astudiaeth hefyd botensial symudiad cydbwysedd yn yr ecosystem mewn ymateb i'r newid cystadleuol o fewn cymunedau dyfrol a'u rhywogaethau, er y byddai'r effeithiau hyn yn llawer llai pendant ac anos i'w rhagfynegi.

Roedd gan yr astudiaeth hon ddau nod: i adnabod y modd gorau o fodelu newid ecolegol dŵr croyw mewn cyrff dŵr dethol ac wedi hynny i ddarparu canfyddiadau rhagarweiniol yn ymwneud â'r effeithiau posibl mewn addasiad hinsawdd ar ecosystemau dyfrol penodol. Mae'r asesiad wedi cymhwyso rhai dulliau presennol a'u cyferbynnu â dulliau anghyfarwydd o fodelu hinsawdd, llif afon ac effaith ecolegol. Defnyddia'r dull symlach lif afon y dyfodol a thymheredd cysylltiedig ynghyd â modelau ecolegol ystadegol a ddatblygwyd o ddata arolwg maes (modelu empirig). Defnyddia'r dulliau mwy cymhleth fodel hinsawdd wedi'i leihau, ynghyd â dalgylch di-dor a modelau estyn-graddfa efelychiedig, i ddarparu data mewnbwn ar gyfer asesiad model cynefin pysgod ('niwlog'). Mae angen data maes ar gyfer y ddau ddull (gyda'r dulliau cymhleth angen cryn dipyn mwy), sydd yn gallu cyfyngu cryn dipyn ar eu cymwysiadau mewn ardaloedd gwan o ran data. Cyflawnwyd yn ogystal, dechneg sydd yn ehangu'r modelu i safleoedd eraill mewn rhanbarth â hinsawdd tebyg.

Ystyriodd yr adroddiad dri prif leoliad: rhan uchaf Wharfe; hydoedd afonydd canol Swydd Efrog yn fwy cyffredinol; a nentydd blaenddwr Tywi uchaf yng Nghanolbarth Cymru. Cymhwyswyd y dull di-dor mwy anodd i Wharfe, lle y datblygwyd model hydrolegol addas, a chymhwyswyd y dull empirig i weddill y safleoedd. Dewiswyd Wharfe oherwydd y data da oedd ar gael, adnabyddiaeth fanwl y tîm y prosiect ohoni a'i phwysigrwydd ecolegol. Dewiswyd ardal astudiaeth Tywi gan fod ganddi un o'r setiau data macroinfertebratau (anifail afon bychan) hwyaf a gorau ar gyfer afonydd ucheldir ym Mhrydain.

Yn achos Wharfe, canolbwyntiodd y dadansoddiad ar effaith newid hinsawdd ar lif afonydd a'r goblygiadau dilynol ar gyfer cynefinoedd eogiaid a brithyll brown. Yn safleoedd afonydd eraill Swydd Efrog, canolbwyntiodd y dadansoddiad yn bennaf ar yr effaith ar macroinfertebratau sy'n deillio o newidiadau i dymheredd a llif afonydd.

Y prif ganfyddiad pan yn ystyried y dulliau asesu oedd bod cofnod hirdymor o safon uchel yn hanfodol, megis data macroinfertebrat lefelau rhywogaethau. Mae amodau eithafol yn yriant pwysig mewn newid ecolegol (megis llifogydd a sychderau), ac mae gwybodaeth ddyddiol ac is-ddyddiol –yn hytrach nag ystadegau sypyn (llif afon cymedrig dros gyfnod o fis) yn ofynnol i wella modelau ymateb ecolegol. Ni all nifer o'r modelau a ddefnyddir yn bresennol ddarparu'r wybodaeth yma ac mae dulliau anos, megis yr un a ddefnyddiwyd ar gyfer yr astudiaeth hon, o bosibl yn fwy addas. Y sialens ydy medru ehangu'r canfyddiadau i ardaloedd mwy, gan fod y dulliau yn cymryd llawer o amser ac yn ddwys o ran data.

Mae'r canlyniadau ar gyfer asesiad effaith ecolegol o ddiddordeb. Yn gyffredinol, roedd cysylltiad gwirioneddol rhwng cymunedau macroinfertebrat a thymheredd afonydd. Awgryma'r astudiaethau, y byddai ymestyn y canfyddiadau hyn i'r dyfodol, lle gallai'r tymheredd cyfartalog fod 2–3^{o}C yn uwch erbyn y 2080au, y byddai cynnydd o'r fath yn fwy na'r ystod presennol a feddiannir gan rai rhywogaethau macroinfertebrat (canolbarth Cymru) a theuluoedd (Swydd Efrog) erbyn 2020. Newidia'r nifer o rywogaethau neu deuluoedd a effeithir gyda gwahanol fodelau ar gyfer hinsawdd y dyfodol, er hynny ceir cysondeb yn y duedd. Y canlyniad fyddai casgliadau macroinfertebrat yn yr amrywiol nentydd ac afonydd a ymchwiliwyd, gan gynnwys gostyngiad sylweddol mewn digonedd a/neu gyfoeth. Gallai hyn, yn ei dro, ddylanwadu ar y cymunedau a'r rhywogaethau a ddefnyddia'r macroinfertebrat fel adnodd bwyd, megis pysgod.

Awgryma canlyniadau rhan uchaf Wharfe, erbyn y 2050au, y gall fod dadleoliad gwahaniaethol o ran eog a brithyll brown o nentydd ucheldir ac afonydd, oherwydd newidiadau yn argaeledd eu cynefinoedd dewisol. Yn gynyddol, bydd llifau isel yn cael effaith gyfatebol ar gyflymder afonydd a dyfnder dŵr ac yn effeithio ar wahanol rywogaethau mewn amrywiol ffyrdd. Yn y rhannau a astudiwyd, byddai'r effaith hwn yn cael mwy o effaith ar eogiaid nag ar boblogaeth y brithyll brown, gyda'r canlyniad y bydd pwysau cyffredinol i symud i lawr yr afon. Bu i'r astudiaeth edrych ar newidiadau blynyddol mewn llifau isel, gallai dadansoddiad tymhorol awgrymu pa adegau o'r flwyddyn y byddai cynefin fwyaf cyfyngedig. Gallai tymheredd dŵr a'r effeithiau canlynol ar ddirlawnder ocsigen tawdd fod yn fwy o ffactor fyth o safbwynt effeithio ar addasrwydd cynefin, ond ni fodelwyd ef yn yr astudiaeth hon.

Ceir rhaeadr o ansicrwydd trwy bob cyfnod dadansoddol. Ni fesurwyd y lefel o ansicrwydd yn yr allbwn astudiaeth a dylid defnyddio'r canlyniadau o'r dulliau modelu a ddefnyddiwyd yn yr astudiaeth hon fel rhai archwiliadol. Er hyn, dengys yr astudiaeth bod nentydd ucheldir yn arbennig o sensitif i hinsawdd a ragfynegwyd i'r dyfodol. Mae cymunedau macroinfertebrat yn debygol o newid, gyda'r angen i adlewyrchu hynny mewn systemau monitro biolegol sydd wedi eu cynllunio i gefnogi rheoliad a chyflawni amcanion cadwraethol. Mae'n debygol y bydd gostyngiad mewn cynefinoedd addas ar gyfer rhywogaethau eogaidd sydd o bwys economaidd mewn ardaloedd blaenddwr.

Gallai strategaethau addasu gynnwys rheolaeth nentydd ucheldir i gynyddu gorchudd cysgodol â photensial i ostwng tymereddau eithaf. Gallai pwysau arall ar gynefinoedd ucheldir, megis tynnu dŵr, gollwng elifiant a llygredd tryledol hefyd gael eu gostwng er mwyn gwella gwytnwch ecosystemau.

Mae angen ymchwil pellach er mwyn asesu sensitifrwydd mathau eraill o gyrff dŵr i hinsawdd, mewn gwahanol ranbarthau a hefyd i benderfynu sensitifrwydd rhywogaethau dŵr croyw yn genedlaethol i hinsawdd.

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1 Introduction

1.1 PRINCE: project background and aims

The project ***Preparing for Climate Change Impacts on Freshwater Ecosystems*** (PRINCE) was jointly commissioned by the Environment Agency, English Nature and the Countryside Council for Wales.

The broad aims of the project were to:

- review current information and understanding on the implications of climate change for freshwater ecosystems;
- inform a wide range of policies;
- communicate an improved understanding of climate change impacts; and
- apply this to a projection of consequences.

The study's accompanying report, entitled *Literature review and proposal methodology*, contained a literature review and proposed a methodology (Conlan *et al*. 2005). The main finding of the study was that the potential for climate change impacts on freshwater ecology remain highly uncertain. There are likely to be direct changes in biological response, particularly to temperature change, and a number of indirect impacts, as a result of changes in hydrology and the consequent availability of water. The report identified, through qualitative analysis, those freshwater ecosystems most sensitive to climate change, highlighting upland catchments as particularly at risk.

The specific objectives of the research described in this report are to determine the potential for climate change impacts on freshwater from both direct climate-mediated effects (such as temperature) and from the effects of changed weather on catchment hydrology, with consequent implications for habitats, communities and species. Upland and middle reaches of rivers were selected and sites were chosen in two different regions – Yorkshire and Wales – to explore different climate impacts. These areas were selected on the basis of available data to support the ecological modelling.

1.2 General approach

To achieve the project objectives, a number of hydrological and ecological modelling approaches could be adopted, ranging from simple factoring to complex mathematical simulations. In order to describe potential future climate change impacts, it was necessary to establish the most suitable modelling framework from the various options. A number of approaches were assessed:

- hydrological and hydrodynamic models (direct modelling or generic scaling factors derived from modelling);
- ecological models (data-derived or process-based).

A key output of the study has therefore been to identify the most suitable modelling approaches and to describe their relative use for future climate impact assessments (see Section 2 for detailed descriptions). The modelling approaches used in this study are suitable for local and potentially regional.scale assessments; they are less useful for a strategic level view of impacts on freshwater ecosystems but can help with consent setting, reviews of abstraction licenses, and POMs under the WFD.

Having defined the modelling approaches, they were then applied to rivers in mid-Wales and Yorkshire. The modelling framework has had to be sufficiently flexible to encompass the range of available data for each of the regional approaches. The full suite of studies for each region is described in Section 2.3. The studies' findings took the relative utility of each modelling approach into consideration.

To explore climate change impacts at all sites, one specific future emission scenario (medium-high emission scenario) was selected from the UK Climate Impacts Programme (UKCIP) and this was used to run two general circulation models (GCMs; HadCM3 and CGCM2). Statistical downscaling of the meteorological climate change data was undertaken using a statistical downscaling model (SDSM) (Wilby *et al.* 2002, 2003), in order to generate realistic future weather patterns and data suitable as model inputs. Details of the climate scenarios are given in the methodology (Section 2.2). Although it is desirable to use more than one emission scenario in any climate impacts study (Hulme *et al.* 2002), it was not practicable to use more than one scenario in this study because the more complex models take too long to run. However, using two GCMs helps illustrate some of the variability in the results, as the choice of GCM can often be the greatest source of uncertainty in climate impacts modelling, particularly up to 2050. There is also some evidence that current temperatures in the UK are tracking the medium-high emissions scenario (Hadley Centre 2005).

The nature of the modelling exercise inevitably means dealing with uncertainties, ranging from the climate data to the parameterisation of models and extrapolation of the predicted impacts to the freshwater ecosystem. It should therefore be recognised that large uncertainties in the data and simulations are inherent in the predictions. The results should be interpreted as providing an indication of the possible future impacts of climate change and giving a possible direction of change rather than an absolute impact.

1.3 Report structure

Section 1 introduces the objectives of the study, the general approach adopted and the structure of the report.

Section 2 presents summaries of the methods used in the five modelling approaches that were applied to either the middle reaches of rivers in Yorkshire and/or to headwater streams in Wales. These approaches are: (1) fully-distributed hydrological modelling using a conceptual deterministic approach (CAS-Hydro); (2) a transfer function approach to applying the results from CAS-Hydro to other rivers within the Yorkshire region; (3) a transfer function approach that was developed for application to all rivers in the UK (Arnell, 2003); (4) statistical modelling of invertebrates using an empirical data-driven approach known as climate invertebrate optima (CLIO) modelling; and (5) fuzzy modelling of fish populations. In addition, the project considered the use of several other modelling approaches, which are also summarised in this report. Detailed descriptions of all the methods are contained in the appendices.

Section 3 describes the modelling results for the UK HadCM3 GCM used in the current UKCIP02 climate futures studies (Hulme *et al.* 2002). Results for an alternative future, modelled using the Canadian GCM CGCM2, have been included for comparison.

Section 4 discusses the implications of the modelling results for the studied freshwater ecosystems and the possibilities and limitations of modelling hydro-ecology interactions and climate change impacts at other locations.

Section 5 presents the study's conclusions and recommendations.

Appendix 1 describes semi-distributed hydrological models that were explored but not used in this study (LowFlows2000, PDM and CatchMod).

Appendix 2 details the calibration of CAS-Hydro for the River Wharfe.

Appendix 3 presents predicted future flows in mid-Wales headwater streams using the Arnell flow factor methodology.

Appendix 4 presents predicted future flows in Yorkshire rivers using the Arnell flow factor methodology and reviews the methodology.

Appendix 5 details the methodology used in generating regional flow factors to extend the application of the detailed modelling (CAS-Hydro) in one catchment to others in the region.

Appendix 6 details the methodology used in modelling fish habitat.

Appendix 7 details the methods used to create future climate scenario data.

Appendix 8 lists the future flows generated at Hubberholme by fully-distributed modelling (CAS-Hydro) using continuous simulation.

2 Methodology

2.1 Introduction

The options available for modelling climate change impacts on freshwater ecosystems have been discussed in the study's earlier report *Literature review and proposal methodology* (Conlan *et al.* 2005). A number of modelling approaches are available to investigate impacts on rivers and streams, either through application of existing methods or through development of novel methodologies (based on emerging catchment modelling techniques). The choice of locations to test these different approaches is largely determined by data availability for model calibration and verification.

This study comprised two key elements:

i) consideration of the most suitable hydrological methods for describing both existing conditions and climate-changed futures;

ii) development of ecological impact models that can simulate the effects of changes in climatic and hydrological conditions on specific habitats, communities and/or species.

2.1.1 Hydrological modelling approaches

A number of hydrological approaches have been considered for generating future flow data to drive the ecological models, with the simplest option involving the use of Arnell flow factors (Arnell 2003). These are regionally-based and use-averaged river flow data for predicting possible future flows as a 'factor' of the existing flow hydrograph. They are widely applied and simple to use, but of necessity do not account for all the variability in the predicted flows and are currently available only up to the 2020s. These flow factors were applied in the upper Afon Tywi catchment in mid-Wales (see Section 2.3.1) and were evaluated against the other hydrological methods in Yorkshire rivers (see Section 2.4.1).

More complex models include the semi-distributed hydrological models commonly used by the Environment Agency, such as PDM, CATCHMOD and LowFlows2000. These models produce flow statistics, but not time series of data (such as the long-term hydrograph). LowFlows2000 is also not yet available for generating future flows. In addition, PDM and CATCHMOD have only been calibrated for a selected number of catchments and the project team did not have access to high resolution biological data for any of these catchments (see Appendix 1 for model descriptions). In principle, these models could be used in this kind of study, but with the proviso that they do not generate time series output. This means that the duration and sequencing of flows, especially extreme events, will not be captured. However, extreme events are likely to be important ecosystem response drivers and this potential limitation must be carefully considered in any future use of these semi-distributed approaches. None of these methods has been considered further in this study.

A more complex fully-distributed hydrological model (CAS-Hydro) has been developed and was available for this study. It has the advantage of being able to produce realistic continuous simulations of river flow, temperature and other abiotic parameters, although it is resource intensive and takes some time to run long-duration simulations of large catchments. The upper River Wharfe was chosen as the exemplar system because much of the data necessary for this kind of modelling approach was available for this river. Further details of the model and the approach are given in Section 2.4.2. CAS-Hydro could not be applied to the upper Afon Tywi catchment because of a lack of suitable river flow gauge data to validate the model output.

CAS-Hydro was further employed to derive empirical transfer functions, based on continuous flow simulations (see Section 2.4.3). The purpose of this work was to extrapolate the findings of the detailed catchment simulation to a greater number of corresponding regional catchments, potentially widening the utility of the approach. The findings of this study were compared to the Arnell factors to assess their compatibility/advantages.

2.1.2 Ecological modelling approaches

Two general ecological modelling approaches were considered for this project.

(1) Using ecological response models of macroinvertebrate communities, based on actual *monitored* community changes over time, and projecting further changes into the climate-changed future.

(2) Using the output from complex climate and hydrological models, which describe future climatic conditions and their resultant hydrological responses, as inputs to an assessment of changes to selected habitats, communities and/or species.

Approach 1 is an empirical, data-driven approach that integrates both abiotic (flows, temperature) and biotic (ecological requirements) factors. It relies on the use or development of models of historic and existing ecosystem function and response, which are then applied to projected trends in the future. However, few models exist that can effectively describe responses to climate drivers. This is due to a poor understanding of exactly which elements (such as flow or temperature) are important in driving ecological response. Opportunities to expand this understanding are currently restricted by the limited availability of biological monitoring data at sufficient spatial and temporal resolution. Data from mid-Wales and Yorkshire represent some of the most useful long-term macroinvertebrate datasets and these have been used to develop the models for this study (see Sections 2.3.2 and 2.4.4 respectively).

Approach 2 is a deterministic modelling approach, in which the CAS-Hydro catchment-scale model of abiotic parameters (meteorology, landscape character and inter-connected channel network) is linked to river channel characteristics (wetted width, wetted depth, flow velocity, bed substrate) and applied to evolving ecological models. These ecological models rely on existing descriptions of the habitat preferences of communities and/or species (such as fish, macroinvertebrates). Changes in habitat availability and suitability can then be projected forward and increases/reductions in habitat availability can be simulated (see Section 2.4.5). At present, the CAS-Hydro model has been calibrated and verified for the upper River Wharfe, for which there is also high resolution topographical survey data and an extensive ecological data archive. The complex ecological modelling approach has therefore been undertaken for this catchment only.

As it is considerably more complex, this approach requires significantly greater computational power and good quality datasets for calibration and verification. Nevertheless, it must be stressed that, at this time, this approach can only simulate some and not all of the drivers of community change. These limitations mean that model outputs should be viewed as potential trends and directions rather than as absolute changes.

The overall modelling approach is described schematically in Figure 2.1 and was applied to a selection of sites in Yorkshire and Wales. Section 3 briefly describes the methods used in the two study regions, and the benefits and limitations of the models and biological datasets. A full explanation of the methodologies is presented in the referenced appendices.

A level of uncertainty is associated with the use of the measured and modelled data. Measured data have uncertainty due to a number of factors, including:

- measurement accuracy;
- data record length, frequency and completeness;
- transferability – the suitability of using site-specific measured data as representative of conditions at other locations;
- data aggregation techniques used to collate summary statistics for input to the macroinvertebrate empirical model.

Modelled data have uncertainty due to factors that include:

- model representation of key processes;
- input data quality;
- transferability – the suitability of using site-specific modelled data as representative of conditions at other locations;
- data aggregation techniques for collating summary statistics, which are then used as inputs into the macroinvertebrate empirical model.

There is a cascade of uncertainty through each analytical stage. No quantification of the level of uncertainty in the study output has been undertaken and the results from the modelling approaches used in this study should therefore be viewed as exploratory.

2.2 Generation of future climate data

For the purposes of this study, the majority of the climate change predictive work was undertaken for the Yorkshire sites. This was done to take advantage of the increased complexity and data simulation capability of the fully-distributed catchment scale CAS-Hydro modelling framework. The continuous simulation capacity of the model is ideally suited to analysis of long-term downscaled data inputs, as described below. The Welsh study was undertaken using Arnell flow factors, which do not utilise future climate data, although the temperature data were simulated using SDSM, as for the Yorkshire sites (see below).

Projections of climate change impacts on the UK environment are couched within uncertainties about future emissions of greenhouse gases, imperfect understanding of climate science, the character of natural variability and the robustness of impacts models. However, uncertainty about future emissions has very little influence on uncertainty about climate change until the latter half of the 21st century. Greater uncertainty is more immediately apparent in the choice of GCM used.

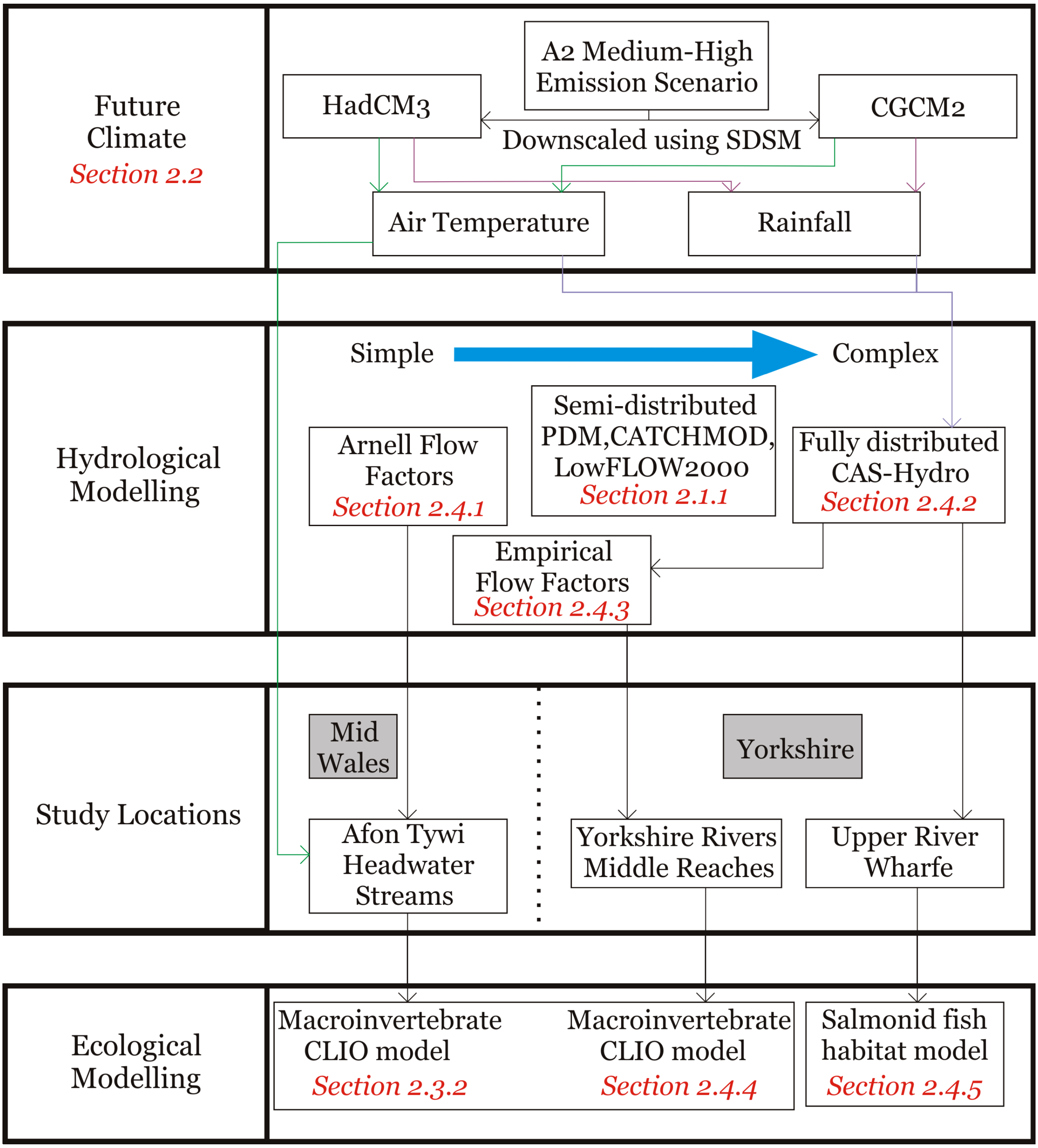


Figure 2.1 Summary of project modelling approach

This study has utilised one future climate emissions scenario (A2, medium-high), which was selected from the UK Climate Impacts Programme (Hulme *et al.* 2002), and two GCMs to capture some of the uncertainty. These models produce large-scale (regional) projections of climate change, which then need to be downscaled to specific UK regions and the required daily time-step for use in impact studies. Statistical downscaling was undertaken using SDSM v3.1 (Wilby *et al.* 2002, 2003), which is freely available and readily implemented.

The SDSM archive contains a set of daily predictor variables (such as atmospheric circulation, stability and moisture content at several levels in the atmosphere) that are used in model calibration and downscaling at a regional scale. Equivalent predictor variables are provided for four GCMs (including the UK HadCM3 model and the Canadian CGCM2 model) for different emission scenarios. These are based on possible future greenhouse gas emissions linked to different economic conditions (SRES 2000). Only one SRES (Special Report on Emissions Scenarios) storyline was selected: A2 medium-high emissions scenario. The SDSM requires calibration with daily recorded data during the period 1961–1990 (minimum of 10 years data recommended). Future prediction is continuous to 2099, and therefore includes the 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099).

Full details of the methodology are contained in Appendix 7. The resultant rainfall and temperature data were then used as inputs to the CAS-Hydro modelling framework, while temperature data was also inputted directly into the macroinvertebrate empirical modelling.

The majority of the following report, including the results, conclusions and recommendations, uses analysis based on the outputs of the HadCM3 modelling. This is because the HadCM3 simulations are the most widely applied in UK studies to date, and can therefore contribute to comparative assessments. However, the relative implications of the HadCM3 and CGCM2 simulations are considered in Section 3.5, which describes the similarities and differences in the various modelled outputs.

2.3 Methodology for assessing impacts of climate change on mid-Wales headwater streams

The upper Afon Tywi has one of the longest continual macroinvertebrate datasets available in the UK, which was collected by Cardiff University. This river was therefore selected to test the empirical data-driven ecological modelling methodology. However, there is no suitable nearby gauging station, which means that there is a limited flow record for the river in this area. It was therefore decided to apply the Arnell flow factor methodology to derived flows established from an adjacent catchment. The CAS-Hydro model was not used, as no suitable validation data were available; similarly, there were no calibrated semi-distributed models that could be adapted.

The steps followed in determining the impacts of climate change on mid-Wales headwater streams are outlined in Table 2.1and Table 2.2.

Table 2.1 Data used for the mid-Wales headwater streams investigations

Methodological approach	Sites investigated	Air temperature data used		River flow data used		Ecological data used
		Present	Future	Present	Future	Present
Empirical data-driven CLIO approach linking data on macroinvertebrate assemblage composition to hydrological input data	Upper Tywi headwater streams, mid-Wales	Recorded data from a local meteorological station	Modelled for the local meteorological station	Recorded data from a river flow gauge in an adjacent catchment	Projected flow statistics using Arnell flow factors	Field survey macroinvertebrate dataset from 14 sites

Table 2.2 Research framework to assess impacts of climate change

Location	Habitats investigated	Abiotic factors investigated	Suitable model	Model runs	Indices
• Upper Tywi, mid-Wales	• Headwaters (upland catchment)	Discharge	Flow factors	1980–2004 2020s climate 2050s climate	Q_5, Q_{10}, Q_{30}, Q_{50}, Q_{70}, Q_{90}, Q_{95} with seasonal pattern
		Air temperature	Empirical		Daily average (mean monthly)

2.3.1 Generating of future flows in mid-Wales headwater streams

In order to encompass uncertainty, the Arnell (2003) methodology identifies a range of characteristic scenarios for the 2020s. Each of these scenarios has been developed from semi-distributed modelling of representative catchments using the HadCM3 A2 (medium-high emissions) future climate model. For each scenario, a set of perturbation factors are available that can be applied to estimate changes in monthly flows from a pre-climate change period (1970s) to the 2020s. The scenarios are low, medium, high, cool and wet, warm and dry, and two anomalies (A and B) to address natural variability.

There has been no continuous river flow measurement in the Upper Tywi upstream of Llyn Brianne. Gauged flow data from the Plynlimon flow gauging station (CEH, Hafren flume; NGR: SN853872), which is less than 40km to the north and on headwater streams of near identical order and altitude, were assumed to reflect trends in the upper Tywi. This assumption was supported by validation against a gauging station on the Afon Cothi (NGR: SN508225), in an adjacent sub-catchment of the Afon Tywi system ($r = 0.89$, $n = 289$ monthly mean values, $P < 0.0001$).

Baseline and future flow exceedence statistics were developed from the 1969–1989 daily average discharge record at Plynlimon flow gauging station. These statistics cover the typical flow envelope (based on percentiles): Q_{95} (extreme low flow), Q_{90} (low flow), Q_{70}, Q_{50} (median flow), Q_{30}, Q_{10} (high flow), Q_5 (extreme high flow). These data were collated into monthly values for each of the 1970s and 2020s periods.

2.3.2 Statistical modelling of macroinvertebrates in mid-Wales headwater streams

The methodology adopted here involved three steps.

i) Determining the parameters of variation in macroinvertebrate character (assemblage composition, abundance, stability, rarity measures) among sites and years either directly or using ordination (such as canonical correspondence analysis).

ii) Developing transfer functions that relate macroinvertebrate character (ordination score, abundance, stability, rarity measures) to hydrometerological drivers (high flow, low flow, temperature) using regression and multiple regression.

iii) Driving the resulting models using new input meteorological and hydrometric data representing future climate scenarios for the 2020s and 2050s.

Streams at the upper Tywi experimental catchments were first sampled in 1981 and 1982 by Stoner *et al.* (1984) and then from 1985–2005 (except 1991) by Cardiff University using identical quality assured methods (Bradley and Ormerod 2002).

The 14 upper Tywi sites from the Llyn Brianne experimental catchments are clustered around Llyn Brianne reservoir in the upper catchment of the Afon Tywi in mid-Wales (Figure 2.2).

Streams in the upper Tywi are upland (300–400m), with mean pH 4.9 to >7.0 (see Table 2.3 and Figure 2.3).

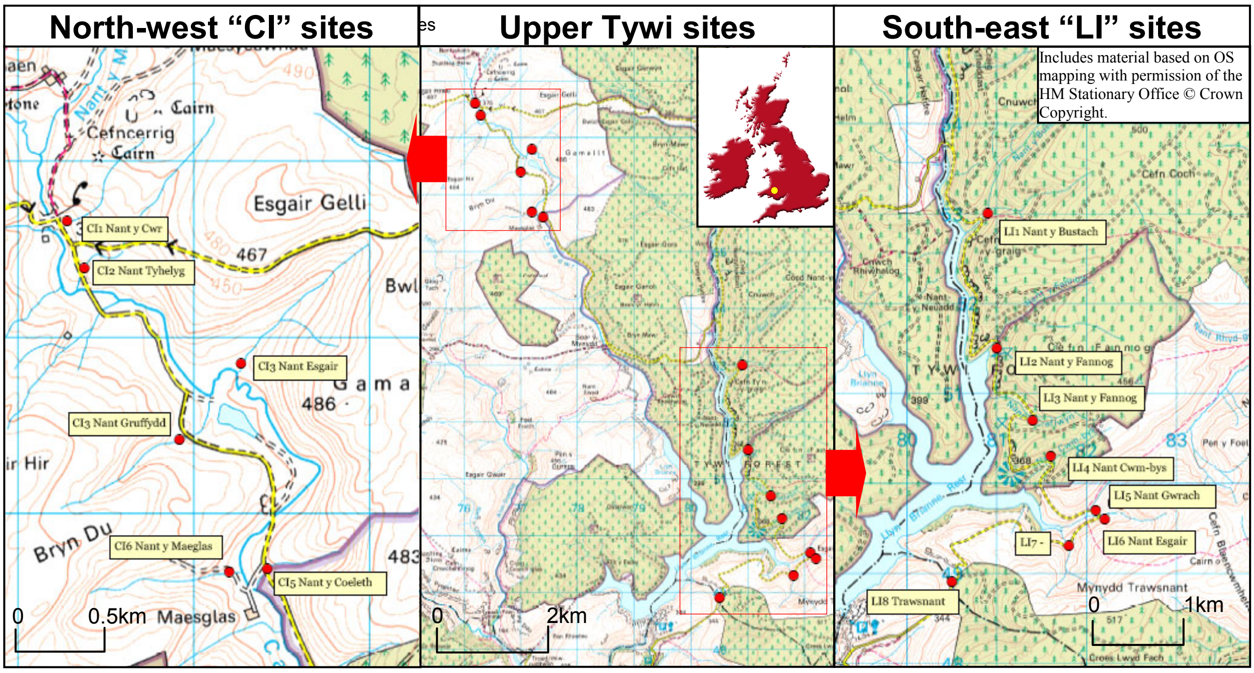


Figure 2.2 Location of the upper Tywi sites

From 14 sites available in the upper Tywi, three replicate pairs were selected (acid forest pH 4.9–5.4 (sites LI1 and LI2); acid moorland pH 5.2–6.0 (sites CI1 and CI4); circumneutral moorland pH > 6.9 (sites LI6 and LI7) (see Bradley and Ormerod 2001)) to eliminate the confounding effects of acid-base status and previous experimental manipulation (such as lime addition and forest clearance). Biological data were averaged across each replicate pair prior to further analysis. Equivalent sampling effort during validation exercises in both 1990 and 2001 collected on average over 90 per cent of all but the rarest taxa present in the upper Tywi streams. Results were consistent between different samplers.

Table 2.3 Key attributes of the upper Tywi dataset used in modelling climatic effects on biota

Parameter	**Upper Tywi**
Altitude	300–400m
Study area	300km^2
Main stream range	Acid-base status
Number of sites retained	Three replicate pairs (from 14 original sites)
Length of calibration run	1981–2005 (not continuous)
Source of data	Cardiff University*
Invertebrate sampling	Kick-samples undertaken during spring
Composition	102 species/species groups (recorded in abundance)
Samples	3 x 21 annual samples
Contextual physico-chemistry	Winter pH/Al
Climatic predictors examined*	Winter temperature (four months preceding the spring macroinvertebrate sampling), winter discharge, previous summer discharge NAO index (December to February)
Biological response variables	Assemblage composition richness, regional rarity index, stability, total abundance

Notes: ‘Winter’ is typically October–March directly preceding sampling; ‘summer’ is April–September inclusive. *Except for 1981–82, taken from Stoner et al. (1984) using identical methods.

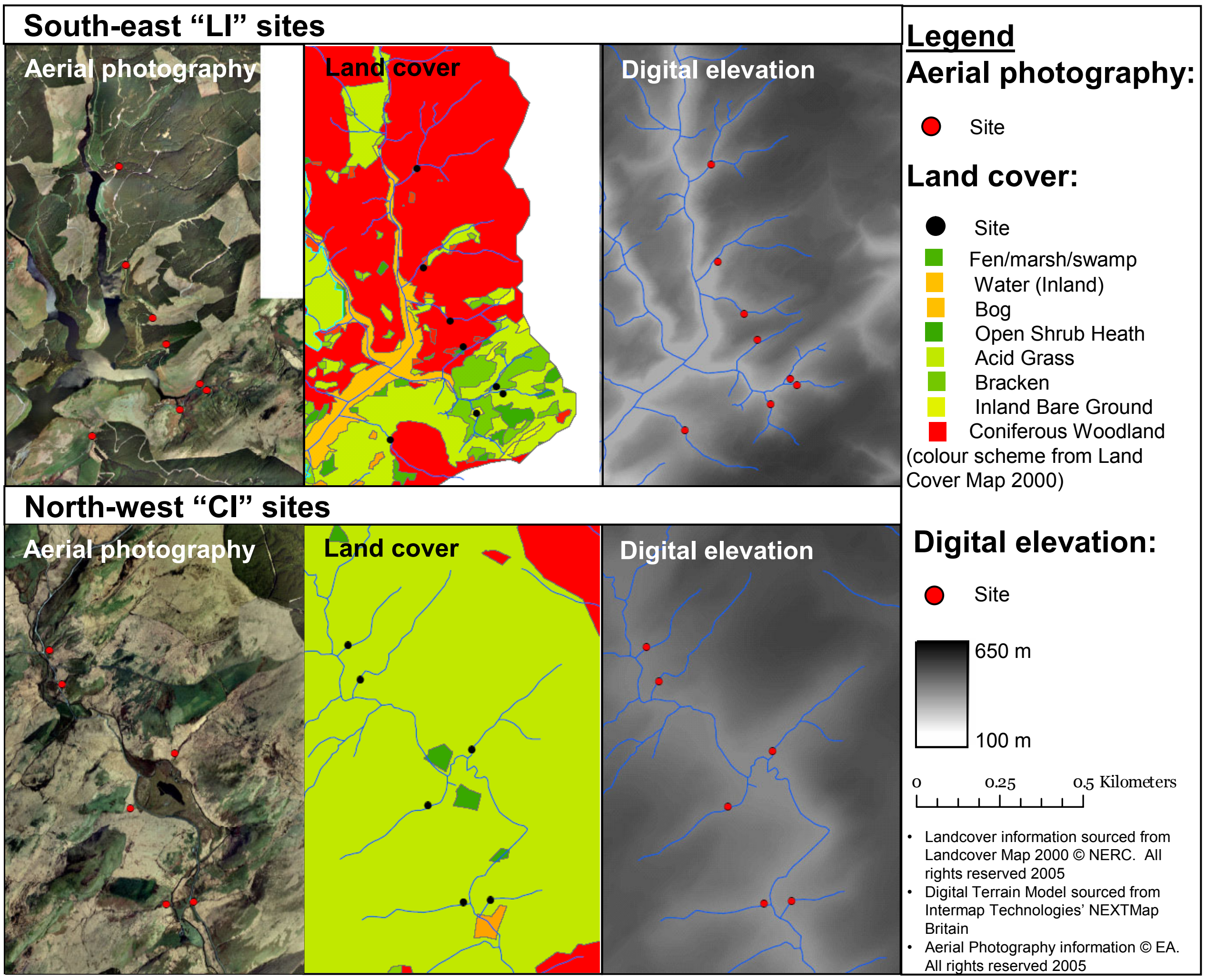


Figure 2.3 Characteristics of the Upper Tywi sites

Biological data

Macroinvertebrate data for the upper Tywi sites were collected in spring (April). Sampling procedures were similar and standardised within each set (three minutes kick-sampling across habitats; Weatherley and Ormerod 1987). Macroinvertebrates were recorded as absolute abundances for each species or species-group.

In addition to abundance and assemblage composition, the study considered stability (=similarity) from year-to-year and rare taxa. Stability was measured as Jaccard indices:

$$J=c/(a+b-c)$$

where a is richness (the number of taxa in a sample) in the preceding year, b is richness in the current year and c is the number of taxa in common. For the upper Tywi sites, a regional rarity index was derived from the percentage frequency of occurrence of each species in the 1984 and 1995 Welsh Acid Waters Survey (WAWS) data (Stevens *et al*. 1997). Rarity values for each species ranged from 1 (rare) to 100 (common/widespread) and a regional rarity (RR) index was derived for each sample as follows:

$$RR=100 - M/N$$

where M is the sum of rarity values for all species in the sample and N is richness.

Physico-chemical data

Physico-chemical data were required for model development because factors other than climate can affect invertebrates. These contextual data might also indicate the types of sites most sensitive to climatic impacts. Upper Tywi sites are generally similar in physical character, but their acid-base status varies through time. Mean pH and aluminium concentrations were calculated during each winter prior to sampling in order to examine any trends that might potentially confound effects ascribed to climate (6–12 samples per site/ year).

The climate variables

April samples collected at the upper Tywi sites were expected to reflect climatic conditions in the immediately preceding winter (for instance, discharge/ temperature during larval development), but effects from the previous summer were also possible (for instance, egg laying (oviposition) and early egg/larval development). Climatically-related variables were then derived, where possible, as means for three-, six- or 12-month periods preceding each invertebrate sample. These variables are detailed below.

i) A range of flow statistics, from extreme low flow to extreme high flow, were generated for the 2020s using the Arnell flow factor methodology. To address inter-annual variation and seasonality, these flow statistics have been calculated for six-month and 12-month periods, commencing at the beginning of the hydrological year (1 October) or mid-hydrological year (1 April).

ii) Monthly average air temperature data were provided by the British Atmospheric Data Centre (BADC) for the Aberporth meteorological station, which is located 50km west of the Upper Tywi. These air temperature data have been adjusted for the altitude of each of the macroinvertebrate sampling sites. Antecedent temperatures were derived from these data, aggregated over four months prior to biological sampling. The process of estimating stream temperature from air temperature is affected by groundwater contributions, evaporative cooling, thermal mass and local shading (Caissie 2006). Local air and stream temperature data were used to factor Aberporth data in order to represent the study sites. Monthly air temperature explained 85–95 per cent of the variation in stream temperature, with slopes of 0.94–0.97 and intercepts at 0.5–0.67°C for moorland site CI6 (see Figure 2.2) and an adjacent mixed forest and moorland site on the Afon Tywi. A lower slope (0.78) and greater intercept (1.6°C) described the air–stream temperature relationship in the afforested LI1 site (see Figure 2.2), reflecting shading and heat exchange effects under a forest (Weatherley and Ormerod 1990, Caissie 2006).

iii) The North Atlantic Oscillation (NAO) winter index (December–March inclusive; after Hurrell 1995) was investigated prior to each biological sample (http://www.cgd.ucar.edu/cas/jhurrell/indices.html). The NAO affects UK weather, with marked consequences for river discharge, temperature and river ecology (Bradley and Ormerod 2001). The 'smoothed' NAO index was also investigated, and corresponded to mean winter index over the three preceding years. Cumulative NAO effects across years might arise: if there were prolonged positive or negative phases over several years; if effects on run-off quality or quantity were cumulative across years; or if invertebrate survival or emergence patterns in one year affected recruitment and assemblage composition in subsequent years.

2.4 Methodology for assessing the impacts of climate change on Yorkshire rivers

The climate change impacts for Yorkshire rivers were investigated using three different methods for generating future flows.

- Arnell flow factors for upper and middle reaches of a number of Yorkshire rivers.
- Continuous simulation of flows for the upper River Wharfe using CAS-Hydro.
- Regional flow factors developed from the CAS-Hydro outputs.

The steps followed in determining the impacts on Yorkshire rivers are outlined in Figure 2.4, Table 2.4 and Table 2.5.

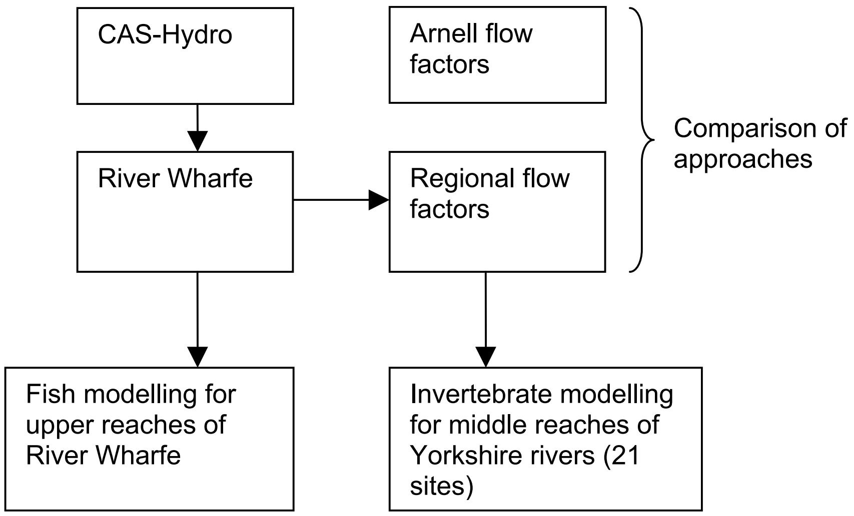


Figure 2.4 Steps taken in the study of climate change impacts on Yorkshire rivers

Table 2.4 Summary of data used for River Wharfe and Yorkshire region studies

Methodological approach	Sites investigated	Air temperature data used		River flow data used		Ecological data used
		Present	**Future**	**Present**	**Future**	**Present**
Empirical data-driven CLIO approach linking data on macroinvertebrate assemblage composition to hydrological input data	Middle reaches of Yorkshire rivers	Recorded data from regional meteorological station	Modelled for the regional meteorological station	Recorded data from 20 flow gauges, each in the locality of a macroinvertebrate survey site	Projected flow statistics using flow factors and empirical transfer functions	Field survey macroinvertebrate dataset from 20 sites
CAS-Hydro mathematical modelling linked to a hydraulic model and fish habitat preference data	Upper River Wharfe, Yorkshire	Recorded data from a local meteorological station	Modelled for the local meteorological station	Recorded data from river flow gauge in the study catchment	Modelled continuous flow record; input air temperature and rainfall data modelled for the local meteorological station	Fisheries habitat preference data

Table 2.5 Research framework to assess impacts of climate change

Location	Habitats investigated	Abiotic factors investigated	Models	Model runs	Indices	Assemblages investigated	Biotic data
Yorkshire rivers	Headwaters	Discharge	Flow factors	1990–98 2020s climate 2050s climate	Q_{10}, Q_{90}, Q_{95}	In-channel benthic macro-invertebrates	Environment Agency annual macroinvertebrate survey across 19 sites 1990–1999
	Middle reaches of river	Air temperature	Empirical		Daily average (mean monthly)		
Upper River Wharfe, Yorkshire	Headwaters and upper river	Discharge; flow velocity, wetted depth, temperature	CAS-Hydro linked to a hydraulic model	2020s climate 2050s climate	Continuous simulation of flow (full hydrograph) including seasonality, extremes, averages, duration and periodicity	Fisheries	Salmonid habitat preferences

2.4.1 Arnell flow factor methodology for generating future flows in middle reaches of Yorkshire rivers

The same methodology adapted for mid-Wales (see Section 2.3.1) was applied in Yorkshire. A total of four scenarios were used: the ‘cool and wet’ and ‘warm and dry’ scenarios and the two types of anomaly (A and B) to encompass the range of uncertainty. For each scenario, a set of perturbation factors are available for estimating changes in monthly flows from a pre-climate change period (1970s) to the 2020s.

River flow gauging stations, providing long-term flow data and in close proximity to the macroinvertebrate sampling sites, were selected. This gave 19 sites (see Appendix 4) with monthly values for the range of flow exceedence statistics for each of the 1970s and 2020s periods. These data were used as inputs into the macroinvertebrate modelling studies.

2.4.2 Continuous simulation modelling on the River Wharfe using CAS-Hydro for generating future flows

The Upper Wharfe in the Yorkshire Dales National Park was selected as the location for evaluating the conceptually-driven deterministic modelling approach. The catchment area is large for this kind of study, at 72km^2. In recent decades, the catchment has experienced the generation and transport of large volumes of coarse sediment, severe bank erosion, increased incidence of downstream flooding and water quality deterioration (Reid 2004). Previous work has synthesised the hydrological, aerial photography, laser altimetry and channel survey data for the proposed modelling. The Upper Wharfe is of significant ecological importance: parts of the upper floodplain area are designated a site of special scientific interest (SSSI) and the river itself is designated a SSSI. The river includes short reaches of limestone pavement, with associated mosses, some higher plants typical of lowland rivers and bankside reeds. There is also herb-rich grassland, a range of sedges (including nationally rare examples) and important birdlife (such as the dipper and kingfisher).

The study involved adapting the UKWIR (UK Water Industry Research)-sponsored CAS-Hydro hydrological model, which is a fully distributed catchment-scale hydrology model and is described in detail in UKWIR (2006). The model currently includes:

i) a fully-distributed hill-slope rainfall run-off and river channel network model;

iii) capability to include downscaled climate scenarios;

ii) routing of the generated flow through the drainage network to floodplain zones;

iv) partitioning of the flow between river and floodplain;

v) modelling the spatial patterns of floodplain inundation;

vi) modelling the spatial patterns of in-stream salmonid habitat using habitat suitability curves.

In order to apply CAS-Hydro to the Upper Wharfe, a site was selected for which good calibration data were available. The Oughtershaw catchment covers an area of approximately 16km^2 with no flow management or significant abstractions or discharges. Model calibration was undertaken with respect to the Environment Agency gauge at Oughtershaw (NGR: SK818866). Extensive measurements of the characteristics of this gauge have been undertaken, including a full extrapolation to higher flows based on cross-section geometry. Its only real weakness is that it tends to underestimate particularly low flows (Q_{95} and lower). Detailed descriptions of the calibration process are given in Appendix 2

Once the study had generated a satisfactory set of model predictions for Oughtershaw, the model was extended downstream to Hubberholme, which is a key biological modelling site for macroinvertebrates and fisheries, assuming that the same parameter values held. This was a reasonable assumption for this area. The only major change was the growing influence of limestone upon the catchment hydrology. However, observations suggest that most of the loss of water to groundwater was temporary, and that the surface water flow was not particularly sensitive to this change.

Once the model was fully calibrated, it was run for the baseline 1970s period to confirm that the model predicted historic conditions accurately. Finally, the model was run for two different future scenarios, in order to compare outputs from GCMs and assess the variability between two different treatments of climate processes. The HadCM3 model was run to 2099 (encompassing the 30 year time-slice of the 2080s) and the Canadian CGCM2 was run to 2069 (encompassing the 30 year time-slice of the 2050s). CAS-Hydro was run continuously with a variable time-step, which is more efficient in model run time. Nevertheless, for the spatial resolution that the model was run at, it still took three weeks to complete a 90-year run.

The study needed to use the CAS-Hydro downscaling method to disaggregate the daily output from SDSM to the sub-daily time-step. To test the effects of this, the study compared a model run from a tipping bucket rain gauge within the catchment with a model run from the rainfall generator. High flow percentiles (Q_{30} and higher) were found to be particularly sensitive to this kind of temporal downscaling, emphasising the need for high resolution temporal data for future rainfall.

2.4.3 Regionalisation of results: empirical flow factor transfer functions for generating future flows in middle reaches of Yorkshire rivers

The main limitation with CAS-Hydro is that it only provides information for one catchment. In order to generalise these results to other catchments within the same region, measured correlations between flow percentiles at sites across Yorkshire were calibrated with those modelled at Oughtershaw and used as a basis for comparison. The method is explained in Appendix 5 and utilises empirical transfer functions based on measured correlations between flow percentiles at sites across Yorkshire and those modelled at Oughtershaw.

The method is similar in principle to the Arnell flow factor method (section 2.1.4), which also seeks to transfer knowledge from a modelled catchment to a series of unmodelled catchments. It differs in that:

- its underlying basis is a model based upon continuous simulation;
- it can provide an indication of flows beyond the 2020s;
- it yields information for each flow percentile of interest;
- it is based on information aggregated from the daily level rather than the monthly level.

The focus of this method is the same Yorkshire catchments used for the Arnell flow factor analysis, in order to be able to map onto the ecological modelling described in Section 2.4.4.

2.4.4 Statistical modelling of macroinvertebrates in the middle reaches of Yorkshire rivers

An empirical modelling approach has been developed to link data on macroinvertebrate assemblage composition to hydrological input data for the River Wharfe, representing river middle reaches, using invertebrate data from the Environment Agency. Historic data have revealed that climate and hydrological responses are major drivers of invertebrate variation (Bradley and Ormerod 2001).

The specific aims of the biological data investigation were to:

i) relate significant variations in invertebrate character (abundance, composition, stability, rarity) to existing climatic variations between years;

ii) derive empirical models (such as transfer functions) that can predict invertebrate variation in response to climate;

iii) simulate future variations among invertebrates under climatic conditions predicted by different GCMs.

Steps i) and ii) sometimes required that other major physical influences on invertebrates (such as channel dimensions and bed substrate) between sites be incorporated into the analysis and model development.

To achieve these specific aims, the study used a combination of different statistical methods. The relationships between invertebrate characteristics and potential predictors were assessed by correlation, while stepwise regression or multiple regression were utilised to derive empirical relationships from which climatic effects could be predicted.

While regressions for abundance, richness or rarity provided a straightforward means of empirical modelling, regression analysis is more difficult to conduct with assemblages of organisms in which many different species vary concurrently. A key need in modelling invertebrate assemblages is thus to reduce this varied composition to univariate scores that can form a basis for prediction. Unconstrained ordination was accomplished using detrended correspondence analysis (DCA), which is a simple, flexible and well established method for this purpose (Van Der Maarel 1969). There are close parallels, for example, to the derivation of River Invertebrate Prediction And Classification System (RIVPACS) and the National Vegetation Classification (NVC).

DCA uses reciprocal averaging to order samples objectively according to the frequency of co-occurrence among their constituent taxa (usually species). Sample scores reflect the turnover in species composition of a family along a sequence of orthogonal axes, such that four standard deviations represent a 100 per cent change in the composition of any one axis. Scores can then be related quantitatively to attributes of the sample or sample conditions. The resulting relationships allow the ordination score to be predicted under new conditions, which in turn allow species composition to be inferred. Because species are ordinated simultaneously with samples, ordination axes allow the assessment of: i) their range or tolerance to the driving variable(s) – in this case temperature or discharge; and ii) changes in their occurrence under new conditions.

A range of well known assumptions characterise empirical statistical modelling of this type. For example, relationships based on correlation are taken to represent cause and effect, while processes driving change are treated as 'black boxes'. An assumption specific to this project is that climatic variation during the calibration period (for example due to variations in the NAO or recent climatic trends) can bracket future climatic effects on biota without over-extrapolation. The method is vulnerable to non-linear effects on future climate (such as alteration of the Gulf Stream), river conditions (alterations in flood/drought frequencies) and river biota (invasive species). Prediction is also dependent on the uncertainties associated with all aspects of the climate and hydrological modelling.

Acknowledging these assumptions, empirical modelling also has distinct advantages. The method is simple, avoiding the need for detailed, reductionist process- or individual-based models. The models can be tested by a range of manipulations or surveys designed a priori to examine required effects. Finally, the blend of climatic variations captured between sites and years offer one of the few ways to represent realistic climate-driven variations in biota at spatio-temporal scales.

Models to simulate the effects of inter-annual climatic variation require biological and climatic data from as many years as possible, but few appropriate datasets are available for British rivers. Long runs of routine Environment Agency data are available for some sites, although most of these datasets have gaps. Those used here cover 1990–1998 and describe 19 sites on rivers in Yorkshire.

The 19 Yorkshire river sites (see Table 2.6) are a subset of the 91 sites at which the Environment Agency undertook annual monitoring of in-channel macroinvertebrates between 1990 and 1998. The number of suitable sites for this study is constrained by the location of flow gauging data. Only those macroinvertebrate sites with a local flow gauging station have been included; the intervening presence of large river confluences or significant abstractions/discharges have also been used to exclude sites. Yorkshire rivers differ from the upper Tywi in physical, chemical and biological character (see

Figure 2.5). Rivers in Yorkshire are at lower altitude (80–150m) and are circumneutral, but have mild organic enrichment at some sites (see Table 2.7).

Table 2.6 Yorkshire sites

Catchment	Sites	
River Derwent	Rye-Nunnington	Costa Beck-Kirby Misperton
	Seven-Barugh Bridge	Dove-Sparrow Hall
River Ouse	Wharfe-Addingham	Wharfe-Boston Spa
	Nidd-Pateley Bridge	Ure-Wensley
	Swale-Thornton Bridge	Ouse-Nether Poppleton
	Kyle-Newton Upon Ouse	
River Aire	Aire-U/S Cononley Beck	Aire-Calverley Bridge
River Calder	Calder-Sowerby Bridge	
River Don	Rother-New Bridge Lane	Sheaf-Queens Road
	Blackburn Brook-At A6109	Dearne-Adwick-Upon-Dearne
West Beck	West Beck-Wansford Bridge	

Table 2.7 Key attributes of the Yorkshire rivers dataset used in modelling climatic effects on biota

Parameter	Yorkshire rivers
Altitude	80–150m
Study area	20,000km^2
Main stream range	Clean to organically enriched
Number of sites retained	20 sites (from 68 original candidates)
Length of calibration run	1990–1999 (not continuous)
Source of data	Environment Agency
Invertebrate sampling	Autumn kick-samples
Composition	69 families (recorded in log abundance)
Samples	129
Contextual physico-chemistry	Channel depth, channel width, bed slope, distance from source, bed substrate
Climatic predictors examined	Summer temperature (six months preceding the autumn macroinvertebrate sampling), summer discharge, NAO index (December to February)
Biological response variables	Assemblage composition, richness, rarity index

Notes: 'Winter' is October–March directly preceding sampling; 'summer' is April–September inclusive.

Biological data

Invertebrate data for the Yorkshire rivers were collected in autumn (usually September–October) and recorded as log abundance categories for each family per sample. For the derived rarity index in Yorkshire, families present in <25 per cent of samples were marked as rare and their percentage contribution to the taxa in each sample was determined.

Physico-chemical data

For Yorkshire rivers, available physical variables were log values of river channel depth, river slope, river channel width, distance from source and a substratum index varying from 0 to 1 (fine to coarse substratum). Chemical data were not regularly collected across the sites and could not be used.

Figure 2.5 Location of the Yorkshire sites

The climate variables

Autumn samples from Yorkshire were expected to reflect antecedent summer discharge and summer temperature. Climatically-related variables were then derived, where possible, as means for three-, six- or 12-month periods preceding each invertebrate sample. These variables are detailed below.

i) Discharge data were available for each site (as for the upper Tywi sites) and a standardised index was developed for discharge (Q) preceding each invertebrate sampling period relative to the long-term mean (discharge index = (Q-m)/(max-min), where 'm' is the mean Q at each site). This standardised index was re-calibrated to account for future discharge variations outside the current range.

The empirical flow factor approach (see Section 2.4.3) was used to develop relevant future flow statistics specific to each macroinvertebrate sampling site for the 2020s, 2050s and 2080s.

ii) Daily average air temperature data (calculated from the daily maximum and the daily minimum), aggregated as monthly means, were provided by the BADC for meteorological stations that are representative of regional climate variation across Yorkshire. Sheffield data have been used for sites in the Don; High Mowthorpe data have been used for sites in the Yorkshire Derwent catchment; and Bradford data were used for sites in the Dales and Pennines (Aire, Wharfe, Ouse catchments). These data were adjusted to the altitude of each of the macroinvertebrate sampling sites. Antecedent temperatures were derived from these data, aggregated over six months and then used in the analysis, depending on correlation with the biological pattern.

    The medium-high emissions scenario for the HadCM3 and CGCM2 climate models, downscaled to the Yorkshire region and to a daily time-step (see Section 2.2), were used to develop future air temperature data for each of the meteorological stations for the 2020s, 2050s and 2080s.

iii) The NAO winter index was investigated as for the upper Tywi sites.

These variables were taken forward into the empirical data-driven modelling.

2.4.5 Conceptual modelling of fisheries habitat in response to climate change

The methodology leads on from and is informed by the hydrological modelling output from CAS-Hydro (see Section 2.4.2). It is generally recognised that detailed habitat modelling requires at least a two dimensional (2D) hydrodynamic treatment to describe changes in habitat features fully. For example, different salmonid life stages require certain water depths and velocities, together with appropriate secondary habitat features, such as water temperature and river bed characteristics. The methodology and approach have two key dimensions, which are summarised below and described in more detail in Appendix 6.

i) Developing 2D predictions of flow depth and velocity for shallow gravel bed rivers using hydrodynamic models.

ii) Applying these predictions to a ‘fuzzy’ habitat model in relation to the species requirements for Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*).

Two dimensional hydrodynamic modelling

The methodology adopted a novel approach to 2D hydrodynamic modelling, based upon the Finite Element Surface Water Modelling System (FESWMS; Froehlich 1989). For a specific river reach with a single outflow and inflow, the model requires: a stage-discharge relationship as an input to one of the boundaries; stage hydrographs at both boundaries; and a channel geometry. CAS-Hydro was used to provide continuous simulation of flow. The stage-discharge relationship was derived from field measurement, allowing the water depth from river flow to be calculated. Channel geometry data were available from LiDar survey.

To assess future climate change impacts on habitat availability, the affects of estimated changes in low flow regime due to climate change were explored. The output of CAS-Hydro was taken from the start of the baseline period (1960) to 2069 and applied to a distributed continuous simulation model of 2D hydrological response in the study reach. The modelled site comprised a weakly curved reach with a riffle at the downstream end.

Fuzzy modelling of habitat suitability

The approach to habitat modelling was restricted to considering depth and velocity, with wetted usable area also provided by the 2D model output. This section explains the ‘fuzzy’ nature of the developed model – the term fuzzy is used here to describe the varying nature of the habitat preferences of the target species and reflects the fact that the species have a continuum of potential preferences rather than a defined optimum.

After consultations with habitat researchers in relation to the depth and velocity requirements of Atlantic salmon and brown trout, depth and velocity were both interpreted into three classes – poor, medium and good – and habitat into six different classes – unsuitable, very poor, poor, good, very good and excellent (see Appendix 6). The six different habitat classes were then allocated to the nine types of habitats produced by mapping each depth class against each velocity class (see Table 2.8). A ‘fuzzy’ rule was specified for each habitat class, with literature values of habitat preferences for spawning, nursery and rearing habitat for Atlantic salmon and brown trout used to define the fuzziness variations in order of preference.

Table 2.8 Fuzzy rule set for habitat classes

Symmetrical	**Velocity poor (presence rarely found)**	**Velocity medium (presence sometimes found)**	**Velocity good (presence often found)**
Depth poor (presence rarely found)	Unsuitable habitat 0	Very poor habitat 1	Poor habitat 2
Depth medium (presence sometimes found)	Very poor habitat 1	Good habitat 3	Very good habitat 4
Depth good (presence often found)	Poor habitat 2	Very good habitat 4	Excellent habitat 5

If there was no variability in preferences within the system, then there would only be a single outcome, which does not reflect natural variability. As the level of preference variability increases, so the number of outcomes increases (to a maximum of nine). In order to provide a single habitat suitability index, the analysis was ‘de-fuzzified’ using a weightings set to produce a single ‘crisp’ number.

3 Results

3.1 Future climate scenarios

Future climate scenarios were used to provide input data to the hydrological and ecological modelling. Because of the broad-scale nature of GCM output, downscaling was undertaken to provide data on a UK regional spatial scale (mid-Wales and Yorkshire) and on a daily temporal time-step.

3.1.1 Mid-Wales

Downscaled future air temperature data were required as inputs to the CLIO macroinvertebrate model of the Afon Tywi headwater streams (see Section 3.2.2). Downscaled future rainfall data were not required, as the Arnell flow factor method does not require rainfall as input data.

Average daily air temperatures were simulated for the local Tregaron meteorological station (see Appendix 7). Using HadCM3 A2, increases of up to 0.7ºC were predicted from the 1970s to the 2020s in spring and autumn, with very little predicted change in other months (see Table 3.1). By the 2080s, increases from the 1970s of between 1.6 and 3.0ºC were predicted. These results are in line with the seasonal summary values included in the UKCIP02 report (Hulme *et al.* 2002).

Table 3.1 Modelled daily average air temperature (ºC), aggregated to monthly means for the 1970s and increases for the 2020s, 2050s and 2080s for HadCM3 A2 at Tregaron

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970s	3.4	3.7	5.4	7.6	10.3	12.8	14.6	14.2	12.3	9.7	6.4	4.6
Increase 1970s–2020s	0.0	0.5	0.5	0.7	0.5	0.5	0.2	0.0	0.6	0.7	0.4	0.1
Increase 1970s–2050s	1.1	1.6	1.3	0.6	0.8	0.9	1.0	1.4	1.2	1.5	1.5	0.8
Increase 1970s–2080s	1.6	2.8	2.2	1.8	2.1	2.0	2.3	2.7	1.9	2.5	3.0	2.0

3.1.2 Yorkshire

Downscaled future rainfall and air temperature data were required as inputs to the CAS-Hydro model of the upper Wharfe catchment (see Section 3.3.2). CAS-Hydro output was used to develop the regional empirical flow factors. These flow factors, together with downscaled future air temperature data, were used as inputs to the CLIO macroinvertebrate model for the middle reaches of Yorkshire rivers (see Section 3.3.5).

Average daily air temperatures and daily rainfall depth were simulated for the High Mowthorpe meteorological station, which is local to the upper Wharfe catchment (see Appendix 7). For the sake of consistency, the magnitude of the downscaled future air temperature change predicted for the High Mowthorpe station was used at all macroinvertebrate sites. Using HadCM3 A2, monthly mean air temperature increases of between 2.0ºC and 3.2ºC were predicted from the 1970s to the 2080s (see Table 3.2). These results are in line with the seasonal summary values included in the UKCIP02 report (Hulme *et al.* 2002).

Table 3.2 Modelled daily average air temperature (ºC), aggregated to monthly means for the 1970s and increases for the 2020s, 2050s and 2080s for HadCM3 A2 at High Mowthorpe

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970s	3.4	3.7	5.4	7.6	10.3	12.8	14.6	14.2	12.3	9.7	6.4	4.6
Increase 1970s–2020s	0.0	0.5	0.5	0.7	0.5	0.5	0.2	0.0	0.6	0.7	0.4	0.1
Increase 1970s–2050s	1.1	1.6	1.3	0.6	0.8	0.9	1.0	1.4	1.2	1.5	1.5	0.8
Increase 1970s–2080s	1.6	2.8	2.2	1.8	2.1	2.0	2.3	2.7	1.9	2.5	3.0	2.0

3.2 Climate change impacts on mid-Wales headwater streams

River flow and air temperature data were developed for the historic, existing and potential future scenarios and used as inputs to the macroinvertebrate CLIO model.

The following section describes the ecological analyses, which linked the hydrological and water quality data to macroinvertebrate preferences before simulating the possible changes in the assemblage as a result of climate-induced modification.

3.2.1 Developing an understanding of appropriate ecosystem conditions

For both acid and circumneutral moorland streams, several aspects of the stream invertebrate assemblage varied significantly with climatically-mediated variables over the baseline period, but no major effects were observed in acid forest streams (Table 3.3). An example ordination plot illustrates how assemblage composition has varied with temperature and discharge through the 24-year period of data collection: warmer or drier years (such as 1990, 1996) experienced significantly different macroinvertebrate assemblages compared with cooler and/or wetter years (such as 1987, 1989) (see Figure 3.1)). Significant assemblage changes correlate with the smoothed NAO trend, which reflects a combination of hydrochemical, hydrological and thermal variables. Increasing temperatures were associated with significant changes in community composition in acid moorland and circumneutral streams ($P < 0.05$; Figure 3.2), while abundance declined in circumneutral streams.

No major effects of winter discharge were detected, although low discharge in the previous summer apparently affected assemblage composition during the following April (Table 3.3; $P < 0.1$).

Table 3.3 Variations in invertebrate character with climate variables at the Upper Tywi sites (1981–2005)

	Winter discharge	Summer discharge	Winter temperature	NAO winter index	Smoothed NAO
Circumneutral moorland streams					
Abundance	0.078	-0.324	***-0.482****	-0.352	-0.151
Richness	0.343	-0.177	-0.162	-0.107	0.017
Stability	0.429 *0.1*	0.166	-0.004	-0.155	***-0.596*****
DCA1 score	-0.338	0.098	0.156	-0.220	-0.046
DCA2 score	0.092	*-0.405 0.1*	0.055	-0.334	-0.039
DCA3 score	-0.092	-0.087	***0.469****	***0.375 0.1***	0.202
Acid moorland streams					
Abundance	0.067	-0.115	-0.059	-0.087	-0.348
Richness	0.052	-0.062	0.030	0.213	0.126
Stability	0.077	-0.1	0.124	-0.088	***-0.503****
DCA1 score	0.026	-0.049	0.033	0.321	***0.614*****
DCA2 score	0.140	0.21	-0.045	0.096	-0.217
DCA3 score	0.298	0.283	*0.392 0.1*	0.341	0.322
Acid forest streams					
Abundance	0.082	-0.246	-0.244	0.023	-0.038
Richness	-0.125	-0.191	-0.334	-0.125	-0.046
Stability	0.239	0.009	0.242	0.081	***-0.465****
DCA1 score	*0.386 0.1*	-0.031	-0.150	0.044	-0.194
DCA2 score	0.143	0.064	-0.219	0.174	0.023
DCA3 score	-0.353	0.148	-0.045	0.187	-0.016

Notes: Values are Pearson correlations with 19 Degrees of Freedom (DF) for circumneutral streams, 18 DF for acid moorland streams and 20 DF for acid forest streams (0.1 = P< 0.1; *P < 0.05; ** P < 0.01).

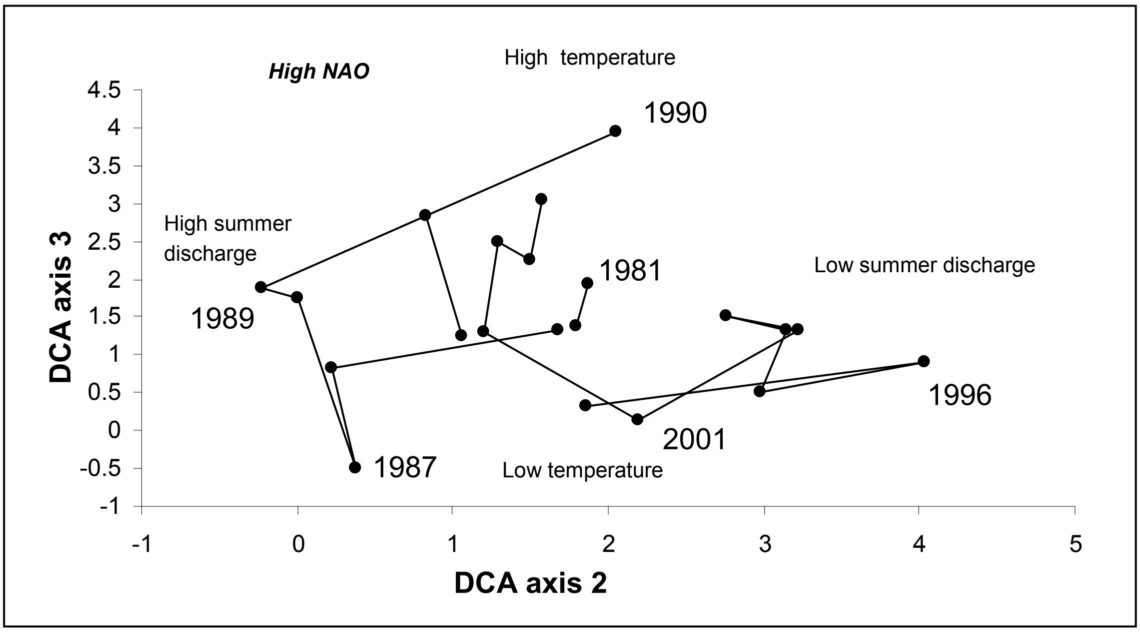


Figure 3.1 Ordination of annual samples from circumneutral streams in the Upper Tywi
Note: The labelled points indicate changes in ordination scores (and hence assemblage composition) over the years indicated.

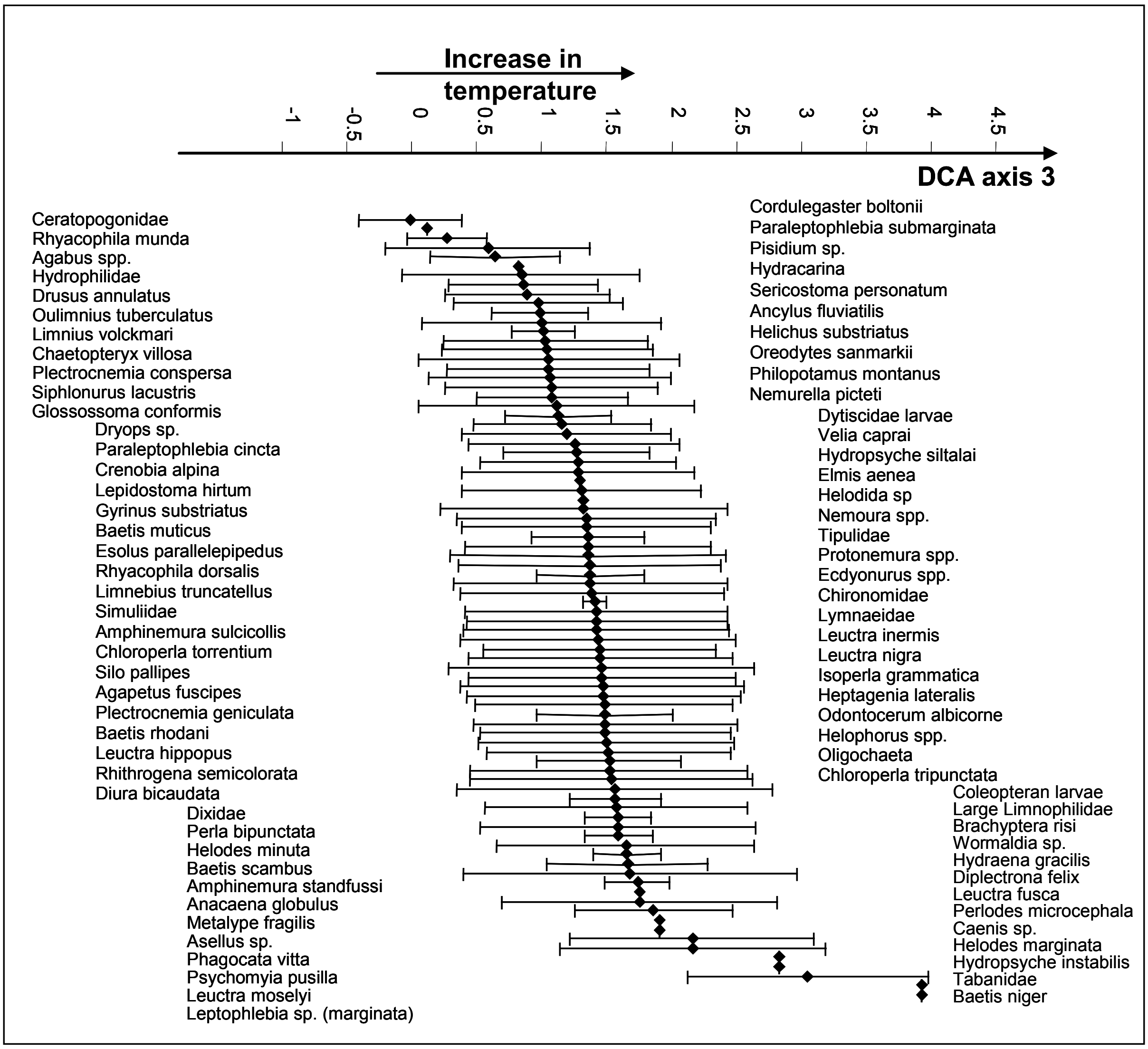


Figure 3.2 The optimum and amplitude of each invertebrate species in circumneutral streams in the Upper Tywi along DCA3 and the effects of temperature

Notes: The points and bars for each species or family indicate its mean scores and variation along the ordination axis most closely related to temperature in rank order. Species towards the upper portion of the figure characterise samples in cooler years.

Figure 3.2 shows the relative position of taxa along DCA axis 3, which is linearly related to temperature. The results suggest that taxa with lower scores on that axis prefer colder waters while taxa with higher scores prefer warmer water. The bars represent the ecological tolerance (also called niche breadth) of each taxa to the variable considered. Some taxa tolerate large variations in temperature: for example, *Brachyptera risi*, *Amphinemura sulcicollis* and *Isoperla gramma*tica are among the 'core' species able to tolerate a wide temperature range. Other species like *Rhyacophila munda* and *Drusus annulatus* are characteristic only of cooler waters.

3.2.2 Macroinvertebrate community response to climate change driven ecosystem changes

Macroinvertebrate response model

The CLIO models used in this study comprise a range of regression relationships that simulate possible climatic effects on the composition and abundance of macroinvertebrate assemblages, dominantly at species level, for headwater streams in the upper Tywi.

Some examples of the regression relationships are presented in Table 3.4, while Figure 3.3 illustrates the tolerance and optima of invertebrate taxa with respect to discharge or temperature. In all the model cases, slopes were significantly different from zero. However, no predictor explained more than 37 per cent of the inter-annual variance among invertebrates. Neither multiple predictors nor alternative procedures improved the model fit. Sources of non-climatic variation (such as acid recovery, changes in land use) were important factors over the temporal and spatial extent of this study in mid-Wales.

Table 3.4 Significant regression relationships (y = ax + b) used in the derivation of the CLIO models for circumneutral streams in the upper Tywi

Dependent variable	Independent variables	a	b1	b2	r^2	Comments
1) Assemblage composition (DCA2)	Previous summer discharge (Q5)	5.468	-6.3496x	$2.3502x^2$	22.4%	Note polynomial structure (see Figure 3.3)
2) Assemblage composition (DCA3)	Winter temperature (6) ºC	0.314	0.390		15.0%	See Figure 3.1 and Figure 3.2
3) Assemblage composition (DCA3)	Winter NAO	1.21	0.203		19.1%	
4) Total invertebrate abundance	Winter temperature (6) ºC	2716	338		25.7%	
5) Inter-year stability (Jaccard index)	Winter discharge (Q5)	0.536	0.0639		48.8%	
	Smoothed winter NAO			0.0508		

Simulating future climates and their effects using CLIO

Discharge

Future discharge projections at Plynlimon (taken to represent conditions in the Upper Tywi) varied moderately relative to current conditions (see Appendix 3). For example, current values of Q_5 (extreme high flow) between 1981–2004 during summer averaged $0.99\pm0.31 m^3/s$, with simulated future mean summer discharge ranging between -20 per cent and +7 per cent of the current values (Table 3.5). These potential deviations in average conditions are within the current inter-annual range (range of Q_5: $0.42–1.62 m^3/s$), and, according to *CLIO*, would lead to risks only for the most sporadic and drought-sensitive organisms in the Upper Tywi (such as *Metalype fragilis*, *Psychomyia pusilla*, *Lepidostoma hirtum*; see Figure 3.3). However, these projections take no account of changes in future variability and potential extremes. Nor do they take account of interactions with other climatic drivers, such as the NAO. Simulations suggest that interactions between NAO-mediated climate and winter discharge might, for example, considerably reduce current faunal stability (Table 3.7, Eqn 5; effects not illustrated) and the projected changes are sustained for multiple decades not just individual years.

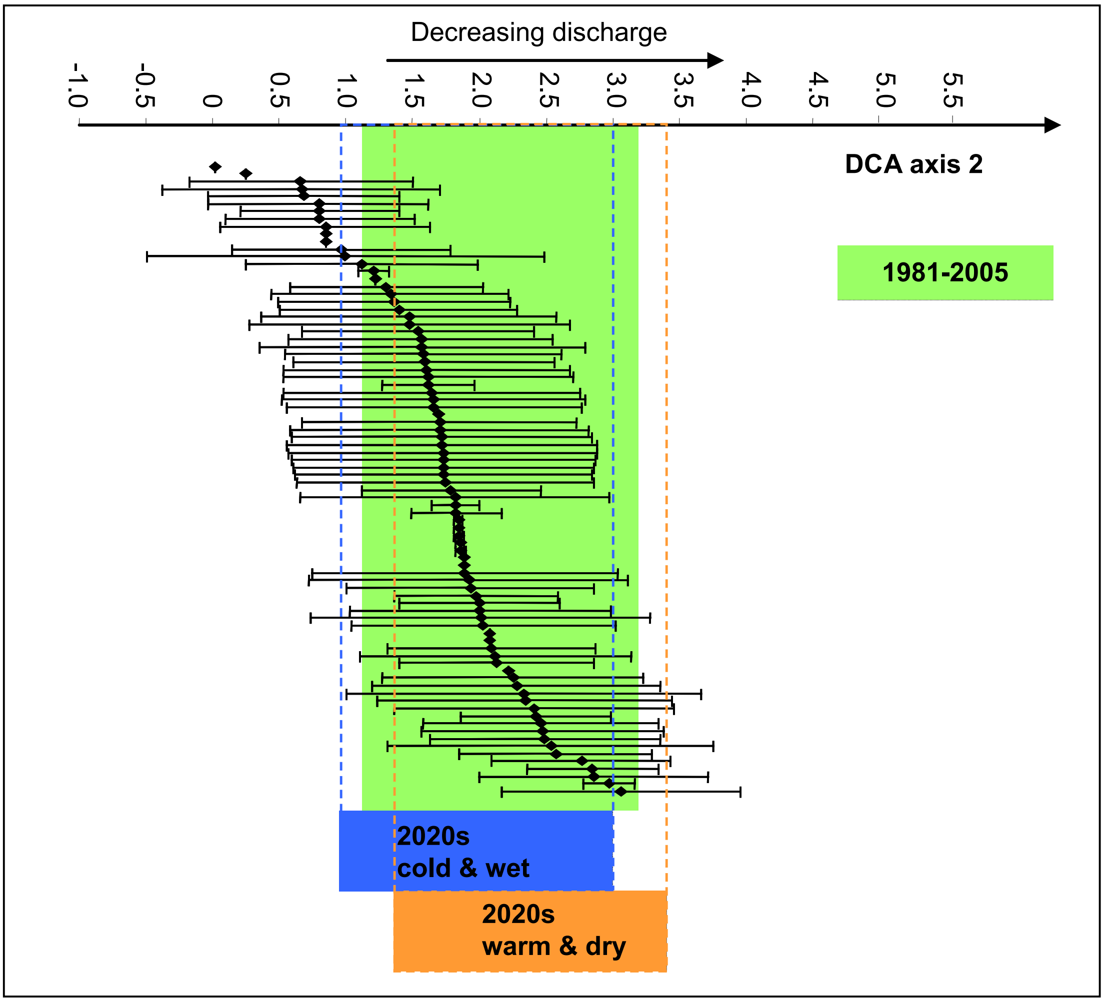


Figure 3.3 The optimum and amplitude of each invertebrate species in circumneutral streams in the Upper Tywi along DCA2 showing the effects according to CLIO of current and projected discharge

Notes: The green area corresponds to the observed range in DCA2 scores between 1981 and 2005. The shaded areas correspond to projected ranges using CLIO. The bars signal one standard deviation about the optimum. The range shown is a lumped value and does not include some of the extreme discharges which explains why some species currently found appear to outside the range.

Table 3.5 Extreme high flow discharge scenarios (Q_5) for Plynlimon (used to represent discharge for the Upper Tywi sites)

	Summer discharge		Winter discharge	
Scenario variant	**2020s[1]**	**Difference from 1981–2005**	**2020s[1]**	**Difference from 1981–2005**
Low	0.89m^3/s	-9%	2.40m^3/s	-21%
Medium	0.87m^3/s	-11%	2.40m^3/s	-21%
High	0.85m^3/s	-13%	2.41m^3/s	-21%
Cool & wet	1.00m^3/s	+3%	2.61m^3/s	-1%
Warm & dry	0.82m^3/s	-16%	2.29m^3/s	-33%
Cool & wet +A	0.95m^3/s	-3%	2.65m^3/s	+3%
Cool & wet +B	1.05m^3/s	+7%	2.58m^3/s	-4%
Warm & dry +A	0.77m^3/s	-21%	2.33m^3/s	-29%
Warm & dry + B	0.86m^3/s	-12%	2.22m^3/s	-39%

Note: [1] Projected future flows using Arnell flow factor methodology.

Temperature

According to CLIO simulations, projected trends in temperature had potentially more profound biological effects than discharge. In the upper Tywi, temperature varied between winters (2.0–4.9ºC) over the calibration period due to the significant effects of both the NAO and trends through time. According to downscaled data from HadCM3, trends into the 2050s and 2080s could add a further 1–2ºC to the current winter mean. CLIO indicates that temperatures in circumneutral moorland streams would begin to exceed the current range occupied by species such as *Cordulegaster boltonii,* Ceratopogonidae, *Rhyacophila munda,* and *Pisidium sp.* (Figure 3.4). Abundances would also fall on average by 23–43 per cent of current mean values (Figure 3.5).

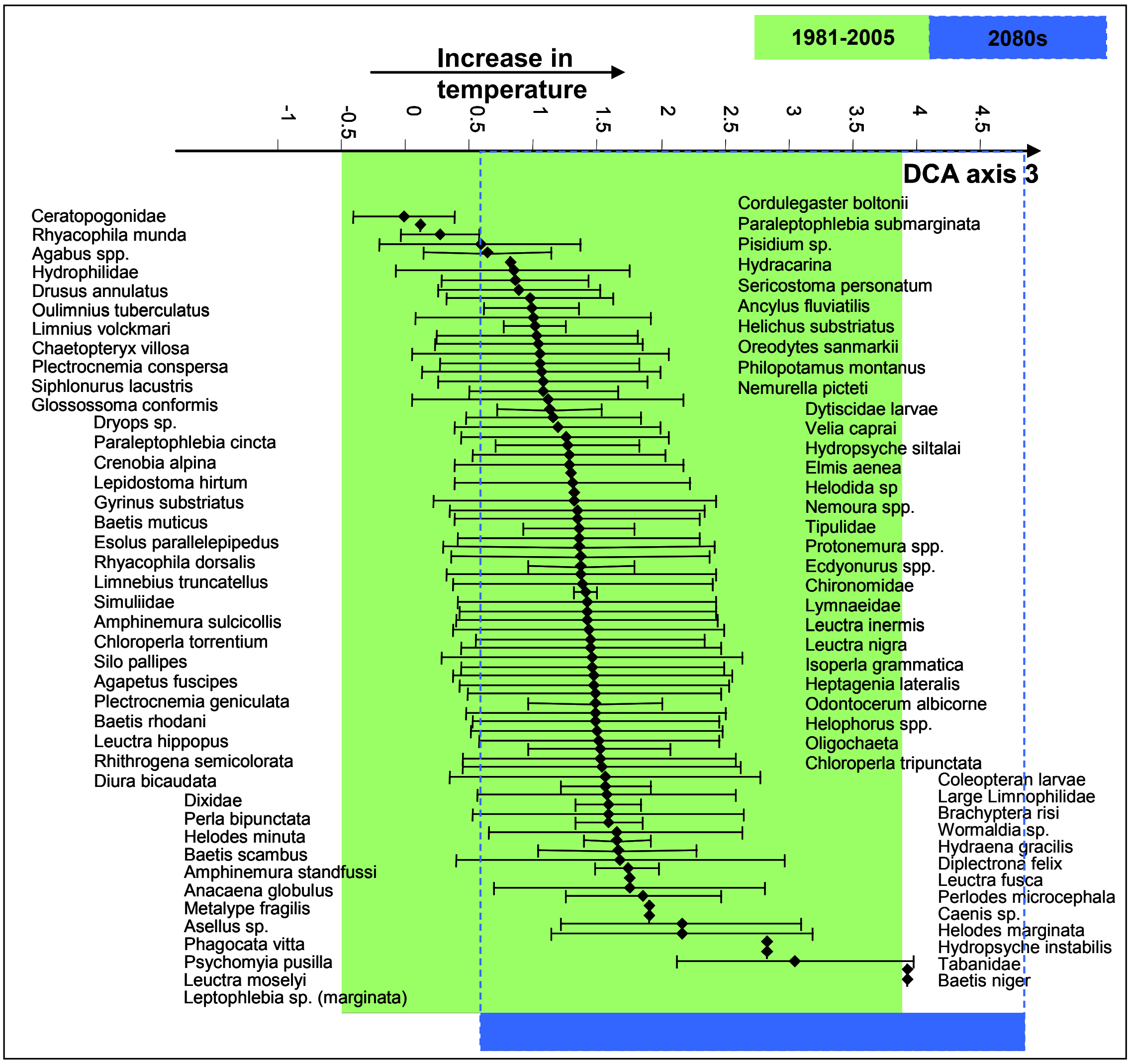


Figure 3.4 The optimum and amplitude of each invertebrate species in circumneutral streams in the Upper Tywi along DCA3 illustrating the effects of current and projected temperature according to CLIO

The green area corresponds to the range of DCA scores observed during the 1981–2005 period. The blue/dotted area corresponds to the range of DCA scores projected using the CLIO models up to the 2080s (see Table 3.4). Based on their observed optima and tolerance range, species falling within the shaded areas are likely to be present.

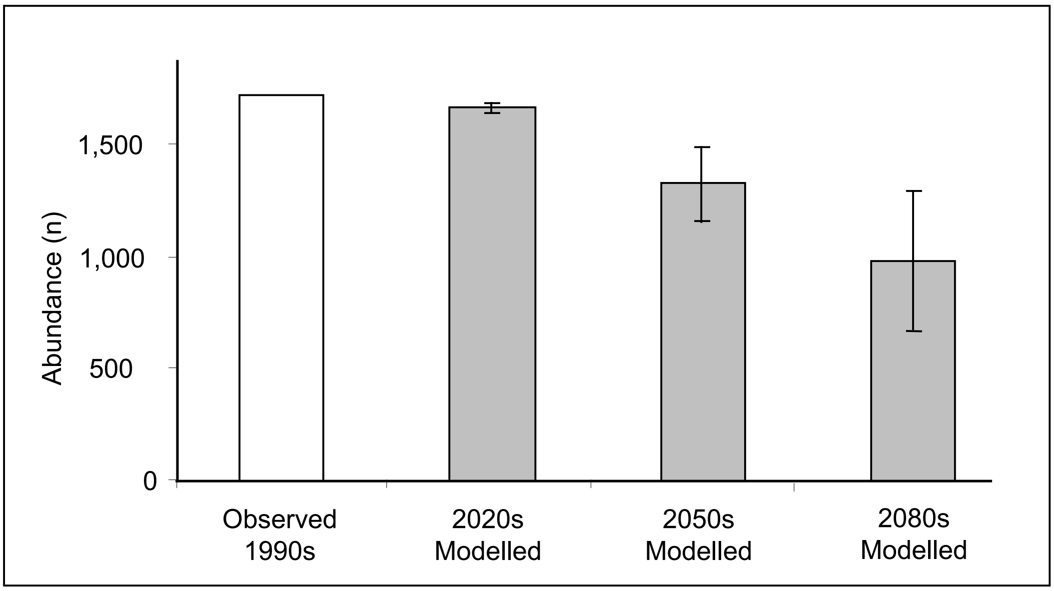


Figure 3.5 Mean observed total abundance of invertebrates at the Upper Tywi sites and mean values (±SE) projected using CLIO across the range of scenarios illustrated for the 2020s, 2050s and 2080s

The exact mechanisms involved are unclear, but two candidates are likely to be involved in reducing spring invertebrate abundance at higher temperatures.

i) Alterations in emergence phenology. Climate change over the period 1981-2005 has detectably advanced the emergence phenology of amphibians in adjacent ponds (Chadwick *et al.* 2006), with likely effects on the abundance of stream invertebrates (Briers *et al.*, 2004). These effects include direct losses through early emergence and the subsequent impact on the development and survival of subsequent cohorts.

ii) Energetic effects. For example, increased predation pressure by fish as temperatures increase (Kishi *et al.*, 2005) or increased decomposition leading to decreased detrital retention and availability (Lepori *et al.* 2005). Experimental evidence shows that both factors can reduce invertebrate numbers.

3.3 Climate change impacts on Yorkshire rivers

Future river flow data were developed at a range of complexities to test whether increasing method complexity delivers significant improvement in future flow prediction. The different flow simulation methods were compared to identify the most suitable for use as an input to the macroinvertebrate CLIO model. Air temperature data were also developed as inputs to the CLIO model. The flow simulation results from the continuous simulation were then used in the fisheries habitat modelling.

The following section describes the output of the hydrological approaches, followed by the ecological analyses, which link the hydrological and water quality data to macroinvertebrate and fisheries preferences. The possible changes in these assemblages as a result of climate change can then be simulated.

3.3.1 Predicted future flows for Yorkshire: flow factor methodologies

The simplest approach to be investigated was the flow factor methodology described by Arnell (2003), which was used for the mid-Wales study.

The 2020s flows estimated using the Arnell (2003) methodology are presented in Appendix 4. Figure 3.6 illustrates the results for Q_{95} and Q_5, which show that the impact on flow percentiles is dependent upon the type of scenario. Under the cool and wet (modification B) scenario, the Q_{95}s (a measure of low flow) are actually higher than baseline, with the other three scenarios lower than baseline. Under both cool and wet scenarios, the Q_{95}s are higher than baseline, with the warm and dry scenarios lower than baseline. As the flow factor is regional, each site responds in the same way. There is no capturing of the possibility of a change in the inter-site variability.

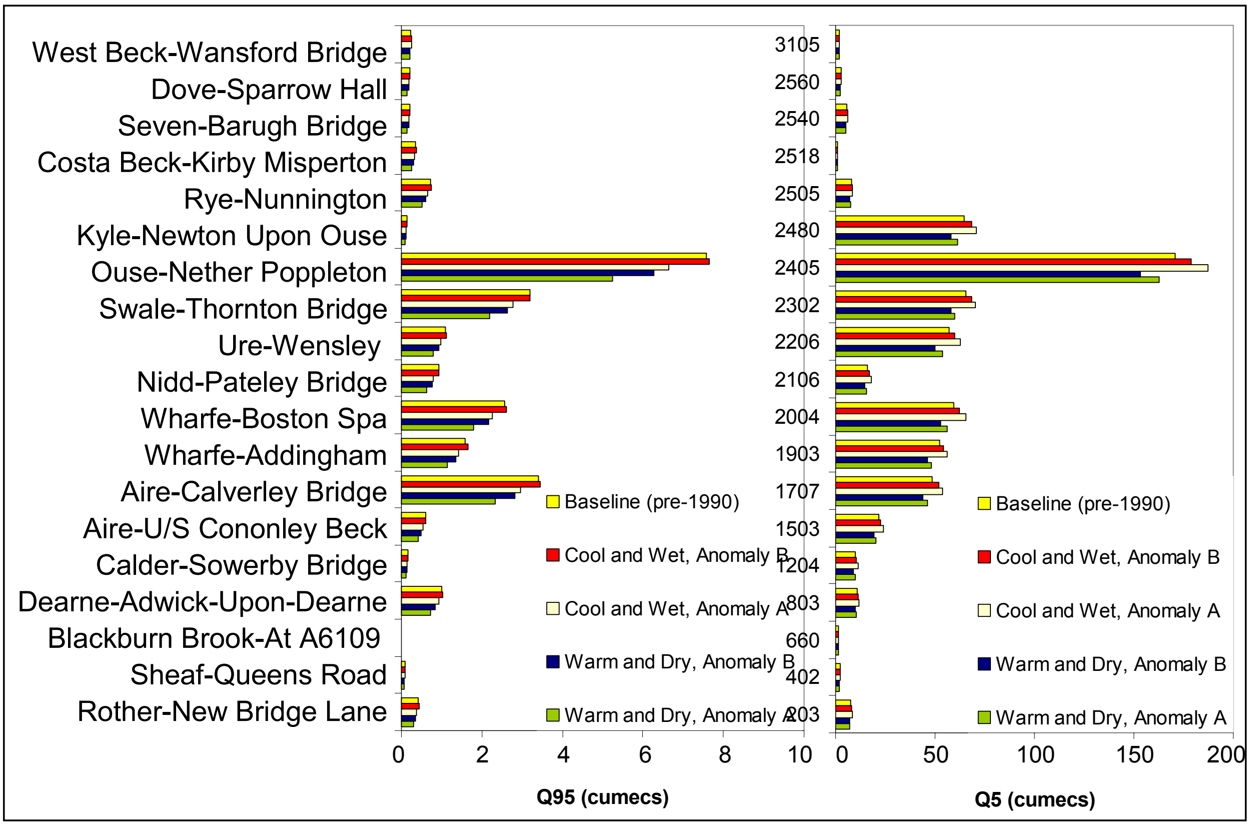


Figure 3.6 Projected flows for the 2020s under the four flow factor scenarios, as compared with the pre-1990 baseline, for Q_{95} and Q_5

Notes: The Arnell methodology identifies two characteristic scenarios for the 2020s, one which represents 'cool and wet' and the other which represents 'warm and dry'. There are also two types of anomalies (A and B) to encompass uncertainty. This makes a total of four scenarios.

A number of issues have been identified with flow factor methodology.

- The approach currently only provides information for the 2020s, and not for the 2050s or 2080s, although conversion factors are available. Climate change signals appear to become statistically significant for both temperature and precipitation only after 2020.
- There are uncertainties over the validity of the approach for larger catchments.
- There is considerable spatial variability in flow percentile estimates between sites depending on the length of flow records, which are highly variable prior to 1990.
- As the approach is based on perturbation of an historic flow record, it generates a range of

future flows that encompass the sequencing, frequency and magnitude of the baseline rather than distinguishing future climates (changes driven by future rainfall and temperature) from the baseline.
- It is highly unlikely to provide meaningful estimates of high flow percentiles, as the factors are designed to apply to monthly averages rather than storm event-scale run-off.

It is acknowledged that the flow factors were not designed with such an application in mind and have only been used as input data to ecological models where other methods were not available (in the mid-Wales study).

3.3.2 Predicted future flows for Hubberholme: continuous simulation with CAS-Hydro

Statistical downscaling of precipitation and temperature was performed to a daily time-step using HadCM3 A2 (see Section 3.1) and should be considered as indicative only. As with all such climate change studies, further modelling using a range of SRES storylines and GCMs is recommended, in order to derive a broader representation of potential climate change risk, although resources may limit such an approach.

Figure 3.7 shows the predicted flows for the baseline period, the 2020s, the 2050s and the 2080s. Initial inspection of these aggregated results would suggest relatively little change. Two characteristics emerge:

i) there is a marginal increase in flow percentile magnitude, for all percentiles, by the 2020s, except Q_1, Q_{60} and Q_{70}, which reduce by very small amounts;
ii) by the 2050s, this trend is reversed for flow exceedence percentiles Q_{50} through to Q_{99}, but not for Q_5 through Q_{40}.

The second of these observations suggests that the primary changes in flow for the 2050s and 2080s are associated with an increase in the duration of higher flows and an increase in the duration of low flows, or a generally more variable hydrological regime. There remains considerable inter-annual variability due to natural variability in the weather, but this is superimposed upon a negative trend and, possibly, greater variability, notably in the lower flow percentiles (see Appendix 2). Tests for the statistical significance of the trend in annual percentiles as a function of time were undertaken, with none shown to be statistically significant (see Appendix 2). However, when this trend is broken down into the period to 2039 and the period post-2039, the difference between the results to the 2020s and the 2050s/2080s becomes clearer. To 2039, most of the flow percentiles are increasing through time, suggesting generally wetter conditions. Post-2039, the higher flow percentiles tend to increase and the lower flow percentiles start to decline, reflecting a tendency towards generally drier conditions during summer periods and increased seasonality of flows. This implies that it may be some time before climate change impacts upon *annual* flow percentiles will be detectable (Wilby 2006).

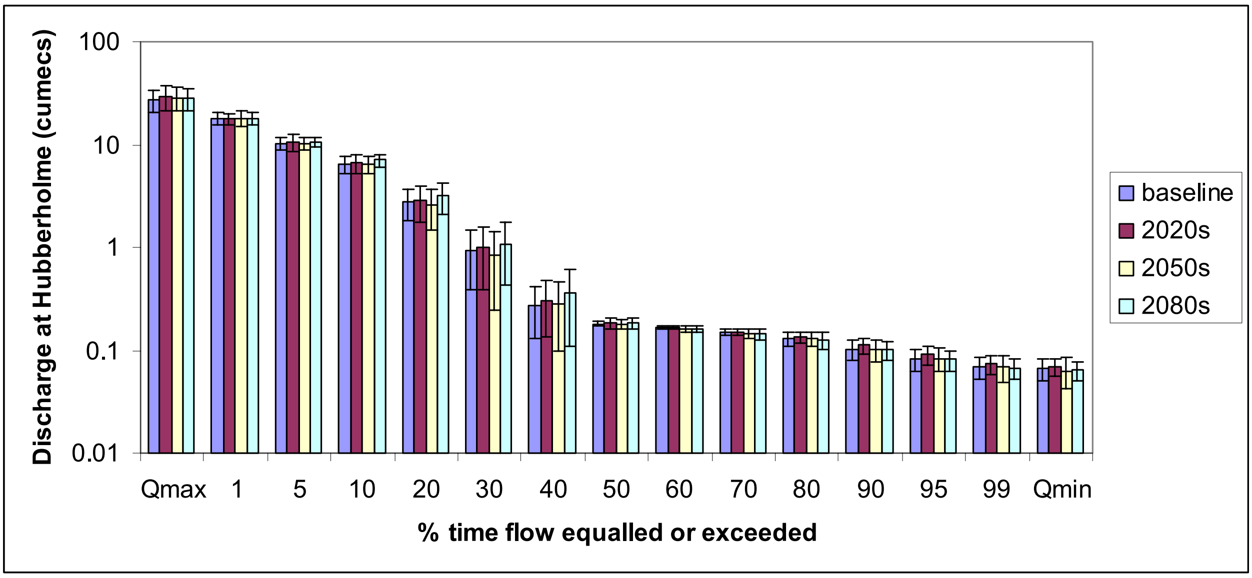


Figure 3.7 Predicted flow percentiles for the baseline period, the 2020s and the 2050s, with standard deviations to show variability

However, this emphasis on the aggregated 2020s, 2050s and 2080s flow percentiles is actually misleading, due to multi-decadal variability in the downscaled precipitation data. Figure 3.8 shows that by the late 21st century a much stronger variability in annual precipitation is predicted.

Figure 3.9 shows the same cyclicity in the flow data, illustrated for the Q_5.

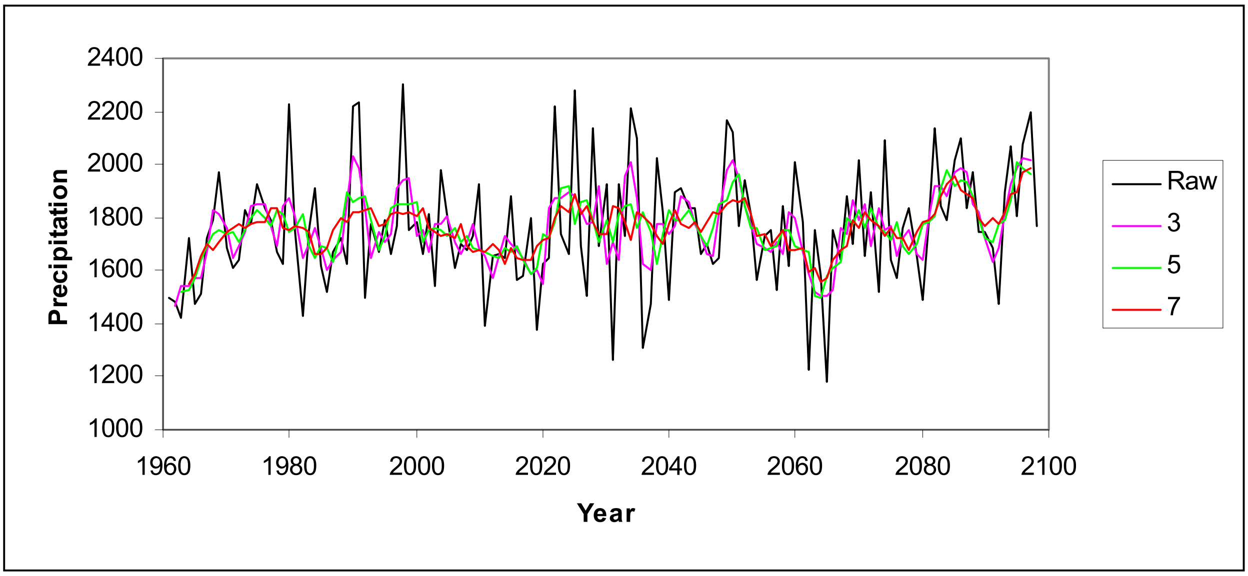


Figure 3.8 Downscaled annual precipitation for 1960 to 2100
Notes: Raw is annual data. 3, 5 and 7 are three-year, five-year and seven-year running means respectively.

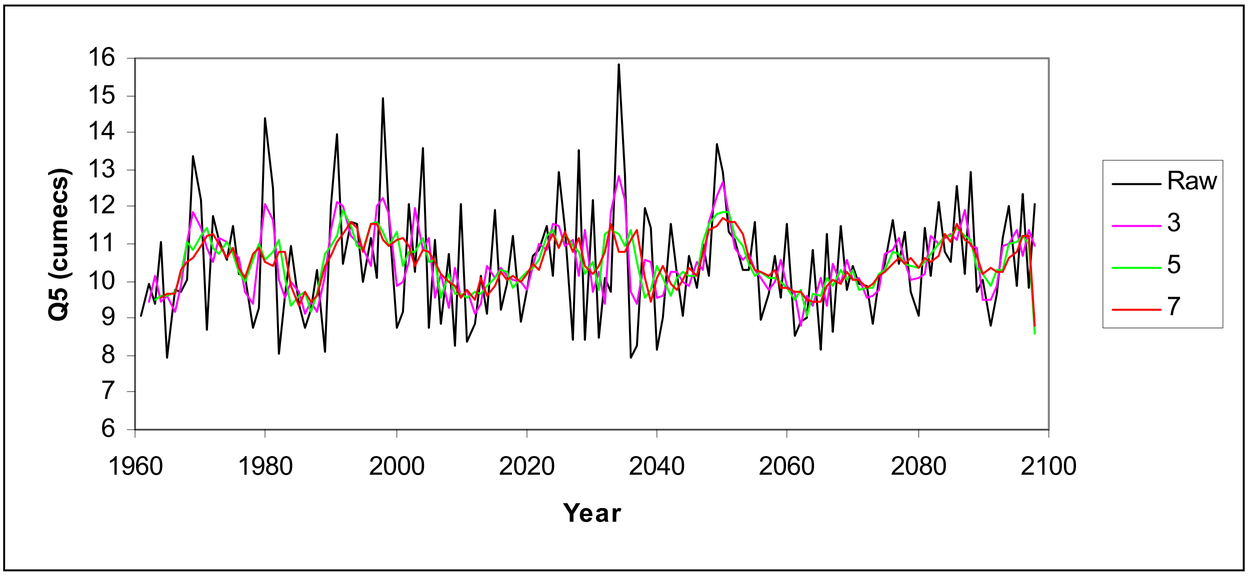


Figure 3.9 Predicted annual Q5 for 1960 to 2100.
Notes: Raw is annual data. 3, 5 and 7 are three-year, five-year and seven-year running means respectively.

These long-term annual variations were explored further for the three-year running mean. Comparison of the three-year running means for flow with those for precipitation indicated some very surprising results. For higher flows (Figure 3.10, Q_5), the association between the three-year running means of rainfall and Q_5 remains strong and clear. However, this is not the case for three-year running means of lower flows (Figure 3.11, Q_{95}), where there is a very marked cyclicity that is only weakly related to rainfall. This variability leads to periods of sustained higher low flow and lower low flow, or a sequencing of years with generally lower flows. This is a reflection of the fact that low flows are much more strongly conditioned by the legacy of periods of dry and wet years, as well as depending on water storage, which means that it takes longer for low flows to adjust to changing rainfall events. It also means that applying 30-year means to low flow data (as when the 2020s, 2050s and 2080s are determined) is not meaningful, as the percentiles that result are highly influenced by inter-annual variability. This also emphasises the problem with looking at annual flow percentiles, as they overlook two important hydrological characteristics:

i) changing probabilities of consecutive dry (or wet) years;
ii) overall reductions in flow across multiple years.

Both may be of direct ecological significance. The statistical treatment that consolidates data into annual percentiles masks the sequencing of extremes, which is of particular significance for extreme low and high flows. The frequency, magnitude and duration of low flows are known to have impacts for aquatic ecological communities, as does the magnitude and frequency of storm flows. The possibility of multiple drought years, which have not occurred on many occasions in the last two centuries, may also be hidden within flow percentile statistics that do not describe the sequencing of events.

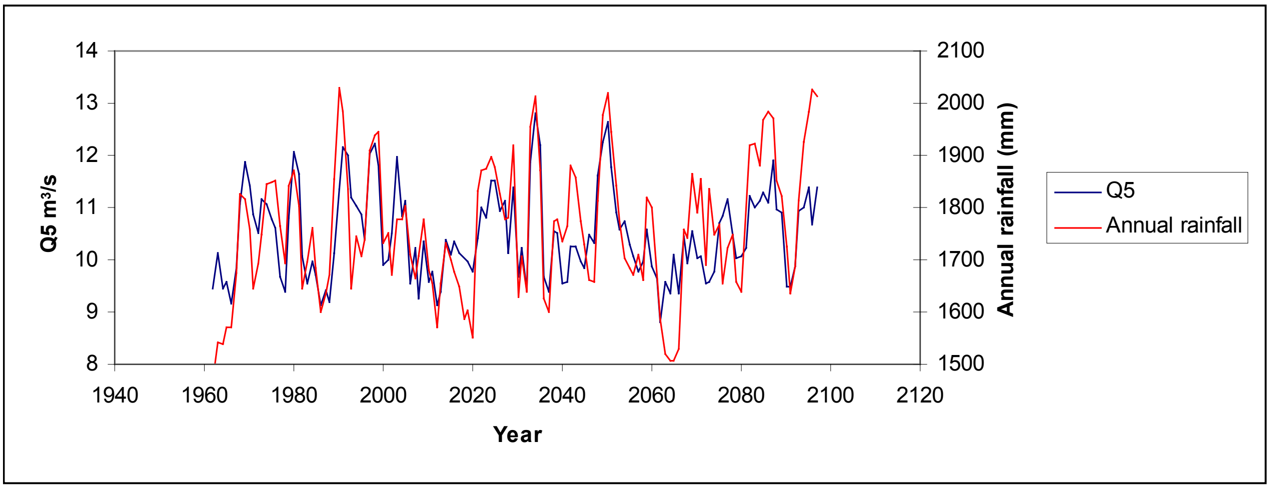


Figure 3.10 Predicted extreme high flow (Q_5) and annual rainfall for 1960 to 2100 with a three-year running mean

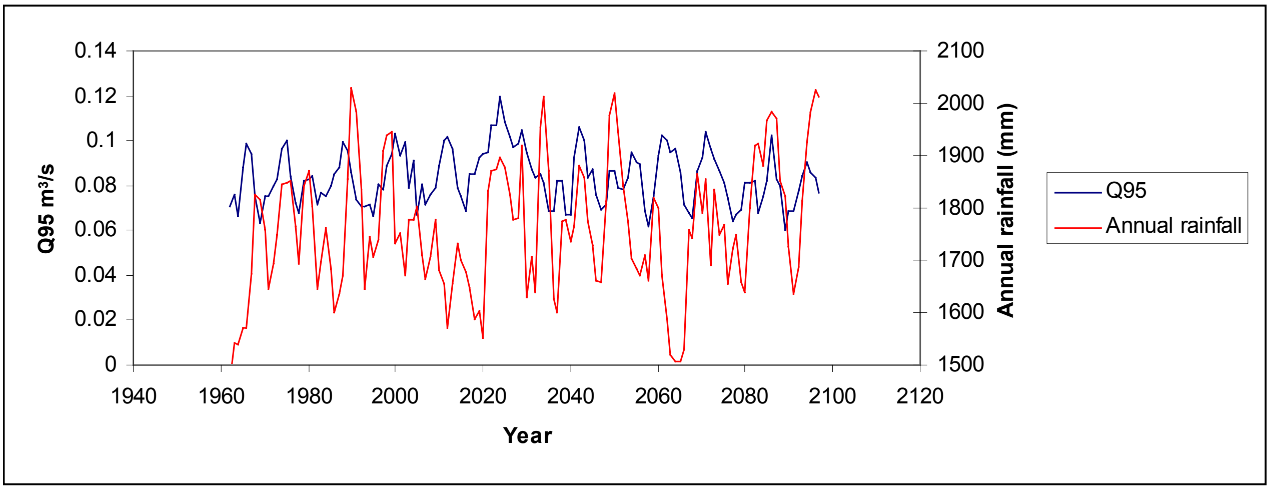


Figure 3.11 Predicted low flow (Q_{95}) and annual rainfall for 1960 to 2100 with a three-year running mean

3.3.3 Empirical flow factors

This methodology (see Appendix 5) uses the continuous simulation results for the River Wharfe to provide an indication of future flows as determined by future climate scenarios and allows flow percentiles for the 2020s, 2050s and 2080s to be estimated. Figure 3.12 compares the empirical transfer function predictions with those obtained using the flow factor approach for the 2020s. Generally, the flow factor methodology, even under the wet year assumption, produces lower estimated Q_{95} values. As the empirical transfer methodology is based directly on continuous simulation and measured correlation, with the assumption that the latter is regionally stable in time, the empirical transfer methodology gives a more reliable indication of future flows for the 2020s. It also allows flow percentiles for the 2050s and 2080s to be estimated. Ideally, the methodology should be extended by simulating a wider range of representative sub-catchments to capture the sub-regional variation more fully.

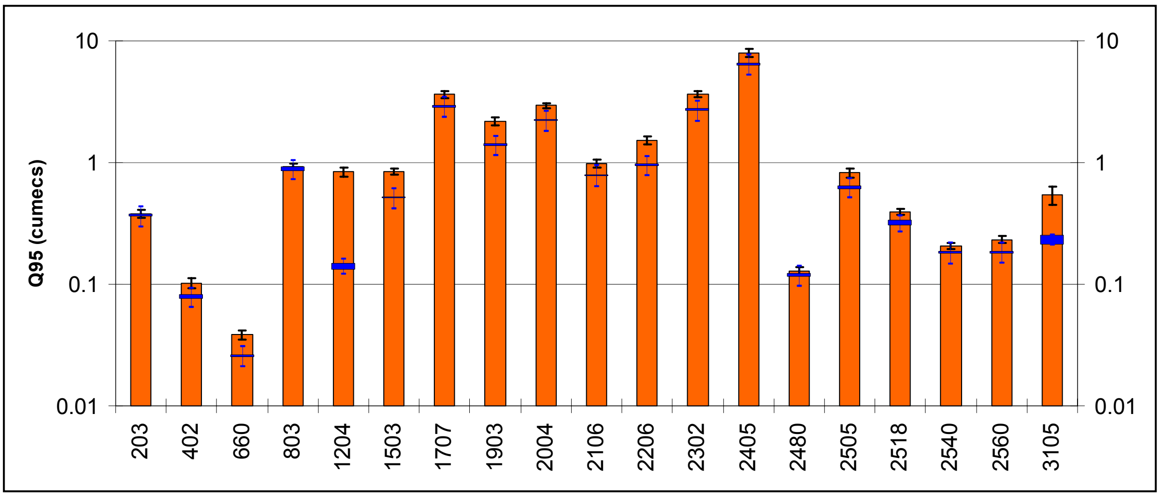


Figure 3.12 Predicted Q_{95} values compared with those determined using the flow factor methodology for the 2020s

Notes: Red bars are predicted Q_{95} values using the empirical transfer function approach, with black uncertainty bars as defined from the regression analysis (see Appendix 5). The blue lines show the range of predictions from the flow factor methodology.

Results from the empirical flow factor approach were used as input data to the macroinvertebrate modelling at the Yorkshire sites.

3.3.4 Macroinvertebrate CLIO model: developing an understanding of appropriate ecosystem conditions for Yorkshire

Most of the variations among invertebrates in Yorkshire reflected variations in width, distance from source, substrate composition and depth (Figure 3.13 and Figure 3.14). However, there were also significant correlations between assemblage composition (DCA axis 1), richness and temperature over the six months preceding sample collection, as a result of differences between site locations and inter-annual variations (Figure 3.13, Table 3.6). Thus, typical headwater families (such as Perlidae, Leuctridae, Nemouridae) occurred in richer assemblages containing more rare taxa at lower temperatures, while several taxa typical of lowland streams characterised samples from higher temperatures (Figure 3.15). By contrast, Gerridae, Coenagriidae and Corixidae were associated with warmer waters.

Table 3.6 Significant variations in invertebrate character with climate variables for Yorkshire rivers (1990–1999)

	Summer temperature (six months)	Discharge (Q_{10})
Richness	***-0.353ºC ****	-0.022m^3/s
Rarity	***-0.328ºC ****	0.002m^3/s
DCA1	***-0.441ºC ****	0.076m^3/s
DCA3	0.072ºC	***-0.307m^3/s ****

Note: Values are Pearson correlations (* P <0.0001). All tests had 129 samples, but repeat samples within sites are non-independent between years within sites. Only effects significant at P< 0.0001 are highlighted.

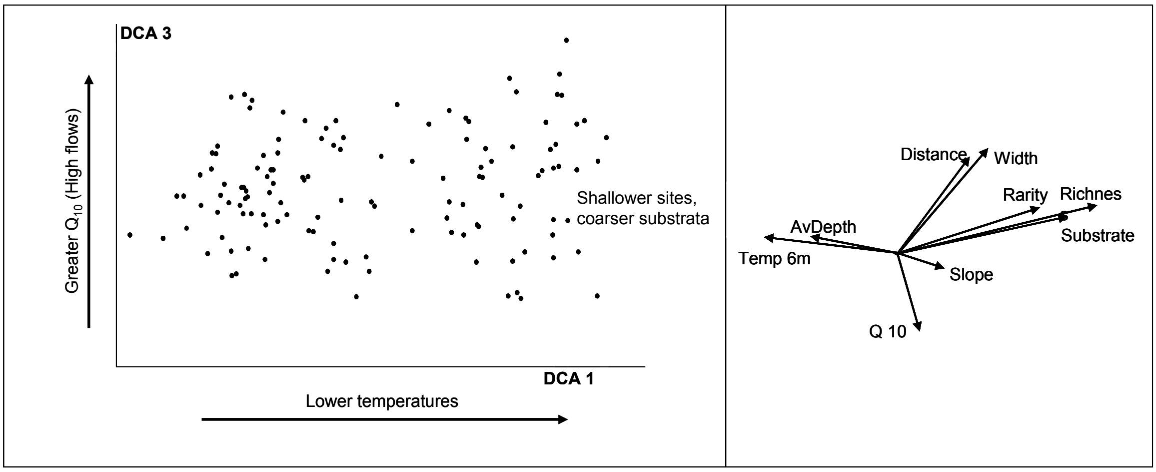


Figure 3.13 Sample ordination from Yorkshire, with inset figure indicating direction and magnitude of dominant environmental correlates

Notes: Samples towards the right of the ordination come from cooler, shallower rivers (headwaters) with coarse substrate, where discharge variations (variations on axis 3) were greatest. See Figure 3.14 for associated variations among invertebrate families.

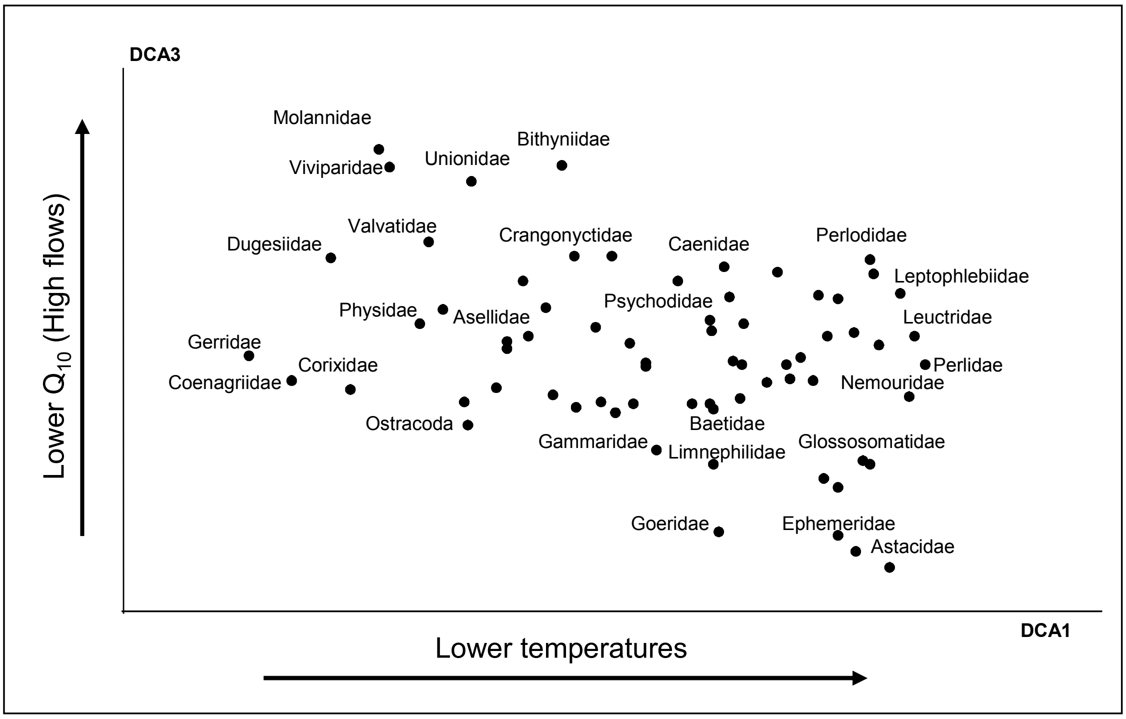


Figure 3.14 The distribution of families along the ordination axes in Figure 3.13

Note: Families towards the lower right are typical of cooler conditions in years with higher flow while those towards the upper left typify warmer conditions in years with lower flow.

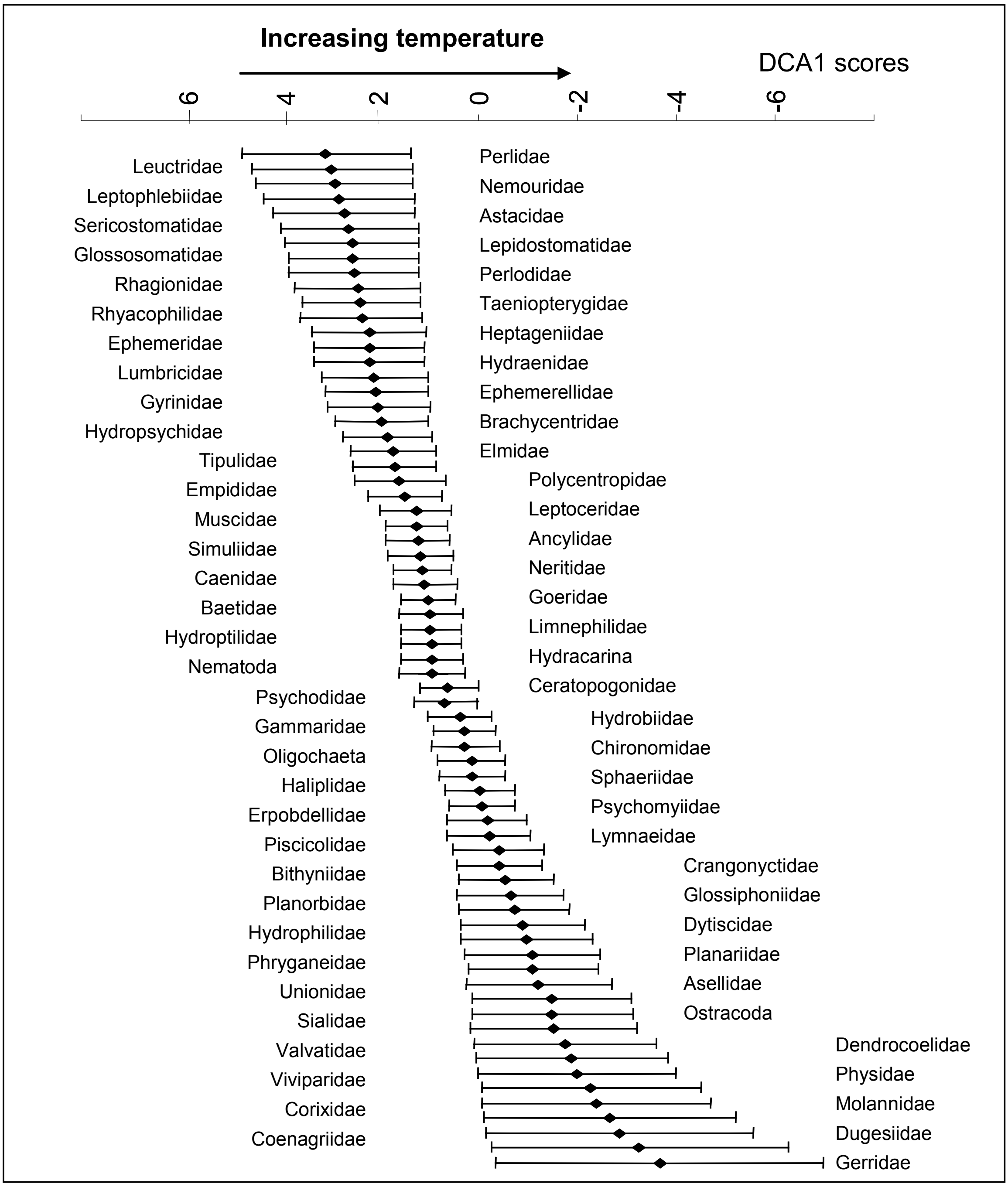


Figure 3.15 The optimum and amplitude of each invertebrate family in Yorkshire samples along DCA1 and the effects of temperature

Note: Families in the upper portion of the Figure characterise samples from warmer conditions.

Assemblage composition on DCA axis 3 correlated significantly with discharge, with variations between years most pronounced at taxon rich sites characterised by coarse substrata (Figure 3.13).

3.3.5 Macroinvertebrate community response to climate change driven ecosystem changes

Invertebrate response model

The CLIO models used in this study comprise a range of regression relationships that simulate possible climatic effects on assemblage composition, rarity and richness for Yorkshire rivers at family level

Some examples of the regression relationships used are presented in Table 3.7.

Table 3.7 Significant regression relationships (y = ax + b) used in the derivation of the CLIO models
Yorkshire rivers

Dependent variable	Independent variables	a	b1	b2	r^2	Comments
1) Assemblage composition (DCA1)	Summer temperature (6) ºC	6.035	- 0.381		19.4%	See Figure 3.15
2) Assemblage composition (DCA3)	Discharge index (Q_{10})	0.189	-0.216		26.3%	
	River width (log_{10})			0.362		
2a) Assemblage composition (DCA3) (adjusted to accommodate future discharge increase)	Discharge index (Q_{10}) River width (log 10)	0.151	- 0.253	0.351	26.3%	
3) Family richness	Summer temperature (6) ºC	74.9	-4.12		12.5%	
4) Rarity index	Summer temperature (6) ºC	18.2	-1.14		10.8%	

Notes: The use of one or two slope parameters (such as b1 and b2) reflects simple and multiple regression (with more than predictor), respectively. Relationship 2a is identical to 2, but has been rescaled to account for increased Q_{10} projected for Yorkshire rivers for the 2020s–2080s.

Simulating future climates and their effects using CLIO

Discharge

For Yorkshire, increases in values of Q_5 and Q_{10} projected for the 2020s were large (all > 129 per cent, with some sites considerably more), thereafter falling moderately during the 2050s and 2080s. Projecting these discharge effects into the future involved extrapolating outside the calibration range. This entailed recalibrating CLIO to account for new discharge conditions (Eqn 2a, Table 3.7). Increasing discharge by this degree would shift DCA3 scores from a mean of 0.59 in the 1990–1998 period (range 0–1.29) to a mean of 0.42. Taxa most at risk would be slower flow specialists such as *Unionidae, Viviparidae, Bithyniidae* and *Molannidae* (Figure 3.16), although sensitivity to changes were low as parameterised.

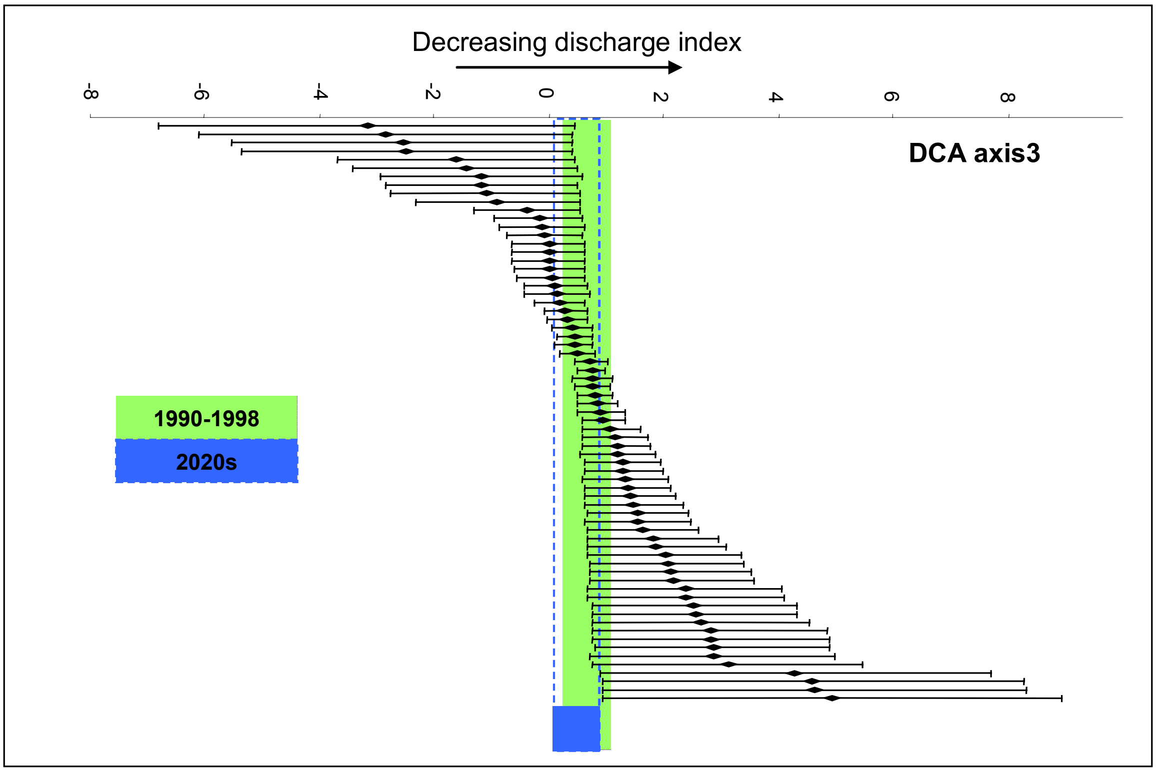


Figure 3.16 The optimum and amplitude of each invertebrate family in Yorkshire streams along DCA3 illustrating the effects of current and projected discharge according to CLIO

Notes: The green area corresponds to the range of DCA scores observed during 1990–1998. The blue/dotted area corresponds to the projected range of DCA scores using the CLIO models for the 2020s (Table 3.7). All families whose optimum and tolerance range fall within the respective shaded areas for the present or projected future are likely to be present in the assemblages.

Temperature

Projected trends in temperature, according to simulations using CLIO, had potentially more profound biological effects than discharge.

For Yorkshire, temperatures modelled by downscaling were on average 0.2°C higher than actual values for the 1990–1998 period, and hence a polynomial correction was applied to future projections ($y = 0.0002x2 - 0.9643x + 967.87$, $R^2 = 0.9965$). With this correction, projected temperatures increased by 0.5°C by the 2020s, 1.2°C by the 2050s and 2.6°C by the 2080s. Changes of this magnitude for the 2050s would imply a shift in DCA site scores by -0.46 units, which is sufficient to exclude several families from the sites sampled. Taxa most at risk include typical hill stream species such as *Perlidae, Leuctridae, Nemouridae, Leptophlebiidae, Astacidae, Sericostomatidae*. Losses of these taxa reduced both richness (by 9–36 per cent) and rarity scores in future simulations (Figure 3.17). Current Environment Agency monitoring of river invertebrates, dominated by family level assessment and ordinal recording of abundances, could mask more precise changes.

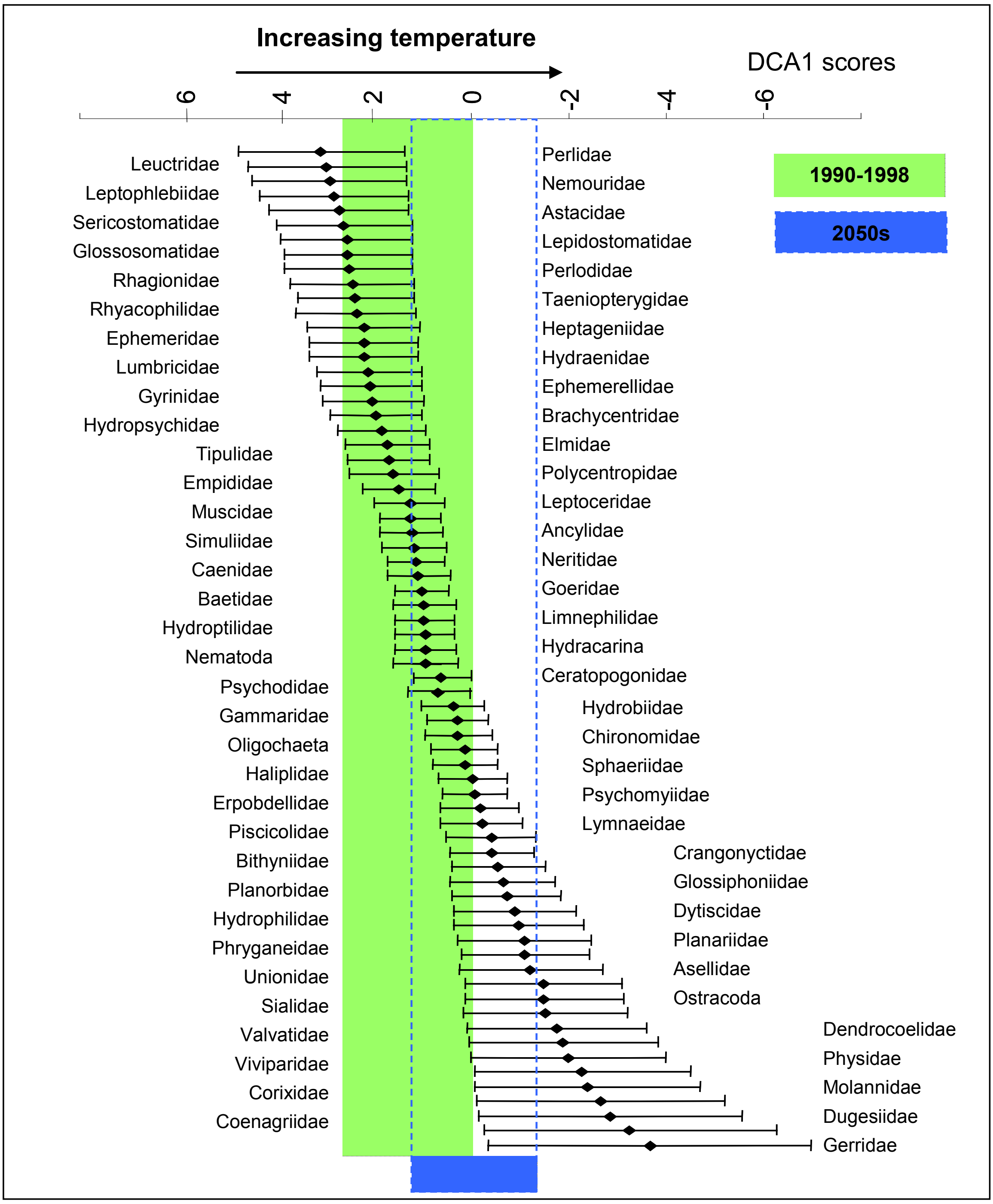


Figure 3.17 The optimum and amplitude of each invertebrate family in Yorkshire along DCA1 showing the effects of current and projected temperature according to CLIO

Notes: The green area corresponds to the range of DCA scores during 1990–1998. The blue/dotted area corresponds to the range of DCA scores projected using CLIO (Table 3.7).

3.4 Fish habitat response to climate change

This sub-section describes how the catchment-scale hydrological representation from CAS-Hydro interacts with a reach-scale hydrodynamic model to identify changes in habitat preference for key indicator species, in this case Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). A further novel development is the use of ‘fuzzy’ logic to define changes in habitat suitability for species in response to climate-mediated changes in flows, velocities and depths. The full transcript of the methodology is given in Appendix 6.

Figure 3.18 to Figure 3.21 give the results for nursery characteristics relating to Atlantic salmon (Figure 3.18 and Figure 3.19) and brown trout (Figure 3.20 and Figure 3.21), under the baseline (Figure 3.18 and Figure 3.20) and 2050s (Figure 3.19 and Figure 3.21) scenarios at the Oughtershaw site in the upper River Wharfe catchment. These results illustrate a number of important points.

There is substantial spatial variability in habitat suitability under all scenarios. Much of this variability relates to the fact that, at low flows, the prime control upon flow depth and flow velocity is the spatial structure of the river bed, including individual cobbles and boulders. This structure is unlikely to change under future climate conditions, as the magnitude of flow velocities required to change cobble and boulder densities are extreme. This fact emphasises the crucial importance of disaggregating discharge change impacts to the within-reach scale. This point is further emphasised by the way in which zones of suitable habitat become less suitable, and vice versa, as predicted discharges fall under the 2050s scenarios.

Finally, the specific impact of the discharge change on habitat suitability depends upon the species under consideration (Figure 3.22). For salmon, the simulations to the 2050s suggest a reduction in suitability for all three life stages, with a dramatic reduction for nursery habitat and smaller reductions for spawning and rearing habitats. For brown trout, however, there are almost no changes. The reason for this difference in response could be two-fold. First, it could reflect differences in the sensitivity of different organisms to different habitat classes: the more blurred ('fuzzy') that preferences become, the less that a given predicted flow change will alter habitat suitability. In other words, if brown trout had less clear preferences, they would be less sensitive to discharge changes. However, inspection of Table 2 in Appendix 6 suggests that this is not the case.

Second, and more likely, it reflects the fact that, in habitat terms, brown trout are more tolerant of the reduced Q_{95} in the 2050 scenario, in terms of the interaction between the flow and the bed topography. The reduced flow produces a velocity and depth field that is still within the range of habitat suitabilities found under the baseline scenario. Again, this emphasises the important contextual influence of particular local river geometries and individual organism habitat preferences in mediating the impact of climate change. This means that no general rules can be derived and inferring changes in habitat suitability from changes in flow alone is likely to be highly misleading. It should be emphasised that the width of the membership functions in Figure 3.18 to Figure 3.21 is a measure of the uncertainty in habitat preferences. The fuzzy approach explicitly maps this uncertainty into the predictions being made.

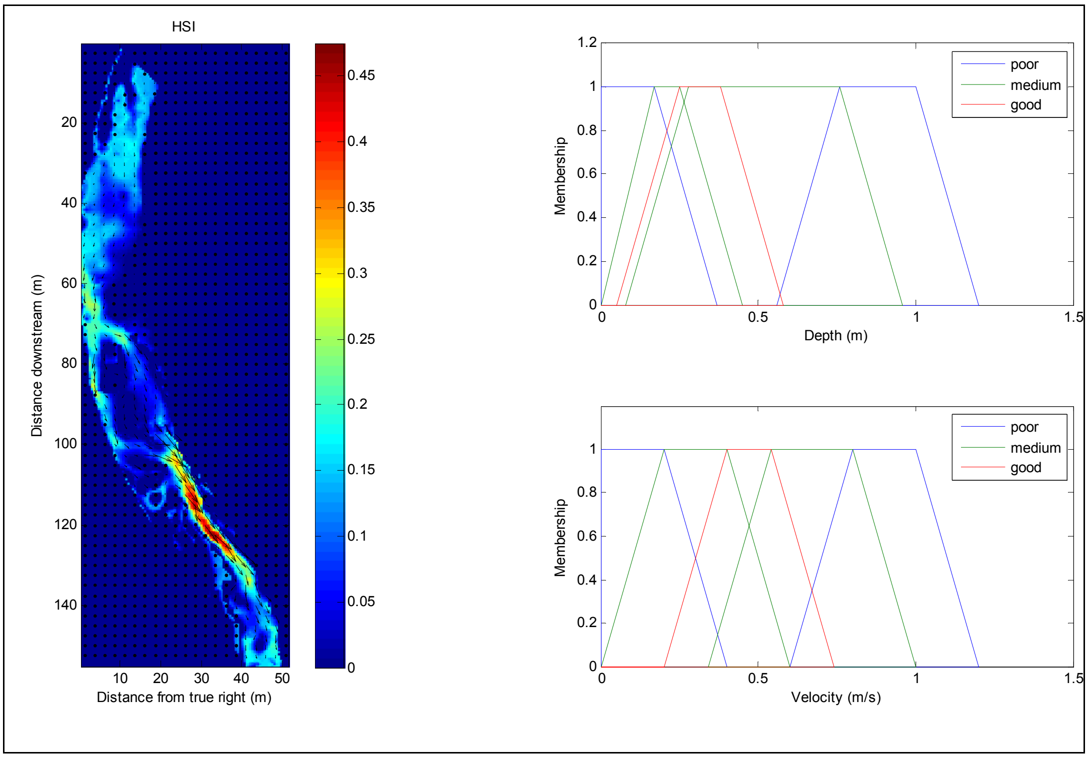


Figure 3.18 Baseline: *Salmo salar* nursery.

Notes: The colour bar shows the habitat suitability index which varies between 0 (unsuitable) to 1 (perfectly suitable). The membership curves are for velocity and depth. Membership curves are derived from a literature review. In the overlap range of reported preferences of velocity/depth for a given species, perfect membership (1) is assumed. Membership decays to 0 over the range of reported preferences that are non-overlapping.

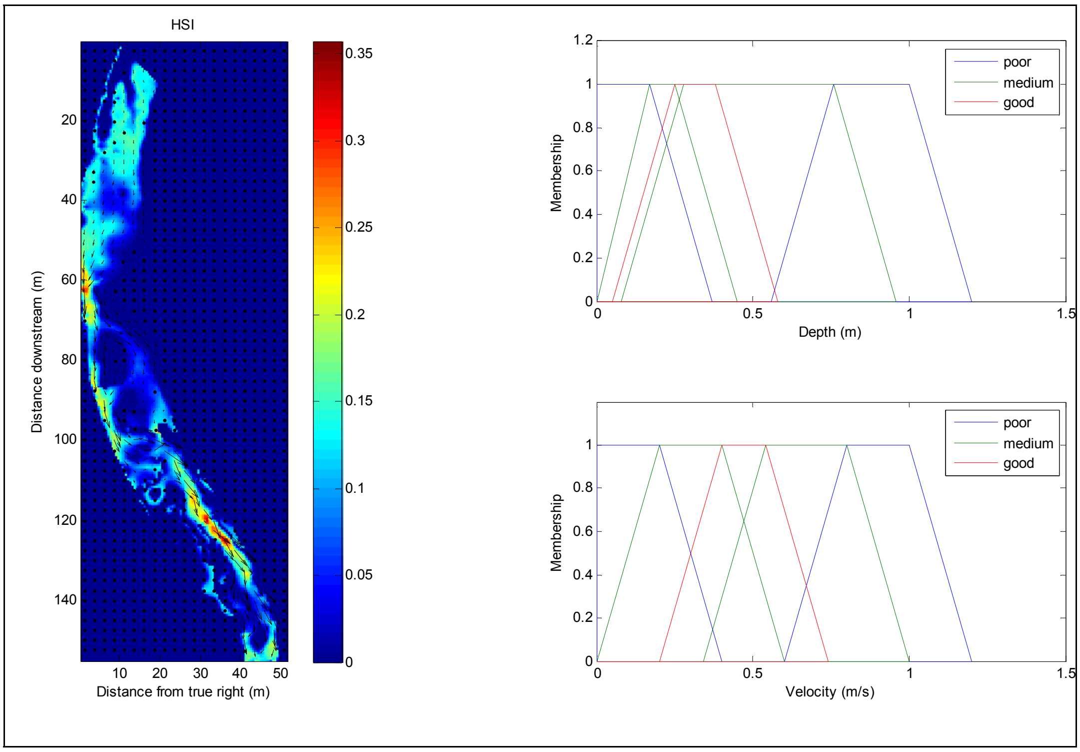


Figure 3.19 Illustrative 2050s: *Salmo salar* nursery

Notes: The colour bar shows the habitat suitability index which varies between 0 (unsuitable) to 1 (perfectly suitable). The membership curves are for velocity and depth.

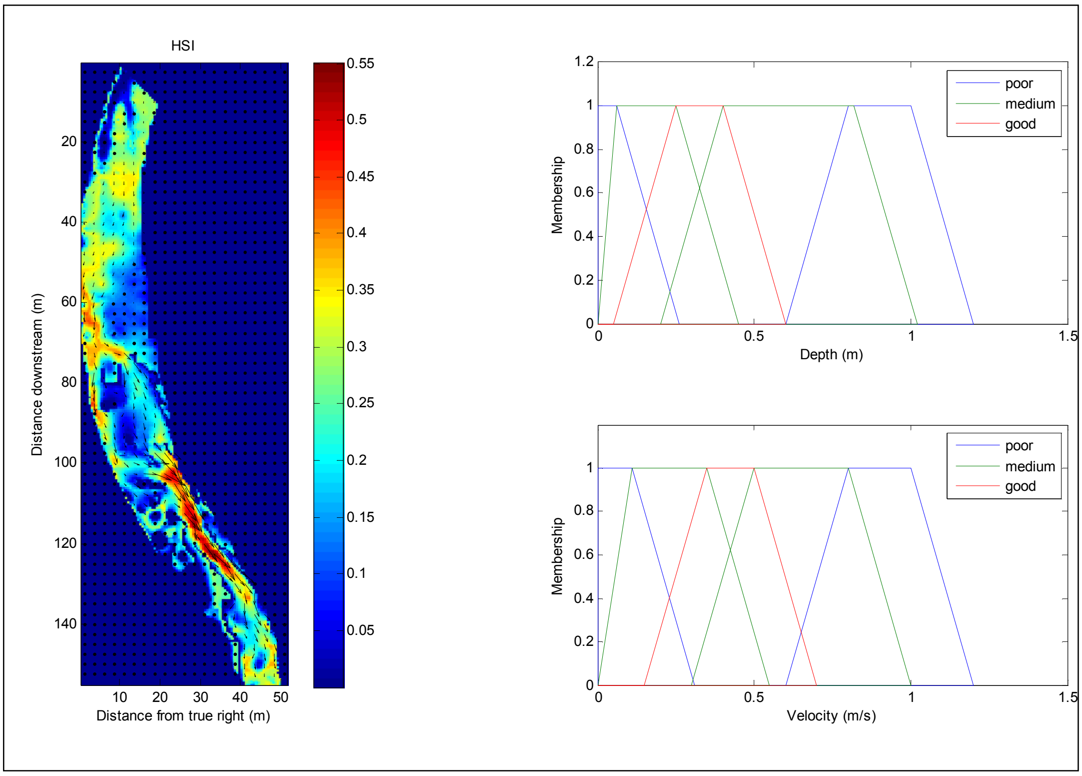


Figure 3.20 Baseline: *Salmo trutta* nursery

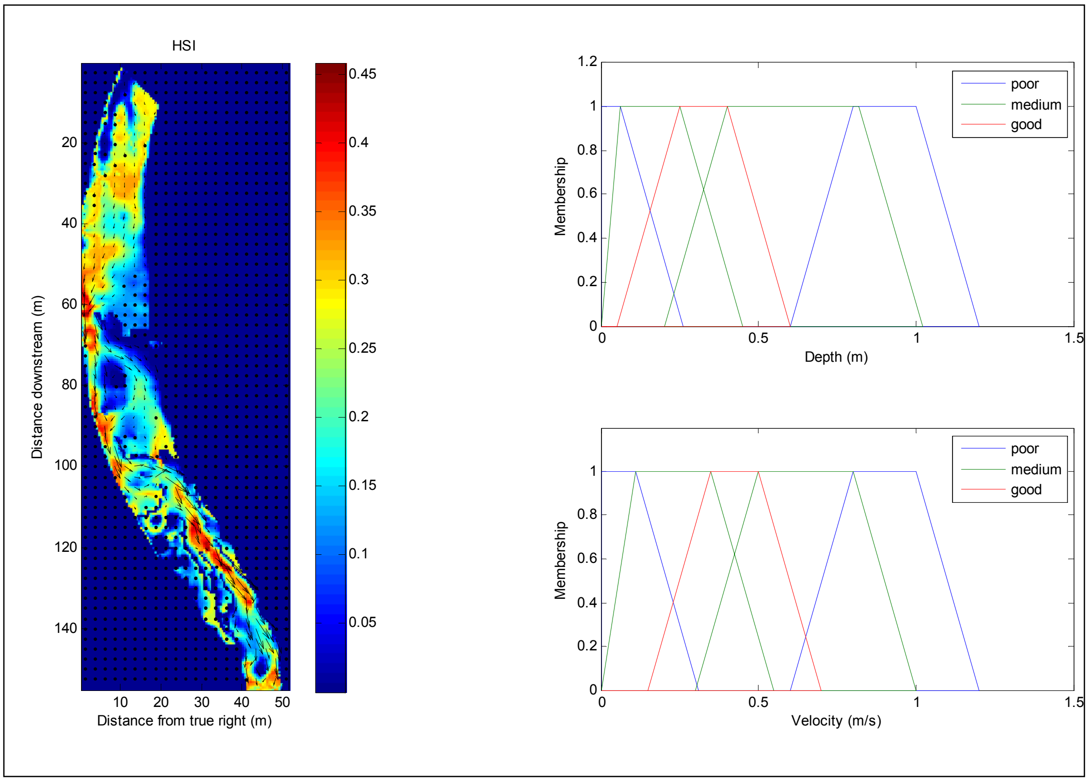


Figure 3.21 Illustrative 2050s: *Salmo trutta* nursery

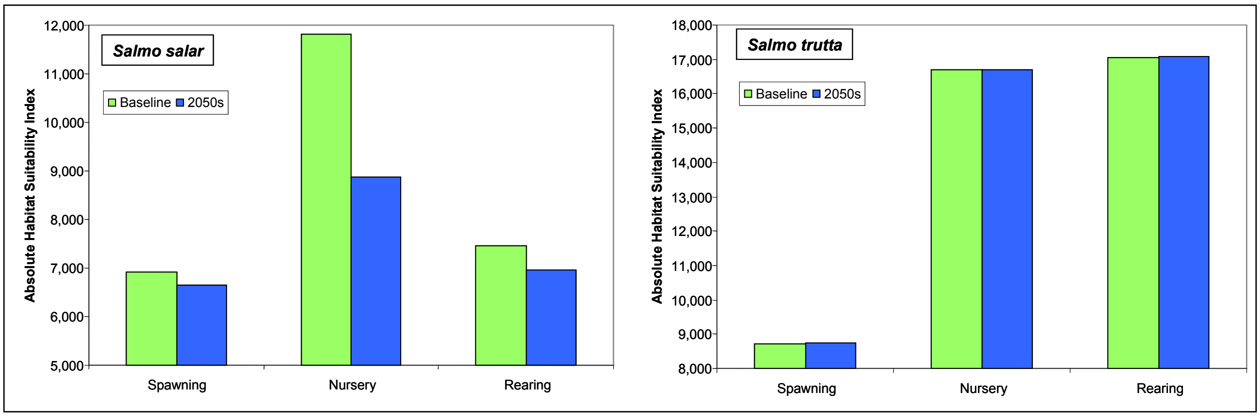


Figure 3.22 Illustrative changes in absolute habitat suitability index from baseline to the 2050s for *Salmo salar* and *Salmo trutta*

The conclusion from this work is that rivers with similar gravel beds in this region are likely to experience a net loss of habitat suitable for salmon due to the impact of discharge changes on velocity and depth. In reality, the evidence suggests that as headwater streams become drier, with reduced depth and wetted perimeter, salmon will have fewer habitats to migrate into and for their fry and parr to inhabit, reducing their upstream range. It is notable that many natural barriers already exist that limit upstream migration by salmon so that utilisation of remaining suitable habitat may be further constrained. Brown trout would then be able to move into and utilise these areas, as they would provide optimal habitat availability. However, it may be that their upstream boundary would also be sequentially reduced due to climate change, forcing them into erstwhile sub-optimal main stem locations. The modelling does not account for inter-species competition and density-dependant mortality, but these factors could clearly play a role in the modulation of salmon and brown trout populations in the upper reaches of rivers if climate change restricts the spatial integrity of habitats available to each or both species.

There are a number of other important caveats to these observations, which are discussed in Section 4. Nevertheless, this methodology and the innovative use of fuzzy logic to define optimal and sub-optimal habitat preference may well represent a significant improvement in the ability to simulate aquatic ecological effects, with particular reference to existing low flow studies and the issues raised in the EU Habitats Directive. Water temperature, and the consequent effects on dissolved oxygen saturation, may be an even greater factor affecting habitat suitability, but was not modelled in this study.

3.5 Comparisons of GCM simulations

Uncertainty regarding the impact of climate change on river flows comes from a range of sources. UKWIR (2007) identified the choice of GCM as the biggest source of uncertainty for river flow modelling – greater than uncertainty in emission scenarios, downscaling techniques, natural variability, hydrological model parameters and model structure. To account for some of this uncertainty, an alternative future was modelled using the Canadian GCM CGCM2. The output from this model was then used to generate empirical flow factors and macroinvertebrate models that could be compared with the UK GCM HadCM3 results.

3.5.1 Future climate scenarios

The Intergovernmental Panel on Climate Change (IPCC) has reported that of nine investigated global climate models all predict an increase in rainfall averaged over the UK by the 2080s relative to the 1970s baseline (IPCC 2001). However, the size of and direction of this change differs greatly from model to model and between seasons.

In the winter, UK average precipitation predictions in this period ranged from +1 per cent to +61 per cent. For the study areas investigated in this report, HadCM3 A2 predicts a large increase in winter mean precipitation for England and Wales (20–30 per cent); CGCM2 A2 predicts a smaller increase (10–20 per cent) (Jenkins and Lowe 2003).

In the summer, UK average changes in precipitation for this period ranged from -30 per cent to +4 per cent. For the study areas investigated in this report, HadCM3 A2 predicts a large decrease in summer mean precipitation for Wales (30–40 per cent decrease) and northern England (20–30 per cent decrease) (Jenkins and Lowe 2003). CGCM2 A2 predicts small increases in summer mean precipitation for Wales and northern England (0–10 per cent increase) (Jenkins and Lowe 2003).

No comparative studies of UK air temperature are available for the two GCMs. HadCM3 A2 predicts an annual average temperature increase of 3.0–3.5ºC for northern England and Wales by the 2080s relative to the 1970s baseline, with highest mean temperature increases (3.5–4.0ºC) in the summer and autumn months (Hulme *et al.* 2002). CGCM2 A2 predicts a lower annual average temperature increase of around 2ºC for the UK by the 2080s relative to the 1970s baseline (Environment Canada 2007).

3.5.2 Climate change impacts on mid-Wales headwater streams

The generation of future flows in mid-Wales headwater streams was constrained – by the nature of the catchment and the lack of hydrometric data – to the Arnell flow factor approach. The Arnell flow factors are derived from modelling with the HadCM3 A2 scenario, and no alternative with CGCM2 is available. No alternative future flows could be generated beyond those presented in Section 3.2.2.

Future air temperature data were developed using both GCMs (see Section 3.5.1). However, due to improvements in the temperature validation prior to CLIO modelling with the HadCM3 A2 scenario, there can be no direct comparison of the predictions generated by both GCMs for the macroinvertebrate community response to temperature-driven ecosystem changes.

3.5.3 Climate change impacts on Yorkshire rivers

Statistical downscaling of precipitation and temperature was conducted to a daily time-step using CGCM2 A2 (see Section 3.1), in order to provide a comparison with HadCM3 A2. These data were modelled using CAS-Hydro for the upper Wharfe catchment to Hubberholme. Figure 3.23 shows the predicted flows for the baseline period, the 2020s, the 2050s and the 2080s for HadCM3 (presented on Figure 3.7) with alternative futures (2020s and 2050s) for CGCM2. As described in Section 3.3.2, initial inspection of these aggregated results would suggest relatively little change between future periods and between GCMs.

Tests for the statistical significance of the trend in annual percentiles as a function of time indicated that none of the correlations are statistically significant and much of this will be because, even by the 2050s, much of the hydrological signal will be contained within natural noise. The correlations are generally negative for CGCM2, reflecting a tendency towards drier conditions. The marginal increase in high flows (Q_5 through Q_{40}) identified for HadCM3, in response to projected wetter winters, is not observed in the high flow trends for CGCM2.

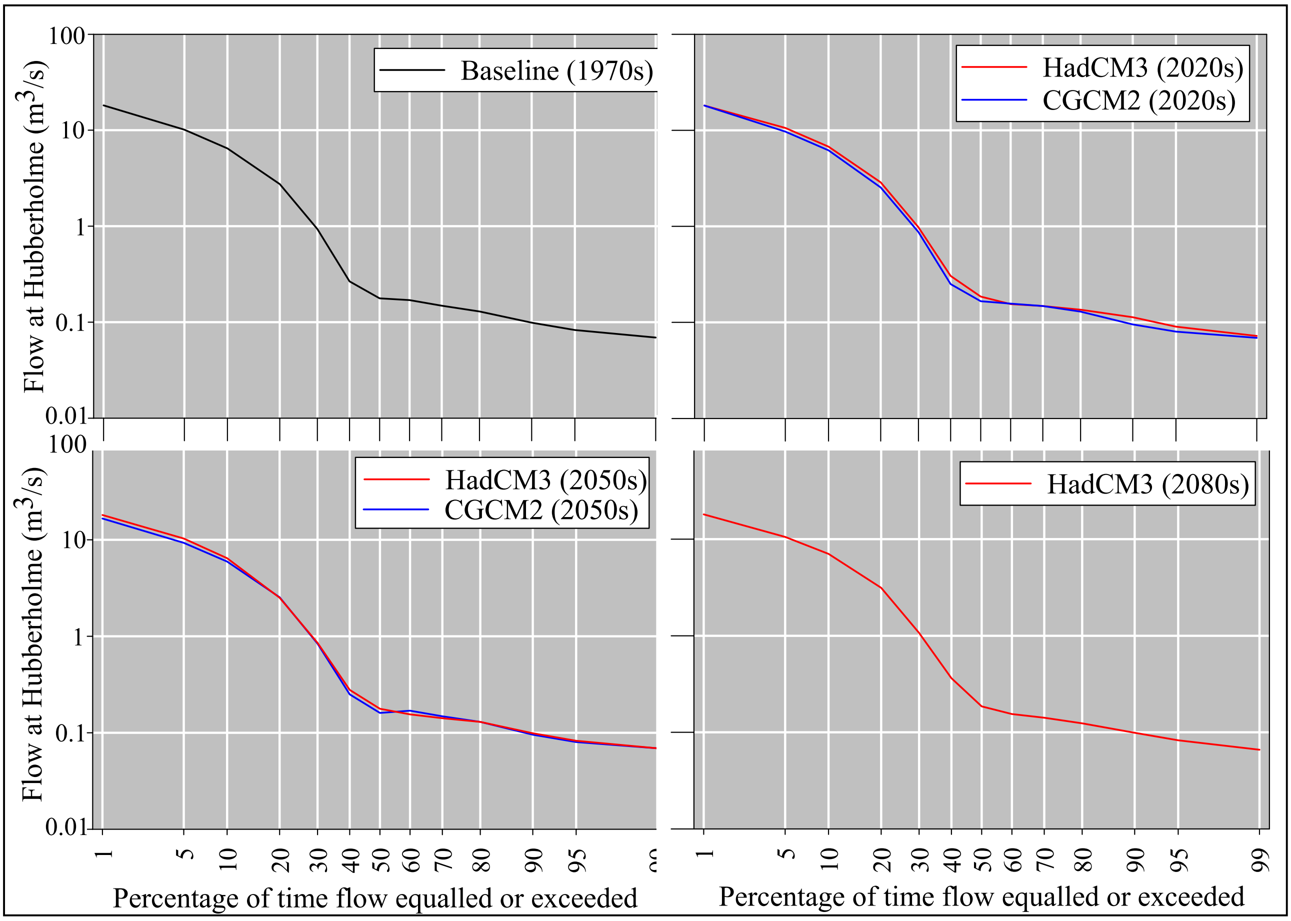


Figure 3.23 Predicted flow percentiles for the baseline period, 2020s, 2050s and the 2080s, showing the HadCM3 A2 and CGCM2 A2 scenarios

The empirical flow factor methodology was applied to the CGCM2 results for the upper Wharfe in order to provide alternative future flow data for use as inputs to the CLIO model of macroinvertebrate response to climate change in Yorkshire. Alternative future air temperature data were developed using both GCMs (see Section 3.5.1).

Discharge

Results determined using the HadCM3 input data are presented in Figure 3.16, while a comparison of the alternative futures (2020s) from the two GCMs is presented in Figure 3.24.

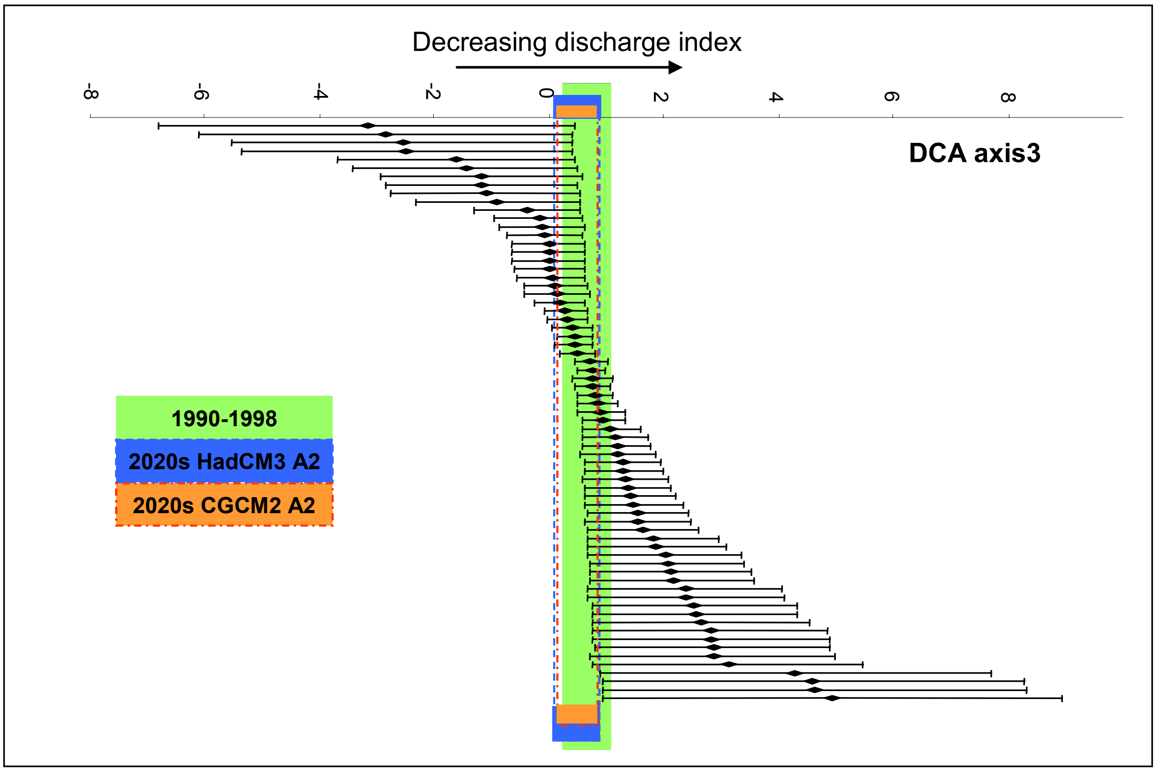


Figure 3.24 The optimum and amplitude of each invertebrate family in Yorkshire streams along DCA3 illustrating the effects of current and projected discharge according to CLIO for two alternative futures

Notes: The green area corresponds to the projected range of DCA scores using the CLIO models for the 2020s (Table 3.7b). The blue area corresponds to the range of DCA scores projected using CLIO for the HadCM3 model, while the orange area corresponds to the CGCM2 model. All families whose optimum and tolerance range fall within the respective shaded areas for the present or projected future are likely to be present in the assemblages.

For CGCM2, reductions in projected discharge for the 2020s–2050s ranged across sites on average by 3.5 per cent (range: 0.12 per cent–19.7 per cent). These reductions would not produce any noticeable biological effect on streams unless the frequency of extreme events also changed.

There is no discernable difference between the two GCMs on low flows (high values on DCA axis 3), although both predict reduced flows compared with the baseline period. The increases in the values of Q_5 and Q_{10} projected for the 2020s using HadCM3 drive the predicted increased impact of high flows (low/negative values on DCA axis 3).

Temperature

Results determined using the HadCM3 input data are presented in Figure 3.17 and a comparison of the alternative futures (2050s) from the two GCMs is presented in Figure 3.25.

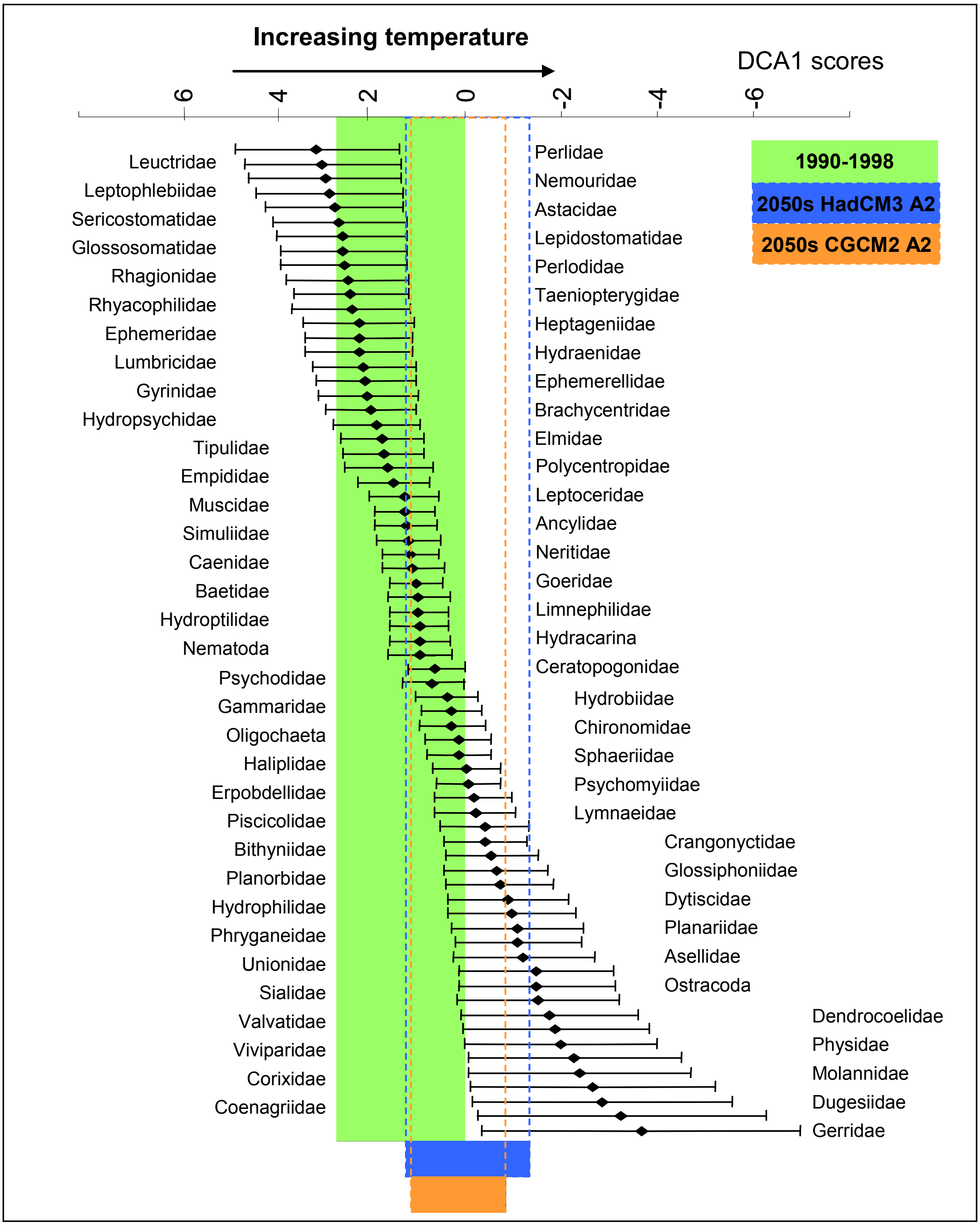


Figure 3.25 The optimum and amplitude of each invertebrate family in Yorkshire along DCA1 showing the effects of current and projected temperature according to CLIO for two alternative futures

Notes: The green area corresponds to the range of DCA scores during 1990–1998. The blue area corresponds to the range of DCA scores projected using CLIO for the HadCM3 model, while the orange area corresponds to the CGCM2 model. All families whose optimum and tolerance range fall within the respective shaded areas for the present or projected future are likely to be present in the assemblages.

For CGCM2, the projected temperatures modelled by downscaling rose by 0.5°C from the baseline period by the 2020s, 1.3°C by the 2050s and 2.1°C by the 2080s, representing a smaller scale of increase than the HadCM3 modelling. The more extreme range of future temperature changes predicted by HadCM3 was portrayed in the CLIO modelling as a wider band of future temperatures than predicted by CGCM2. As with HadCM3, the taxa most at risk include typical hill stream species; however, more species are modelled as being at risk with CGCM2, including *Lepidostomatidae*, *Glossosomatidae* and *Perlodidae*. This is because fewer species are modelled as within their optimal temperature ranges with CGCM2, with consequent effects on future species' richness and rarity.

4 Discussion

The findings of this research project are discussed below in five topic areas:

- generation of future climate data;
- methodological issues with flow modelling approaches;
- impacts of climate change on macroinvertebrate assemblages;
- impacts of climate change on fisheries habitat;
- implications for water and biodiversity policy.

4.1 Generation of future climate data

This project has been ambitious in the range of applied techniques and the integration of these methods within the study framework. A significant element of the workload has been identifying and developing suitable baseline and climate change meteorological datasets.

4.1.1 Temperature

Water temperature data have presented the least challenges, although the lack of such data has necessitated the extensive use of air temperature data. This has highlighted problems in identifying suitably located meteorological stations with data covering the period 1960–1989 (a minimum 10-year block of data is required to calibrate SDSM, but a longer record is advisable).

The studies have used available daily average air temperatures (stream temperature responds slowly to air temperature, so changes in daily maxima and minima are not as relevant). However, SDSM cannot incorporate or link these variables and instead requires modelling of the maximum and the range. The method produces good forecasts of future average temperature as a monthly aggregate of daily averages.

However, relying on data aggregation to arrive at the indicative futures (30 continuous years of modelled output data are aggregated to mean values indicative of the 2020s) has a number of disadvantages. Aggregation – out of necessity for the resolution of ecological data – loses the ability to identify the sequence of events, such as multiple hot, dry summers. However, these events may be a significant constraint or throttle to ecosystem function, particularly where such conditions may become increasingly prevalent. This is less of a problem for air and water temperature, but presents some difficulties for sub-daily and particularly sub-hourly rainfall.

4.1.2 River flows

When using increasingly sophisticated catchment-based hydrological models, the data needs often become greater, as is the case for CAS-Hydro. Here, rainfall and air temperature are used as CAS-Hydro inputs. Statistical downscaling using SDSM was undertaken to forecast future rainfall and average air temperature on a daily basis up to the 2080s. The future climate scenario is based on the perturbation of a measured meteorological record, with a preference for a continuous daily measured record of the 1970s for the pre-climate change period (1960–1989). The SDSM daily time-step is suitable for temperature (with caveats about generating a time series out of the maxima and range). However, the continuous hydrological simulation models are able to utilise sub-daily rainfall to calculate storm flow peaks. This is a level of sophistication that is in-built within CAS-Hydro and is not required in other less sophisticated catchment hydrology models. Sub-daily downscaling has already been identified elsewhere for storm modelling and urban sewer system capacity (UKWIR 2003), representing the limit for current climate modelling (see BETWIXT project at http://www.cru.uea.ac.uk/cru/projects/betwixt/).

Although the emerging hydrological modelling systems are capable of simulating future climates, there remain some difficulties in matching the capability of current climate modelling (from the global and regional models through to the downscaling to sub-hourly rainfall generators) with the data requirements of empirical and deterministic models. These issues are now recognised by the research community and are gradually being addressed. The next generation of GCMs will provide probabilistic output and thereby give more insight into key uncertainties affecting GCM projections.

In summary, for the purposes of the ecological interpretation of potential impacts, it would be an advantage to gain a better understanding of the changes in sequencing and periodicity of climate for worst case years. This is especially the case for any increase in the occurrence of multiple dry years and the magnitude and frequency of storm events. Future ecosystem impact studies may therefore benefit from the generation of downscaled data with finer resolution, which can capture sub-daily hydrological extremes (although these scenarios may be highly uncertain). This would be more relevant for high flow assessments, as high flow is likely to be an important throttle to ecosystem productivity (such as flushing juvenile fish).

4.1.3 Comparison of GCM simulations

To account for some of the uncertainty regarding the impact of climate change on river flows and air temperatures, two alternative futures were modelled using the UK HadCM3 A2 model and the Canadian GCM CGCM2 model, both for the medium-high (A2) emissions scenario. In general, as reported elsewhere, the HadCM3 model predicts a more extreme set of future air temperatures than many other GCMs, and lower summer rainfall. As a result, the modelling of macroinvertebrate response to predicted climate change led to more severe impacts for the HadCM3 model, although the direction of change was generally replicated for both GCMs. The HadCM3 A2 scenario also predicts higher winter rainfall, resulting in an increase in future high flow statistics; this is not replicated in CGCM2 A2.

Although uncertainty in climate futures results from the choice of GCM, a range of GCMs can help interpret the direction and magnitude of modelling uncertainty. However, the use of aggregate statistics in the data-driven (empirical) ecological modelling may mask specific aspects of climate change, as discussed further below.

4.2 Methodological issues with flow modelling approaches

The study has reported on two methodologies (flow factors and continuous simulation) for estimating future flows in response to possible climate changes. These methodologies were chosen as they represent two extremes of a spectrum ranging from simple empirical approaches, albeit informed by underlying predictive models, through to more advanced continuous simulation models, which are developed to have a physical basis but depend upon calibration/parameterisation and have significant computational demands.

To illustrate the simple empirical approach, the study applied the Arnell (2003) flow factor methodology to provide future flow predictions to the 2020s. This methodology is based upon the regionalisation of rainfall run-off models for future perturbations to monthly climate. For forecasting future flows in relation to ecological needs, this approach has a number of problems.

i) The approach currently only provides information for the 2020s, and not for the 2050s or 2080s, although conversion factors are available. Climate change signals only appear to become statistically significant for both temperature and precipitation after 2020.
ii) There are uncertainties over the validity of the approach for larger catchments.
iii) There will be considerable spatial variability in flow percentile estimates between sites depending on the length of flow records, which are highly variable prior to 1990.
iv) As the approach is based on perturbation of an historic flow record, it generates a range of future flows that encompass the sequencing, frequency and magnitude of the baseline rather than distinguishing future climates (changes driven by future rainfall and temperature) from the baseline.
v) It is highly unlikely to provide meaningful estimates of high flow percentiles, as the factors are designed to apply to monthly averages rather than storm-event scale run-off.

To illustrate a more complex approach, the study used the CAS-Hydro continuous simulation model, calibrated on a catchment in North Yorkshire. This approach has a number of advantages compared to the flow factor methodology.

i) It can provide a continuous record of future daily mean flows through to, and including, the 2080s.

ii) It retains sufficient information on catchment characteristics to allow an explanation of future climates to be considered (for example, the relative contributions of temperature and precipitation changes to changes in future flows due to climate change).

iii) In theory, the methodology is generic, in that such models can be applied to any catchment, provided that they are parameterised with respect to each catchment. But CAS-Hydro is a data hungry tool.

iv) Information can be aggregated to any time scale, such as sub-daily, daily, monthly and so on.

v) It is possible to estimate the complete flow duration curve from model predictions.

vi) The model can also form the basis for regionalised flow factors, as discussed in Section 3.3.1.

The advantages of using a continuous hydrological simulation model such as CAS-Hydro for ecological assessments have been demonstrated in this study. Such models are capable of simulating the ecologically-relevant sequencing and extremes of river flows and the duration and temperature that are required to determine potential ecological responses. These include the duration and frequency of low flow events and the magnitude and frequency of extreme high flows, which are known to be of great importance to ecosystem function and dynamics. These data are not available through the flow factor methods that, of necessity, use lumped statistical approaches (mean monthly flows).

However, fully-distributed continuous CAS-Hydro simulation has a number of disadvantages and these are significant.

i) The model is computationally demanding, limiting the extent to which a full propagation of parameter uncertainty can be undertaken without the use of some form of parallel processing. It may also limit the number of catchments and climate scenarios that may be modelled quickly.

ii) Although the model was run with a 50m resolution for computational reasons, there are still debates over whether or not this resolution will capture the actual hydrological response. Not least because running the model with a finer spatial resolution is now possible given the available data (topographic data with 2m or 5m resolution).

iii) The model requires certain assumptions to be made for parameters that can't be measured (such as soil depth) and this means that the model requires careful calibration and verification against observations.

Of these advantages, (i) is the most important, as parameter uncertainty represents a form of noise in model predictions. Establishing model uncertainty is necessary in order to be able to assess the extent to which future predictions of flow are statistically different from present, given parameter and data uncertainty. This is especially the case for high flow events, whose magnitude is particularly sensitive to parameterisation. Similarly, the methodology used to generalise predictions for Yorkshire rivers (empirical flow factors) assumes that all catchments (regardless of location or size) will respond in the same way to climate change. This was done because applying the model to multiple catchments was impractical given the timescale and budget. This assumption may not reflect reality, but is a more reliable generalisation than those applied for previous aggregated statistical approaches, such as the Arnell flow factors.

Both of the methods also suffer from one major challenge. Implicit in the modelling exercise is that the prime control on future river flows will be related to climate change. However, a number of study catchments are heavily regulated (such as for flow abstraction, where the predominant flow regime is a fixed compensation flow during low flow periods). In such catchments, it is vital that future modelling methodologies take into account the management regimes associated with flow regulation and the ways in which those regimes might be impacted upon by climate change, as these management regimes may provide the dominant hydrological signal.

4.3 Impacts on macroinvertebrate assemblages in response to climate change

4.3.1 Relating significant variations in macroinvertebrate character to existing climate variations

In mid-Wales, for both acid and circumneutral moorland streams, several aspects of the stream invertebrate assemblage (such as abundance, stability and composition) varied significantly with climatically-mediated variables, but no major effects were detected for acid forest streams. The most frequent effects involved the NAO, but increasing temperatures also significantly changed community composition in acid moorland and circumneutral streams and markedly reduced abundance.

Macroinvertebrate sampling in spring (April) reflects changes in winter discharge. No major effects of winter discharge were detected, although low discharge in the previous summer apparently affected assemblage composition during the following April.

For the Yorkshire rivers, climate variables had a major influence but were still less significant than variables describing the type of river (distance from source, substrate composition and depth), as may be expected. Significant correlations were recorded between assemblage composition, richness and temperature over the six months preceding sample collection, as a result of differences between site location and inter-annual variation. Macroinvertebrate sampling was undertaken in autumn (usually September-October) and was typically only to family level. There was no significant association with flow, including low flow in the preceding summer.

Having data only at family level does mask the impact of environmental variables, as each species within a family may have different ecological requirements. Hildrew and Edington (1979) showed, for example, that there is a marked downstream sequence of Hydropsychidae and that this is related to sequential differences in temperature. Although the species within some families (such as Baetidae) tend to have similar responses to temperature, this is often not the case. In freshwaters, temperature and discharge are often the key ecological variables controlling distribution of macroinvertebrate species. It is believed that species-rich assemblages achieve co-habitation through a fine partitioning of resources (for example, in terms of adequate habitat). A broad partitioning of resources occurs through differences in family traits (mainly morphology and life cycle), but fine partitioning of resources results from specific differences in species traits (such as behaviour and competition). It is thus most probable that limiting the analysis to family level will mask climate impacts, suggesting that family-level surveys lack precision to understand fine assemblage processes.

4.3.2 Empirical modelling of macroinvertebrate variation in response to climate change

Trends of future climate into the 2050s and 2080s could add a further 1–2ºC to both the current average air and water temperatures. The studies suggest that such increases would exceed the current range occupied by certain macroinvertebrate species (mid-Wales) and families (Yorkshire). The consequence would be a change to the macroinvertebrate assemblages in the various streams and rivers under investigation, including a significant reduction in the communities' abundance (mid-Wales) or richness (Yorkshire). Springtime macroinvertebrate abundances in some streams might decline considerably, with consequences for energy transfer to predators, food web function and other ecological processes. For example, this effect may influence the communities and species, such as fish populations, that rely on macroinvertebrates as food sources.

The identified effects also appear to be variable between river types, with species rich, unpolluted (non-acidified) shallower rivers apparently most at risk. Unshaded upland headwaters track air temperatures very closely, due to the minimal effects of evaporative cooling, groundwater inputs and thermal mass, and hence appear to be highly sensitive to temperature gains and the consequent ecosystem effects. In general, the species and families whose preferences will be most affected are those adjusted to higher flows and lower temperatures. The study does not consider whether new species are likely to be found in future.

Interestingly, the key predicted changes to the communities are temperature-mediated, with few signals of flow-related impacts. This would appear to be counterintuitive, as it is generally held that higher temperatures and lower summer rainfall will lead to decreased summer river flows (and consequent aquatic ecological effects). However, the hydrological simulations using HadCM3 have demonstrated that once the data are aggregated into mean statistics (monthly/annual means), the extremes become less clear and the sequencing of events gets lost. It may well be that the treatment of the data has led to the loss of information that would be available from continuous simulation to support the analysis. There would appear to be a need for a better link between the magnitude, frequency and duration of flood and drought events into the future, in order to further understand the potential for variance in community structure. This was not undertaken for this project because detailed macroinvertebrate data were only available for mid-Wales, while the continuous simulation modelling that produces such flow variables could only be run for Yorkshire rivers. The lack of high resolution invertebrate data is a significant constraint to further study.

4.4 Impacts on fisheries habitat in response to climate change

Habitat suitability modelling is a well established technique that is benefiting from significant advances in both hydrodynamic and habitat suitability analysis.

4.4.1 Predicted effects of hydrological change on salmonid habitat

The salmonid studies in the upper Wharfe considered the implications to habitat availability and preference of changes to the hydrodynamic regime. The studies used a novel approach for simulating habitat availability and quantifying the consequent change in suitability as a result of hydrological/hydrodynamic modifications to stream character. The analysis was applied to a short (150m) reach of gravel bed river in North Yorkshire, which is characteristic of the flow sensitive reaches often used in water resources and drought impact studies.

The embedded modelling framework, which links catchment scale CAS-Hydro hydrological analysis into a detailed 2D hydrodynamic model, allowed climate-induced flow changes to be incorporated into a reach-scale assessment. Key findings of this model include the potential for climate change to displace salmon from upper headwater and stream locations, as their preferred habitats are constrained by low flows. There would be fewer implications for brown trout in these locations, as their water depth and flow velocity preferences fall within the acceptable envelope of change for this site.

Other potential influences on fish community structure, including changes to temperature profile and the flow requirements for other life-stages (such as smolt migration and spawning), could be undertaken using this approach. Any impacts would be cumulative, particularly where habitat preference and/or life-stage flow requirements may be further limited. Effects could be exacerbated by off-setting key life-stage periodicities, such as fry emergence. These preliminary findings suggest that there may be significant effects of climate change on fish communities in headwater reaches and that these effects could be exacerbated by as yet untested cumulative effects (for example, temperature changes, availability of macroinvertebrate prey). Extension of this analysis is recommended, as the ‘fuzzy’ analysis can accommodate multiple habitat preferences.

A consequence of changes in flow and temperature may be changes in salmonid and macroinvertebrate species distribution and community composition, potentially resulting in local extinctions. This research highlights the vulnerability of upland sites, which can contain important biodiversity fragments for susceptible species.

It is possible that the trends identified may be more acute in the south of England, where previous research has predicted more extreme hydrological effects resulting from climate change. This could clearly have implications for headwater assemblages of macroinvertebrates and fish, with earlier and greater impacts.

4.4.2 Benefits and limitations of methods

The developed approach is important because it demonstrates that the biological response to climate change is likely to be much more complex than might initially be thought.

The findings emphasise that parameterising biological changes through change in a flow percentile is unlikely to capture the full range of possible biological impacts. This is because organisms have preferences for particular combinations of velocity and depth. How a given change in flow affects the distribution of velocities and depths will depend upon the local morphology of the river being considered. This was demonstrated by using morphological data that included key ecologically-relevant information (such as individual cobbles and boulders) in the model. It follows that the ecological significance of any change in a future flow percentile can only be interpreted through an understanding of the river type in which it is occurring. This approach may be transferred to any situation where there are predicted flow percentiles and associated morphological data, and where species preferences can be determined from a literature review.

However, there is a need to emphasise some caveats to the approach.

- The analysis is only relevant for predicting changes in future habitat, which are only ecologically-relevant if habitat is the limiting variable.
- Implicit in the analysis is the assumption that velocity and depth do limit habitat. Clearly, both have a major impact upon the wetted usable area, which has been shown to map reasonably well onto system productivity when habitat is limiting. However, climate change will cause changes in other variables (such as water temperature and fine sediment delivery) and these have the same or greater importance than depth and velocity. In some cases, velocity and depth may be a surrogate for some other parameters: for instance, higher velocities and deeper flows will have cooler temperatures, while faster velocities will have lower fine sediment contents. This is implicit in the habitat preference data used to populate these models (see Appendix 6), because the data are based on observations of parameters such as temperature and substrates that are difficult to control. The main issue to be established is the extent to which depth and velocity capture these other variables and, depending on this extent, what additional variables may be required.
- The individual methods themselves may have limitations. For instance, the hydrodynamic modelling may poorly represent velocity and depth gradients at points where the rate of change of topography is rapid, such as close to boulders. Similarly, the model focuses upon depth-averaged velocity, whereas what matters for organisms is the velocity at which they rest/move (the nose velocity), which commonly happens closer to the bed. Ecological data rarely refer to exactly what velocity is being recorded, which emphasises the need to model uncertainty explicitly, as in the fuzzy analysis presented above.
- Habitat suitability analysis of this kind requires an assumption that the reaches are representative, although they may not be. In future studies, evolving habitat mapping techniques (such as for salmon) should be considered, in order to identify key sensitive life-stage habitats for the indicator species within the river reaches of concern. It may then be possible to extrapolate reach-scale data to wider spatial scales.
- The preceding caveat maps onto perhaps the biggest problem with this kind of analysis, which is the variability in the extent to which organisms can adjust to the changes. When viewed in terms of rearing habitat, organisms will have much more capability to move in order to find the right habitat. When viewed in terms of spawning, or nursery habitat, this will be much less the case. The model does not take into account larger scales of habitat variability as the mobility of the life stage of the organism increases, but these larger scales of analysis will become increasingly relevant. Methods are emerging that link different life-stage preferences to the availability of suitable ‘next generation’ life-stage habitats.
- The complexity of the modelling means that uncertainty analysis and/or multiple scenarios (emissions and GCMs) are not feasible.

4.5 Implications for water and biodiversity policy

4.5.1 Policy issues

It is likely that there will be unavoidable changes in the composition of macroinvertebrate communities, which will impact on our understanding of conservation status. Identifying a climate change response (fingerprint) at a variety of sites may allow a distinction to be made between climate and other drivers of change in ecological status and add to the debate about the need to mitigate against further climate change.

Changing natural base flows may also change the sustainable limits of exploitation, implying that changes may need to be made to the way that fishing licenses and consents are awarded. Further consideration of the catchment management implications (for water resources, wastewater treatment and diffuse pollution) is also recommended.

Changes in land use and river management may therefore represent important factors in the development of adaptation and resilience strategies.

4.5.2 Nature conservation designation

These preliminary findings have potentially significant implications for water and biodiversity policy. Designated upland watercourses or habitats (Natura 2000 sites through to Biodiversity Action Plan (BAP) habitats and species) could be vulnerable to climate-induced effects, including changes to macroinvertebrate assemblages and fish populations. This may have implications for conservation and water quality objectives. Equally, changes to biological communities may affect the characterisation of all water bodies which will need to be taken into account in implementing the EU Water Framework Directive (WFD). It should be noted that these preliminary findings are based on simple hydro-ecological relationships and that consideration of more complex interactions may lead to greater predicted changes in ecological response.

Consideration should also be given to profiling climate-sensitive catchments. These may include watercourses with characteristics that are particularly vulnerable to hydrological- or temperature-induced change. Regional variations may also need to be considered, including the susceptibility of certain catchments in southern England to more rapid hydrological change and greater predicted climatic variation in the future.

4.5.3 Aquatic monitoring

The availability of suitably robust long-term datasets at the required resolution (such as species level analysis for macroinvertebrates) has been a major issue for this project. There is a strong recommendation for a review of current baseline ecological monitoring to be conducted. This is to ensure that those assemblages being monitored are being considered at the correct spatial and temporal resolution and at the most useful level of detail (usually to species level). Other data (hydrological and/or physico-chemical) may also be of use if measured concurrently, in order to aid our understanding of biotic responses to climate variables.

It may be useful to consider reviewing the Environmental Change Network, in order to ensure that it supports the validation of future climate change analyses and possibly aids parameterisation (this needs further verification). Existing biological monitoring tools may need assessment to ensure they are capable of detecting climate change driven responses.

A key finding of this research is the fundamental need for a long-term monitoring programme with explicit goals. This is emphasised and enforced by recent work (by members of the project team) on the environmental monitoring plans for drought studies in England and Wales, where it is currently difficult to identify specific climate-mediated impacts without access to long term species-level macroinvertebrate records.

4.5.4 Adaptation strategies

The current research has identified that species and communities will be affected by climate change, but it is unclear whether these effects (and any cumulative impacts not yet considered) can be mitigated. Given that creation, and loss of habitats are only possible in dynamic systems able to adjust to changing regimes, restoring natural processes in catchments should be considered a 'no regrets' adaptation strategy.

The findings of this research suggest that there will be substantial climate-driven biodiversity impacts on upland headwaters. Adaptation strategies should therefore seek to limit any adverse effects. These strategies may include adopting land use management practices that promote natural habitat evolution, identifying protective refuges and promoting catchment management practices that limit climatic influence (such as wetland protection and tree planting in river corridors).

The modelling approaches described and used in this study have provided regional and habitat specific information for a limited range of species. Adaptation strategies also need to be informed by a national awareness of sites and species most likely to change in response to climate. Some of this information may come from analysis of existing data and further modelling. In addition, we may need monitoring specifically designed to track changes in climate driven freshwater ecology.

5 Conclusions and recommendations

5.1 Conclusions

A number of key conclusions have emerged from this research.

i) Climate-driven changes to both the average and extreme values for ecologically-relevant parameters (such as flows and temperatures) need to be identified and included in the models, as extreme events may often be the throttle to ecological impacts. This will require continuous simulation of meteorological conditions and catchment hydrology to identify peaks, durations, frequencies and sequencing of key events (floods, droughts). It may then be possible to use transfer functions (such as empirical flow factors) to extrapolate findings to similar catchments and thereby reduce the reliance on computationally-demanding modelling.

ii) Species-level data, and in some circumstances life-stage requirements (for fish fry and adults), will be required to identify ecological impacts to the required level of definition. This specifically applies in the present studies to macroinvertebrate data (many of the surveys only identified samples to the family level), but will be applicable to other communities in the future.

iii) The studies have confirmed that upland headwaters and rivers are sensitive to climate-induced change. These types of ecosystems, with habitats and species at the extremes of their range, may require specific legislative protection and adaptation strategies to preserve their integrity. It is likely that a wider range of habitats, communities and species will be affected by climate change and recommendations have been made to asses the wider implications on freshwater catchments.

iv) Communities and species will be impacted to varying degrees by climate change, depending on their niche requirements. These impacts will be integrated with a complex series of inter- (such as density-dependant) and intra-species (such as competition) interactions, as well as immigration and emigration, which will together define the future dynamic evolution of freshwater ecosystems. The current studies have investigated a limited number of habitat preferences, which are shown to moderate community and species structures. Future studies will need to consider other interacting factors that can influence community structure.

v) Habitat modelling has been developed to describe potential impacts at the reach scale. The development of better sub-catchment and catchment characterisations could widen this modelling to sub-catchments and eventually whole catchments. Emerging work on catchment typologies for the WFD may improve our understanding of the potential habitat linkages, as well as the up-scaling that may be possible.

vi) The potential changes in habitat availability and consequent ecological impacts in response to climate-modified freshwater catchment characteristics will be of concern to catchment managers currently considering the implications of the Habitats Directive and the WFD. Possible climate-induced changes to the future ecological baseline could clearly influence maintenance and restoration programmes for protected habitats and species.

5.2 Recommendations for future investigations

Given the indications from these studies of likely climate-mediated impacts for habitats and species in the assessed locations, as well as the finding that the methodologies are sufficiently well developed to identify future changes, the project team would make the following recommendations.

- Implement further catchment- and reach-scale modelling using the developed techniques to establish potential implications for a wider range of habitats and species. Specification of indicator habitats and species should be informed by the findings of the previous scoping report.
- Develop a better understanding of the primary climate drivers of ecological response, especially more sensitive flow variables (such as peaks over threshold, and the sequence and duration of flood and drought events). This could be achieved by a more detailed analysis of historic time series of biological data.
- Develop more comprehensive ecological impact assessment models with enhanced process representations that can simulate the response to environmental variability.
- Develop catchment- to reach-scale typologies to allow the extrapolation of sub-catchment assessments to wider spatial scales; for example, through the use of geo-referenced remote sensing techniques.
- Determine the relative effects of other non-climatic influences on assemblages and species that could mediate or exploit climate-induced changes. The possible consequences for climatically-sensitive organisms (displacement, extinction, adaptation and replacement by invasion) are currently very poorly understood.
- Support more high resolution ecological monitoring to allow detailed analysis of niche-specific impacts caused by climate change, as a result of subtle inter-species habitat preferences.
- Apply the UKCIP probabilistic climate change scenarios, when they become available, to establish a better understanding of the range of potential changes in meteorological conditions and their potential ecological impacts.
- Establish a standard sub-hourly downscaling routine to produce rainfall data at a suitable resolution for use as an input to continuous hydrological modelling.
- A specific adaptation response to the findings of this study should be prioritising the maintenance of habitats, improving and restoring upland headwaters to reduce vulnerability and increase the resilience of the ecosystem. Measures could include, for example, planting riparian trees to increase watercourse shading and providing protection against increased abstraction.
- Assess the climate sensitivity of other habitat types in other regions
- Assess species sensitivity to climate at a national scale

Glossary

Abiotic	Non-living objects, substances or processes.
Abundance	A measure of the number of organisms in a sample or per unit area.
Biota	The types of plant and animal life found in specific regions at specific times.
Calibration	The process of choosing attribute values and computational parameters to ensure that a model properly represents the real-world situation being analysed.
Circumneutral	Typically neutral pH, neither strongly acidic or alkaline.
Correlation	An association between two or more things, often where one of the things causes or influences the other.
Downscaling	Method to derive regional gridded or point data from a General Circulation Model (see below).
Ecosystem	The dynamic and interrelating complex of plant and animal communities and their associated non-living environment.
Empirical	Data based on experience or observation rather than theory.
General Circulation Model	Also known as Global Climate Model is a global, three-dimensional computer model of the climate system, which can be used to simulate human-induced climate change. GCMs are highly complex and can represent such factors as reflective and absorptive properties of atmospheric water vapour, greenhouse gas concentrations, clouds, annual and daily solar heating, ocean temperatures and ice boundaries. The most recent GCMs include global representations of the atmosphere, oceans and land surface.
Indicator species	A species that is a good indicator of the living conditions in a particular habitat.
Macroinvertebrate	Invertebrates visible to the naked eye.
Meteorology	The scientific study of the processes that cause particular weather conditions
Monte carlo simulation	A technique used in computer simulations, which works by sampling from a random number sequence to simulate characteristics or events or outcomes with multiple possible values.
North Atlantic Oscillation	A climatic process caused by differences in the sea-level pressure between Iceland (low) and the Azores (high). This process controls the strength and direction of westerly winds and storms across the North Atlantic.
Ordination	A statistical method that groups objects characterised by multiple variables such that the distance between the objects denotes their level of similarity (similar objects are close together, dissimilar objects are further away).

Parameterisation	For climate models, this term refers to replacing processes that are too small-scale or complex to be represented physically with a simplified process.
Percentile	Values that divide a sample of data into one hundred groups containing (as far as possible) equal numbers of observations.
Physico-chemical	Relating to physical chemistry (water quality).
Qualitative	Observations that involve descriptions rather than measurements and numbers.
Quantitative	Observations that involve measurements and numbers.
Rarity	A situation where the current status of an organism is restricted either in numbers or area by any combination of biological or physical factors to a level that is demonstrably less than the majority of other organisms of comparable taxonomic entities.
Richness	The number of species in a community, habitat or sample.
Species	A set of animals or plants in which the members have similar characteristics to each other and can breed with each other.
Standard deviation	A measure of the spread or dispersion of a set of data.
Taxa	A group or category, at any level, in a system for classifying plants or animals.

Abbreviations

BADC	British Atmospheric Data Centre
CCW	Countryside Council for Wales
CEH	Centre for Ecology and Hydrology
CGCM2	Coupled Global Climate Model (Canadian Centre for Climate Modelling and Analysis)
CLIO	Climate Invertebrate Optima model
DCA	Detrended Correspondence Analysis
DF	Degrees of Freedom
FESWMS	Finite Element Surface Water Modelling System
GCM	General Circulation Model
HadCM3	Hadley Centre General Circulation Model
HPI	Habitat Probabilistic Model
HSI	Habitat Suitability Index
IPCC	Intergovernmental Panel on Climate Change
Ksat	Saturated hydraulic conductivity constant
NAO	North Atlantic Oscillation
NGR	National Grid Reference
NVC	National Vegetation Classification
PRINCE	Preparing for Climate Change Impacts on Freshwater Ecosystems
RR	Regional Rarity
SC	Channel slope depth
SD	Slope soil depth
SDSM	Statistical DownScaling Model
SRES	Special Report on Emissions Scenarios (by the IPCC)
SSSI	Site of Special Scientific Interest
UKCIP	UK Climate Impacts Programme
UKWIR	UK Water Industry Research
WAWS	Welsh Acid Water Survey
WFD	Water Framework Directive
1D	One dimensional
2D	Two dimensional

References & bibliography

Armstrong, J.D., Kemp, P.S., Kennedy, G.J.A., Ladle, M., and Milner, N.J., 2003. Habitat requirements of Atlantic salmon and brown trout in rivers and streams. *Fisheries Research*, **62**, 143–170.

Arnell, N., 2003. *Effects of climate change on river flows and groundwater recharge using the UKCIP02 scenarios.* Report to UK Water Industry Research.

Bardonnet, A. and Baglinière, J.L., 2000. Freshwater habitat of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences*, **57**;497–506.

Bradley, D.C. and Ormerod, S.J., 2001. Community persistence among upland stream invertebrates tracks the North Atlantic Oscillation. *Journal of Animal Ecology,* **70**, 987–96.

Bradley, D.C. and Ormerod, S.J., 2002. Evaluating the precision of kick-sampling in upland streams: the effects of sampling effort, habitat and rarity. *Archiv für Hydrobiologie,* **155**, 199–221.

Briers, R.A., Gee, J.H.R. and Geoghegan, R., 2004. Effects of the North Atlantic Oscillation on growth and phenology of stream insects. *Ecography*, 27, 811-817.

Caissie, D., 2006. The thermal regime of rivers: a review. *Freshwater Biology,* **51**, 1389–1406.

Chadwick, E.A., Slater, F.M. and Ormerod, S.J., 2006. Inter- and intraspecific differences in climatically mediated phenological change in coexisting Triturus species. *Global Change Biology*, **12**, 1–10.

Conlan, K., Lane, S., Ormerod, S. and Wade, T., 2006. *Preparing for climate change impacts on freshwater ecosystems (PRINCE): literature review and proposal methodology*. Science report to Environment Agency (Report No: SCHO0805BJJF-EP).

Crespin De Billy (De), V. and Usseglio-Polatera, P., 2002 Traits of brown trout (*Salmo trutta*) prey in relation to habitat characteristics and benthic invertebrate communities. *Journal of Fish Biology*, **60**, 687–714.

Crowder, D.W. and Diplas, P., 2000 Using two-dimensional hydrodynamic models at scales of ecological importance. *Journal of Hydrology*, **230**, 172–191.

Crowder, D.W. and Diplas, P., 2002. Assessing changes in watershed flow regimes with spatially explicit hydraulic models. *Journal of the American Water Resources Association*, **38** (2), 397–408.

Elso, J.I. and Giller, P.S., 2001. Physical characteristics influencing the utilisation of pools by brown trout in an afforested catchment in Southern Ireland. *Journal of Fish Biology*, **58**, 201–221.

Environment Canada, 2007. *CGCM2 data: GHG+A IPCC A2 scenario runs*. Available from: *http://www.cccma.ec.gc.ca/data/cgcm2/cgcm2_a2.shtml* [Accessed April 2007].

Froehlich, D.A., 1989. HW031.D–Finite element surface-water modelling system: two–dimensional flow in a horizontal plane: users manual. *Federal Highway Administration Report* (FHWA–RD–88–177).

Ghanem, A., Steffler, P., Hicks, F. and Katapodis, C., 1996. Two dimensional hydraulic simulation of physical conditions in flowing streams. *Regulated Rivers: Research and Management*, **12**, 185–200.

Guay, J.C., Boisclair, D., Rioux, D., Leclerc, M., Lapointe, M. and Legendre, P., 2000. Development and validation of numerical habitat models for juveniles of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences*, **57**(10), 2065–2075.

Hadley Centre, 2005. *Climate change and the greenhouse effect*. A briefing from the Hadley Centre, Met Office, Exeter, December 2005.

Hardy, R.J., Lane, S.N., Lawless, M.R., Best, J.L., Elliott, L. and Ingham, D.B., 2005. Development and testing of a numerical code for treatment of complex river channel topography in three-dimensional CFD models with structured grids. *Journal of Hydraulic Research*, **43**, 468–480.

Hayes, J.W. and Jowett, I.G., 1994. Microhabitat models of large drift-feeding brown trout in three New Zealand rivers. *North American Journal of Fisheries Management*, **14** (4), 710–725.

Heggenes, J., 1990. Habitat utilization and preferences in juvenile Atlantic salmon (*Salmo salar*) in streams. *Regulated Rivers: Research and Management*, **5**, 341–354.

Heggenes, J., 1991. Effect of habitat availability on habitat use by an allopatric cohort of juvenile Atlantic salmon (*Salmo salar*) under conditions of low competition in a stream. *Holarctic Ecology*, **14**, 51–62.

Heggenes, J., 1996. Habitat selection by brown trout (*Salmo trutta*) and young Atlantic salmon (*S. salar*) in streams: static and dynamic hydraulic modeling. *Regulated Rivers: Research and Management*, **12**, 155–169.

Hildrew, A.G. and Edington, J.M., 1979. Factors facilitating the coexistence of *Hydropsychid caddis* larvae (Trichoptera) in the same river. *Journal of Animal Ecology*, **48**, 557–576.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S., 2002. *Climate change scenarios for the United Kingdom: the UKCIP02 scientific report*. Norwich: Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. *Science,* **269**, 676–9.

IPCC, 2000. *Special report on emissions scenarios*. Cambridge: Cambridge University Press.

IPCC, 2001. *Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Jenkins, G. and Lowe, J., 2003. *Handling uncertainties in the UKCIP02 scenarios of climate change*. Hadley Centre technical note 44, 20 November 2003.

Kishi, D., Murakami, M., Nakano, S. and Maekawa, K., 2005. Water temperature determines strength of top-down control in a stream food web. *Freshwater Biology*, **50**, 1315–1322.

Lancaster, J. and Hildrew, A.G., 1993. Characterizing in-stream flow refugia. *Canadian Journal of Fisheries and Aquatic Sciences*, **50**, 1663–1675.

Lane, S.N., 2005. Roughness – time for a re-evaluation? *Earth Surface Processes and Landforms*, **30**, 251–253.

Lane, S.N., Hardy, R.J., Ingham, D.B. and Elliott, L., 2004. Numerical modeling of flow processes over gravelly-surfaces using structured grids and a numerical porosity treatment. *Water Resources Research,* **40**, W01302.

Leclerc, M.A., Boudreault, P., Bechara, J.A. and Corfa, G., 1995. Two-dimensional hydrodynamic modeling: a neglected tool in the instream flow incremental methodology. *Transactions of the American Fisheries Society*, **124** (5), 645-662.

Leclerc, M., Bechara, J.A., Boudreau, .P and Belzile, L., 1996. Numerical method for modelling spawning habitat dynamics of landlocked salmon (*Salmo salar*). *Regulated Rivers: Research and Management*, **12**, 273–287.

Lepori, F., Palm, D. and Malmqvist, B., 2005. Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition. *Journal of Applied Ecology*, **42**, 228–238.

Maddock, I.P., Bickerton, M.A., Spence, R. and Pickering, T., 2001. Reallocation of compensation releases to restore river flows and improve instream habitat availability in the Upper Derwent catchment, Derbyshire, UK. *Regulated Rivers: Research and Management*, **17**, 417–441.

Milhous, R.T., Wegner, D.L. and Waddle, T., 1984. *User's guide to the Physical Habitat Simulation System (PHABSIM). Instream flow information paper No. 11*. US Fish and Wildlife Service (FWS/OBS-81/43 revised).

Milhous, R.T., Updike, M.A. and Schneider, D.M., 1989. *Physical habitat simulation system reference manual: version II. Instream flow information paper 26*. US Fish and Wildlife Service Biological Report 89 (16).

Pasternack, G.B., Wang, C.L. and Merz, J.E., 2004. Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California. *River Research and Application*, **20**, 205–225.

Reid, S.C., 2004. *The source, transfer and sinks of coarse sediment in an upland environment.* Unpublished PhD thesis, University of Leeds.

Rimmer, D.M., Paim, U. and Saunders, R.L., 1983. Autumnal habitat shift in juvenile Atlantic salmon (*Salmo salar*) in a small river. *Canadian Journal of Fisheries and Aquatic Sciences*, **40**, 671–680.

Ross, T.J., 1995. *Fuzzy logic with engineering applications*. New York: McGraw-Hill.

Stevens, P.A., Ormerod, S.J. and Reynolds, B., 1997. *Final report on the Welsh acid waters survey*. NERC ITE/Cardiff University Report to the Welsh Office, Environment Agency, Countryside Council for Wales and the Forestry Commission.

Stoner, J.H., Gee, A.S. and Wade, K.R., 1984. The effects of acidification on the ecology of streams in the upper Tywi Catchment in West Wales. *Environmental Pollution Series A – Ecological and Biological,* **35**, 125–57.

Tiffan, K.F., Garland, R.D. and Rondorf, D.W., 2002. Quantifying flow-dependent changes in subyearling fall chinook salmon rearing habitat using two-dimensional spatially explicit modeling. *North American Journal of Fisheries Management*, **22** (3), 713–726.

UK Water Industry Research, 2003. *Climate change and the hydraulic design of sewerage systems. Volume II: rainfall data production & analysis. IIA – time-series and design event update* (03/CL/10/4).

UK Water Industry Research, 2006. Effects of climate change on river water quality. Report prepared by Cascade Consulting and the University of Leeds (05/CL/06/4).

Van Der Maarel, E., 1969. On the use of ordination models in phytosociology. *Vegetatio*, 19, 21–46.

Weatherley, N.S. and Ormerod, S.J., 1987. The impact of acidification on macroinvertebrate assemblages in Welsh streams: towards an empirical model. *Environmental Pollution*, **46**, 223–240.

Weatherley, N.S. and Ormerod, S.J., 1990. Forests and the temperature of upland streams in Wales – a modelling exploration of the biological effects. *Freshwater Biology*, **24**, 109–22.

Wilby, R.L., Tomlinson, O.J. and Dawson, C.W., 2003. Multi-site simulation of precipitation by conditional resampling. *Climate Research*. **23**, 183–194.

Wilby, R.L., 2006. When and where might climate change be detectable in UK River flows. *Geophysical Research Letters*, **33**, L19407.

Wilby, R.L., Whitehead, P.G., Wade, A., Butterfield, D., Davis, R.J. and Watts, G., 2006 Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology*, **330**, 204–220.

Wilby, R.L., Dawson, C.W. and Barrow, E.M., 2002. SDSM – a decision support tool for the assessment of regional climate change impacts. *Environmental Modelling & Software*, **17**, 147–159.

Appendix 1
Semi-distributed hydrological models

The study investigated a range of semi-distributed hydrological models. Such models are catchment-specific, with the ability to generate flow statistics but not time series output.

- LowFlow2000 is a CEH (Centre for Ecology and Hydrology) model used routinely by the Environment Agency to generate flow statistics for ungauged and hydraulically-modified catchments and to inform Catchment Abstraction Management Strategies (CAMS). LowFlow2000 is currently restricted to determining flow duration statistics for present conditions. Meteorological data are held in the model in the form of geospatial layers for the period 1961–1989. Following calibration from a suitable local gauged catchment, the model can predict flow duration statistics for any reach of a catchment. However, for LowFlow2000 to be able to derive flow duration statistics for future climate data, geospatial layers would have to be generated for each input dataset or the program would have to be modified considerably.
- PDM is another CEH model used by the Environment Agency. It allows the user a good degree of freedom to change the way in which flows are derived, thus helping the prediction to be as accurate as possible. The model runs in two modes: calibration mode and simulation mode. Calibration mode requires precipitation, evaporation and flow data, which allow the relationships between climate and flow to be estimated. Simulation mode then uses modelled climate data to estimate future flows. To implement PDM on a new (uncalibrated) catchment takes a minimum of 1–2 days. Time and budget constraints prevented further investigation of this approach in this study.
- CatchMod is an emerging Environment Agency spreadsheet-based model. It has been tested on a number of catchments in the River Thames and southern Environment Agency regions and is comparable with PDM. CatchMod requires separate calibration for each catchment. The developmental nature of the model, together with time and budget constraints, prevented further investigation of this approach.

The project team recommend further consideration of an intermediate-level hydrological model for future climate change simulation, as it may have advantages over flow factor approaches for widespread application. These methodologies do not, however, provide the sequencing or duration of extreme events, which are known to have a fundamental influence on ecological function, and are therefore not able to produce suitable data for this type of study.

Appendix 2 Calibration of CAS-Hydro for the River Wharfe

In order to apply CAS-Hydro to the Upper Wharfe, a site needed to be selected for which good calibration data were available. The Oughtershaw catchment, which covers an area of approximately 16km^2 with no flow management or significant abstractions or discharges, was chosen. Model calibration was undertaken using data produced by the Environment Agency gauge at Oughtershaw (NGR: SK818866). This gauge is based upon a continuously recording pressure transducer, which is parameterised using point discharge measurements. Extensive measurements of the characteristics of this gauge have been undertaken, including a full extrapolation to higher flows based on cross-section geometry. Its only real weakness is that it tends to underestimate particularly low flows (Q_{95} and lower).

CAS-Hydro was run with a 50m resolution based on an elevation model interpolated from 2m Environment Agency Lidar data (Lidar is a remote sensing system to detect topography). The land cover characteristics of the Oughtershaw catchment are uniform (extensive pasture) and comprise shallow peaty soils overlying millstone grit. Rainfall data for the period from 1 April 2004 to 31 March 2005 were provided by the Environment Agency in the form of a 15-minute time series. CAS-Hydro can uses a variable time-step. Rainfall input to the model takes the form of a per-minute interval time series and this was: i) downscaled by linear interpolation for situations where the model needed a time-step of less than 15 minutes (the shortest time step possible is 1 minute); and ii) aggregated where the model time-step could be increased beyond 15 minutes to the maximum possible (six hours). The application carried out in this study assumes uniform rainfall across the catchment. However, it should be noted that, in reality, there can be considerable variability in rainfall, even within the scale of catchment considered here. Along with the rainfall input, CAS-Hydro requires temperature input for the same time-step as rainfall. Daily maximum and minimum temperature data from an adjacent catchment at the same elevation were used to provide daily minimum and maximum temperature and interpolated to give temperature for each time-step.

Calibration focused on the six key parameters that previous work had shown to be important in a study of a similar upland environment:

- saturated hydraulic conductivity (KSat);
- KSat decay with depth (found to be important for low flows only);
- soil depths estimated for both channel and slope areas;
- bedrock conductivity (the prime means by which groundwater effects were dealt with);
- albedo (reflectance of the surface);
- emissivity (energy radiated by the surface).

The main part of the analysis compared model predictions of flow percentiles for the period from October 2003 to March 2005. A six-month period of model initialisation was included, such that flow percentiles were considered for April 2004 to March 2005. The time taken for a single model run did not allow a full Monte Carlo simulation to be undertaken for all possible parameter sets. Rather, the study focused on identifying, for each parameter, those values known to give the best levels of agreement. This strategy was used to constrain possible parameter ranges. Joint parameter variability was explored until the final parameter set was chosen. Central to this process was judging model behaviour in terms of both quantitative agreement with model predictions and qualitative response. This involved:

i) beginning with the most sensitive parameter, looking at its response, and focussing on those values that gave best fit to observations;
ii) looking at how this narrowed the range of parameters varying with the next most sensitive parameter, in order to test the model's stability and also with a view to the physical plausibility of the model response.
iii) continuing until all parameters were explored.

As an example of how this was undertaken, Figure 1 shows that reducing the saturated hydraulic conductivity reduces the magnitude of low flow percentiles (Q_{95}) and increases the magnitude of high flow percentiles (for example, Q_5). This is physically plausible, as for lower saturated hydraulic conductivity there should be slow subsurface run-off, higher rates of overland flow generation and hence a more rapid run-off response from slopes during high flow events. With more run-off during storm events, there should be lower run-off during long periods of low flow. This parameter is a measure of the flashiness of model response. However, Figure 1 shows that this parameter alone does not faithfully reproduce the distribution of flow percentiles, as matching observed low flow percentiles results in an over-estimation of the higher flow percentiles. The study then considered Ksat for the channels as the next most sensitive parameter, checked the robustness of the narrowed parameter range for Ksat(slopes), identified a narrowed range of Ksat(channels) and so on.

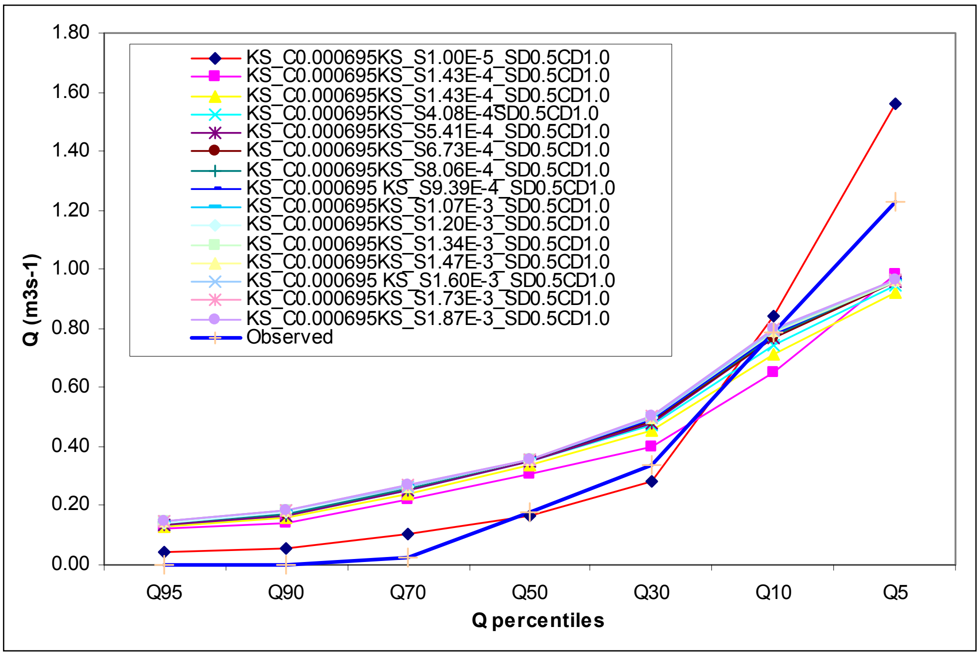


Figure 1 Predicted flow percentiles as Ksat (slopes) is varied
Notes: KS_C indicates KSat for the channels, followed by the value used. KS_S indicates KSat for the slopes, followed by the value used. SD is the slope soil depth (m) and SC is the channel slope depth in m.

After a similar analysis for channel Ksat, the study then identified a smaller range of parameters and explored joint sensitivity.

Once the study had generated a satisfactory set of model predictions for Oughtershaw, the model was extended downstream to Hubberholme, which is a key biological modelling site, assuming the same parameter values. This was a reasonable assumption for this area. The only major change was the growing influence of limestone upon the catchment hydrology. However, observations suggest that most of the loss of water to groundwater was temporary and that the hydrology was not particularly sensitive to this change.

Finally, the model was run for the baseline period (1961–1990), the 2020s and the 2050s, with the HadCM3 A2 temperature and precipitation data. This required one additional step. The study needed to use the CAS-Hydro downscaling method to disaggregate the daily output from SDSM to the sub-daily time-step. To test the effects of this, the study compared a model run from a tipping bucket rain gauge within the catchment with that run from the rainfall generator. Figure 2 shows that the flow percentiles (Q_{30} and higher) are particularly sensitive to this kind of temporal downscaling. It may therefore be better to use sub-daily rainfall generators if continuous simulation models are being used to assess high flow percentiles, although there is considerable uncertainty attached to these methods.

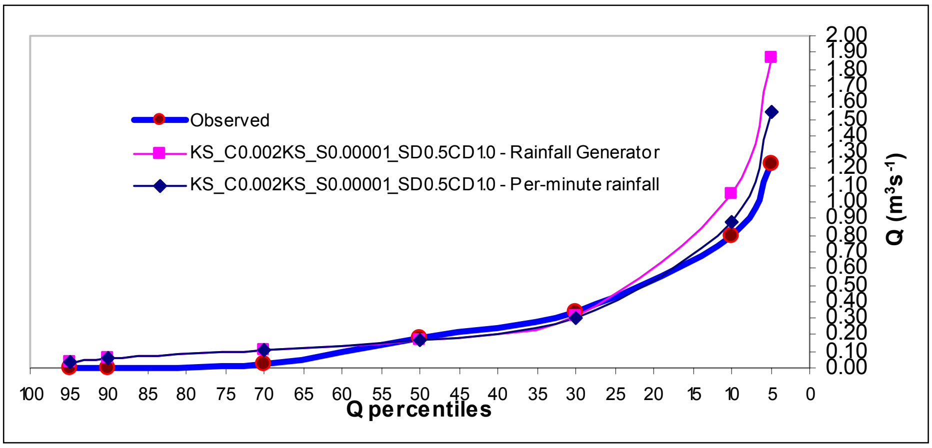


Figure 2 A comparison of measured and downscaled precipitation predictions
Notes: KS_C indicates KSat for the channels, followed by the value used. KS_S indicates KSat for the slopes, followed by the value used. SD is the slope soil depth (m) and SC is the channel slope depth in m.

Appendix 3
Predicted future flows in mid-Wales headwater streams using flow factor methodology

RESULTS

Monthly flow statistics were developed at the Plynlimon flow gauging station in mid-Wales. The typical flow envelope – Q_{95} (extreme low flow), Q_{90} (low flow), Q_{70}, Q_{50} (median flow), Q_{30}, Q_{10} (high flow), Q_5 (extreme high flow) – is summarised as annual values in Table 1 for the baseline period (1970s) and the future flow scenarios (2020s).

Table 1 Mid-Wales flow: baseline and futures data (all flows m^3/s)

Scenario	Q95	Q90	Q70	Q50	Q30	Q10	Q5
Baseline (1970s)	0.050	0.071	0.152	0.263	0.475	1.186	1.823
Low (2020s)	0.040	0.057	0.136	0.241	0.444	1.140	1.775
Medium (2020s)	0.039	0.056	0.134	0.239	0.441	1.129	1.760
High (2020s)	0.038	0.055	0.133	0.237	0.440	1.125	1.755
Cool & wet (2020s)	0.046	0.065	0.150	0.266	0.487	1.248	1.943
Warm & dry (2020s)	0.037	0.053	0.128	0.227	0.420	1.076	1.667
Cool & wet +A (2020s)	0.043	0.061	0.145	0.260	0.479	1.251	1.938
Cool & wet +B (2020s)	0.047	0.067	0.152	0.267	0.487	1.236	1.906
Warm & dry +A (2020s)	0.035	0.050	0.122	0.221	0.411	1.072	1.686
Warm & dry + B (2020s)	0.039	0.056	0.130	0.229	0.420	1.066	1.667

Appendix 4
Predicted future flows in Yorkshire rivers using flow factor methodology

RESULTS

Monthly flow statistics were developed at the 19 selected Yorkshire flow gauging stations. The typical flow envelope – Q_{95} (extreme low flow), Q_{90} (low flow), Q_{50} (median flow), Q_{10} (high flow), Q_5 (extreme high flow) – is summarised as annual values in Table 1 for the baseline period (1970s). Future flows (2020s) for the four investigated flow factor scenarios are presented in Tables 2–5.

Table 1 Yorkshire sites: baseline data (all flows m^3/s)

Site reference	Q95	Q90	Q50	Q10	Q5
Rother-New Bridge Lane	0.43	0.49	1.25	4.89	7.63
Sheaf-Queens Road	0.09	0.11	0.35	1.46	2.18
Blackburn Brook-At A6109	0.03	0.04	0.16	0.83	1.30
Dearne-Adwick-Upon-Dearne	1.01	1.16	2.27	7.22	10.91
Calder-Sowerby Bridge	0.16	0.24	0.79	6.74	9.90
Aire-U/S Cononley Beck	0.60	0.73	2.98	15.30	21.70
Aire-Calverley Bridge	3.40	3.80	9.46	35.42	48.78
Wharfe-Addingham	1.60	1.94	7.11	36.25	52.43
Wharfe-Boston Spa	2.56	3.04	10.10	43.06	59.63
Nidd-Pateley Bridge	0.92	1.06	2.51	12.09	16.27
Ure-Wensley	1.11	1.52	7.74	38.84	57.27
Swale-Thornton Bridge	3.20	3.96	12.01	45.32	65.68
Ouse-Nether Poppleton	7.57	8.81	28.90	122.57	170.71
Kyle-Newton Upon Ouse	0.14	0.18	0.82	38.60	64.65
Rye-Nunnington	0.73	0.92	2.51	6.16	7.96
Costa Beck-Kirby Misperton	0.36	0.40	0.56	0.79	0.89
Seven-Barugh Bridge	0.22	0.27	0.87	3.62	5.63
Dove-Sparrow Hall	0.22	0.27	0.76	1.99	2.72
West Beck-Wansford Bridge	0.24	0.28	0.69	1.80	1.96

Table 2 Yorkshire sites: predicted 2020s flow percentiles under the warm and dry scenario with anomaly A (all flows m^3/s)

Site reference	Q95	Q90	Q50	Q10	Q5
Rother-New Bridge Lane	0.30	0.35	1.08	4.65	7.13
Sheaf-Queens Road	0.06	0.08	0.30	1.36	2.04
Blackburn Brook-At A6109	0.02	0.03	0.14	0.76	1.21
Dearne-Adwick-Upon-Dearne	0.73	0.87	1.95	6.69	10.19
Calder-Sowerby Bridge	0.12	0.16	0.65	6.46	9.89
Aire-U/S Cononley Beck	0.42	0.52	2.54	14.03	20.40
Aire-Calverley Bridge	2.34	2.75	8.02	33.37	46.45
Wharfe-Addingham	1.14	1.41	6.17	33.43	48.34
Wharfe-Boston Spa	1.81	2.18	8.83	39.23	56.06
Nidd-Pateley Bridge	0.63	0.73	2.21	11.72	15.64
Ure-Wensley	0.78	1.08	6.69	35.37	53.56
Swale-Thornton Bridge	2.19	2.83	10.47	42.55	59.84
Ouse-Nether Poppleton	5.25	6.37	24.54	116.47	162.96
Kyle-Newton Upon Ouse	0.10	0.13	0.71	36.26	61.36
Rye-Nunnington	0.52	0.66	2.08	5.86	7.50
Costa Beck-Kirby Misperton	0.27	0.30	0.47	0.73	0.82
Seven-Barugh Bridge	0.15	0.19	0.74	3.31	5.33
Dove-Sparrow Hall	0.15	0.19	0.65	1.86	2.50
West Beck-Wansford Bridge	0.21	0.23	0.56	1.50	1.70

Table 3 Yorkshire sites: predicted 2020s flow percentiles under the warm and dry scenario with anomaly B (all flows m^3/s)

Site reference	Q95	Q90	Q50	Q10	Q5
Rother-New Bridge Lane	0.36	0.41	1.11	4.43	6.88
Sheaf-Queens Road	0.08	0.09	0.31	1.30	1.95
Blackburn Brook-At A6109	0.03	0.03	0.14	0.75	1.19
Dearne-Adwick-Upon-Dearne	0.84	0.99	2.01	6.54	9.88
Calder-Sowerby Bridge	0.13	0.20	0.72	6.01	8.91
Aire-U/S Cononley Beck	0.50	0.62	2.62	13.56	19.35
Aire-Calverley Bridge	2.82	3.25	8.27	31.50	44.00
Wharfe-Addingham	1.36	1.66	6.25	32.08	46.12
Wharfe-Boston Spa	2.16	2.59	8.90	38.34	52.64
Nidd-Pateley Bridge	0.77	0.88	2.25	10.80	14.53
Ure-Wensley	0.93	1.28	6.85	34.54	50.19
Swale-Thornton Bridge	2.62	3.35	10.60	40.19	58.16
Ouse-Nether Poppleton	6.27	7.44	25.46	109.62	153.24
Kyle-Newton Upon Ouse	0.11	0.15	0.73	34.13	58.19
Rye-Nunnington	0.60	0.77	2.21	5.55	7.12
Costa Beck-Kirby Misperton	0.30	0.34	0.48	0.72	0.80
Seven-Barugh Bridge	0.18	0.23	0.77	3.23	5.14
Dove-Sparrow Hall	0.18	0.23	0.67	1.78	2.41
West Beck-Wansford Bridge	0.21	0.23	0.59	1.65	1.80

Table 4 Yorkshire sites: predicted 2020s flow percentiles under the cool and wet scenario with anomaly A (all flows m^3/s)

Site reference	Q95	Q90	Q50	Q10	Q5
Rother-New Bridge Lane	0.38	0.44	1.29	5.40	8.28
Sheaf-Queens Road	0.08	0.10	0.36	1.57	2.37
Blackburn Brook-At A6109	0.03	0.04	0.17	0.88	1.41
Dearne-Adwick-Upon-Dearne	0.93	1.09	2.33	7.80	11.77
Calder-Sowerby Bridge	0.15	0.21	0.82	7.51	11.43
Aire-U/S Cononley Beck	0.53	0.65	3.02	16.53	23.90
Aire-Calverley Bridge	2.95	3.44	9.55	39.14	53.63
Wharfe-Addingham	1.43	1.74	7.36	39.20	56.33
Wharfe-Boston Spa	2.27	2.73	10.44	46.14	65.43
Nidd-Pateley Bridge	0.80	0.92	2.60	13.60	17.96
Ure-Wensley	0.98	1.35	7.96	41.58	62.65
Swale-Thornton Bridge	2.78	3.57	12.38	49.53	70.32
Ouse-Nether Poppleton	6.64	7.93	29.46	134.71	187.43
Kyle-Newton Upon Ouse	0.12	0.16	0.84	42.29	70.97
Rye-Nunnington	0.65	0.83	2.50	6.78	8.72
Costa Beck-Kirby Misperton	0.34	0.38	0.57	0.84	0.94
Seven-Barugh Bridge	0.19	0.24	0.88	3.90	6.21
Dove-Sparrow Hall	0.19	0.24	0.78	2.15	2.90
West Beck-Wansford Bridge	0.26	0.28	0.67	1.78	1.99

Table 5 Yorkshire sites: predicted 2020s flow percentiles under the cool and wet scenario with anomaly B (all flows m^3/s)

Site reference	Q95	Q90	Q50	Q10	Q5
Rother-New Bridge Lane	0.44	0.50	1.31	5.16	8.05
Sheaf-Queens Road	0.09	0.11	0.37	1.54	2.28
Blackburn Brook-At A6109	0.03	0.04	0.17	0.86	1.38
Dearne-Adwick-Upon-Dearne	1.03	1.19	2.38	7.62	11.50
Calder-Sowerby Bridge	0.16	0.24	0.84	7.01	10.39
Aire-U/S Cononley Beck	0.61	0.75	3.11	15.91	22.79
Aire-Calverley Bridge	3.44	3.91	9.86	36.98	51.79
Wharfe-Addingham	1.65	2.00	7.37	37.97	54.45
Wharfe-Boston Spa	2.62	3.13	10.53	45.02	62.05
Nidd-Pateley Bridge	0.94	1.08	2.64	12.74	16.89
Ure-Wensley	1.13	1.56	8.08	40.64	59.69
Swale-Thornton Bridge	3.20	4.08	12.52	47.54	68.43
Ouse-Nether Poppleton	7.65	9.03	30.17	128.28	178.74
Kyle-Newton Upon Ouse	0.14	0.18	0.86	40.43	68.53
Rye-Nunnington	0.74	0.94	2.61	6.47	8.34
Costa Beck-Kirby Misperton	0.37	0.42	0.58	0.84	0.93
Seven-Barugh Bridge	0.22	0.27	0.91	3.80	5.95
Dove-Sparrow Hall	0.22	0.28	0.79	2.08	2.84
West Beck-Wansford Bridge	0.25	0.29	0.70	1.92	2.08

REVIEW OF THE FLOW FACTOR METHODOLOGY

The focus of the flow factor methodology was on those flow gauging stations that mapped onto sites with good macroinvertebrate data. Thus, for each of the macroinvertebrate sampling sites, the associated flow factors and natural variability anomalies were identified based upon the Yorkshire flow factors (Table 4 in Arnell 2003). Unless the site was in one of the modelled catchments, in which case the modelled data were used (Appendix 3 in Arnell 2003).

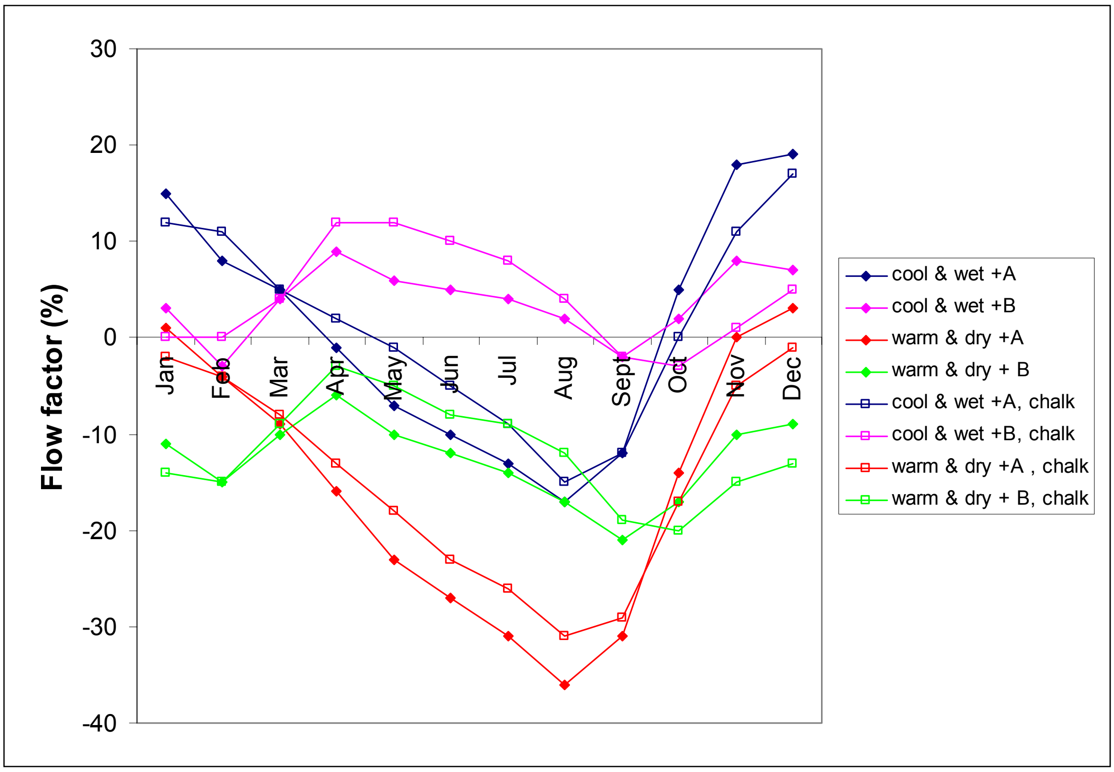


Figure 1 **Comparison of anomaly perturbed flow factors for the 2020s for Yorkshire catchments and Yorkshire chalk catchments.**

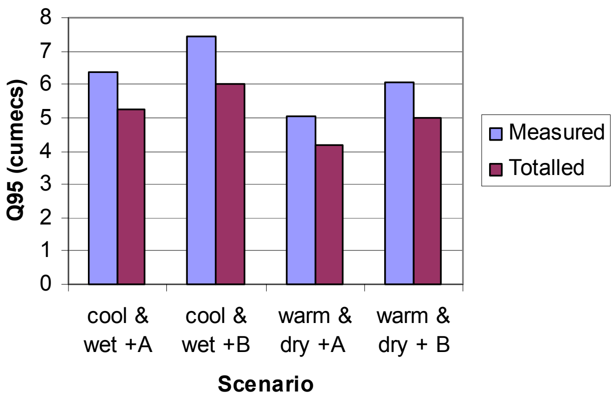
It was noted that some of these catchments were groundwater dominated, in which case the Yorkshire chalk factors for chalk geology were used (Table 6 in Arnell 2003), but in all other cases the project team followed Arnell (2003) by applying his Table 4. The Yorkshire anomaly-perturbed flow factors for non-chalk and chalk catchments are compared in Figure 1. In general, chalk catchments have higher flow factors in the spring and summer and lower flow factors in the autumn and winter, reflecting the lag effects associated with groundwater recharge. For snowmelt catchments in Yorkshire, Arnell's recommendation was followed for Yorkshire and his Table 4 was also used.

Flow factors were applied to data supplied by the Environment Agency for each site, up until 31 December 1990.

The flow factors refer to changes in monthly run-off. However, the unit of analysis was daily run-off, which was applied to daily mean flows. Note that the key issue here is desegregating from monthly flow factors to daily flow factors. In this case, it was assumed that the monthly flow factors downscale proportionately to the daily scale (they apply equally at the monthly and the daily scales). Mirroring conventional climate downscaling from monthly to daily flows (for example, Prudholme *et al.* 2002), the effects of alternative downscaling methods were assessed (such as non-linear scaling). However, it was found that simple proportionate scaling was the only method that retained the known auto correlation in discharge hydrographs. It also effectively reduced the magnitude of low flows and increased their duration in ways that were physically plausible. The other downscaling methods did not do this. However, high flow percentiles are likely to be much less robust to proportional scaling due to the importance of timing effects of sub-catchment response, which will become stronger as the timescale is reduced.

The Arnell analysis only strictly applies to catchments with areas smaller than 1,000km^2. Arnell (2003) recommends that where this figure is exceeded the analysis should be undertaken for individual sub-catchments and then aggregated. Of the five catchments that exceeded 1,000km^2

in size, only one had instrumented records for all sub-catchments: the Skelton on the River Ouse, which comprises the Swale, Ure, Nidd and Kyle. Figure 2 shows the effects of applying the flow factors on individual sub-catchments with application to the measured record at Skelton. Figure 2 shows that for both Q_{95} and Q_5 the measured flows are significantly greater than those obtained by aggregation. The differences for Q_5 are most severe, reflecting the difficulty of combining daily gauge records of high flows without proper flow routing. As noted above, by applying the flow factor methodology to daily flows, these flow extremes are likely to be most unreliable anyway. However, the difference in Q_5, which is likely to be more ecologically significant than Q_{95}, is clear. It takes the form of a systematic bias, with a magnitude that is similar to the variance between the cool-wet A/B scenarios. The main reason for this bias is the fact that discharge and direct precipitation associated with the small tributaries and drains entering the Ouse between each of the tributary gauging stations and Skelton are not captured by the four gauges. Given these problems regarding the aggregation of sub-catchments, the measured data were used in all cases. Note that the aim was to get an index of current and future flow changes driven by inter-annual variability, which may mean that getting absolute estimates of changes in flow is less critical.



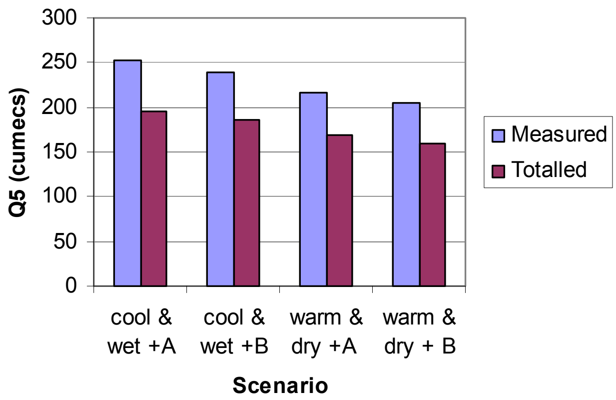


Figure 2 Predicted flows for the 2020s using both the measured Skelton record and data aggregated from individual sub catchments

A second major issue arose when considering the flow factors. Arnell (2003) recommends that the flow factors are applied to the period 1961–1990. As Table 6 shows, many of the flow records for the Yorkshire macroinvertebrate sites start in the latter half of this period. Crucially, the records vary in the extent to which they include the anomalous drought period of 1975–76. To assess this, the longest record available was taken (Flint Mill on the Wharfe) and used to simulate the estimated 2020s Q_{95}, Q_{90} and Q_5 under the 'warm and dry' anomaly A scenario (the most extreme in terms of low flows) but with the record start dates (Table 1) shown for all the other catchments.

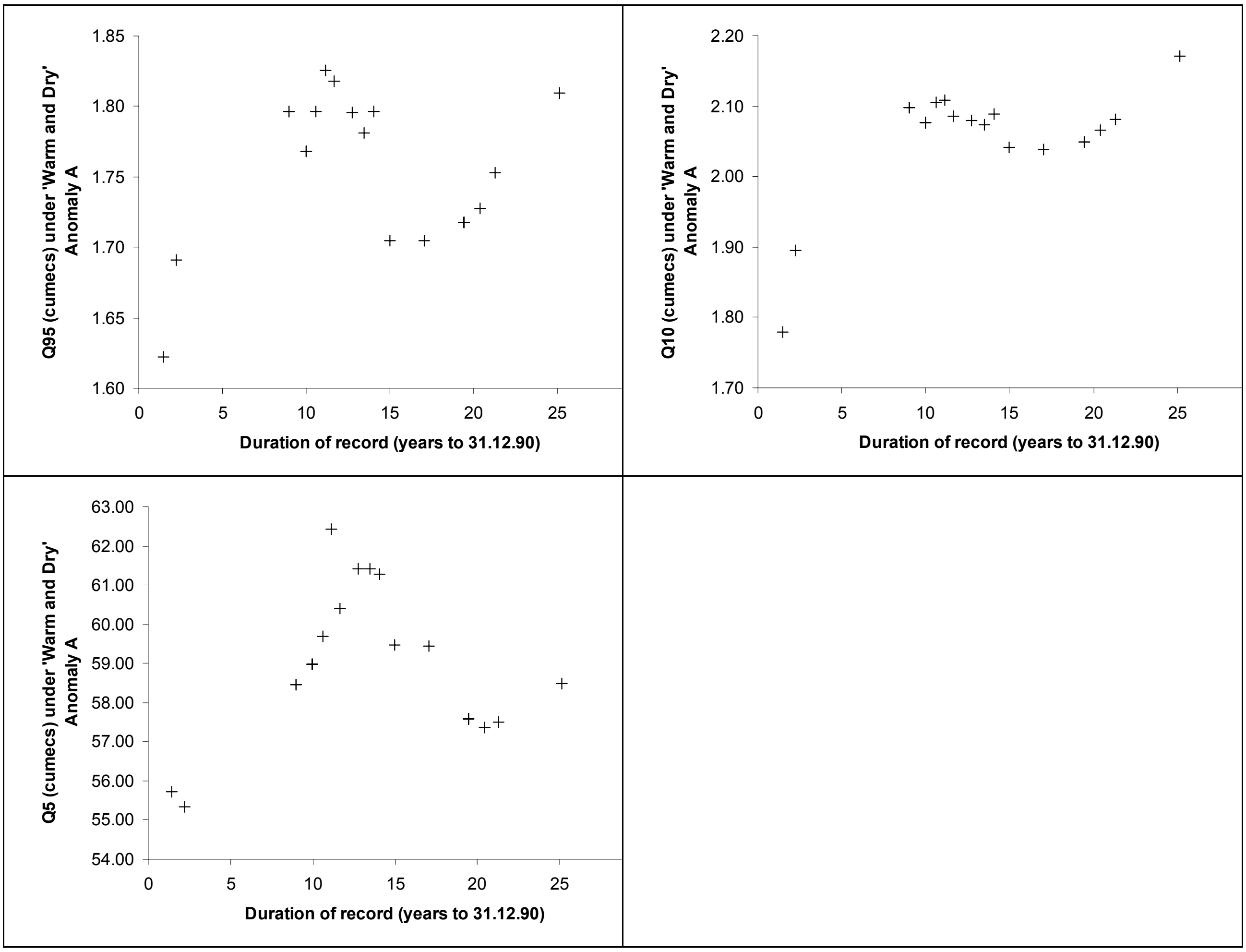
Figure 3 shows that there is considerable variance between sites due to changes in record length. As expected, where the record starts with respect to the 1975–76 drought (15 years) has a major effect on the Q_{95} and Q_{90}, with sites that start less than 15 years before 31 December 1990 having significantly higher flow percentiles than those that start more than 15 years before 31 December 1990 (Figure 3). If only the long duration Flint Mill record is considered, Q_{95} and Q_{90} for the 2020s are both estimated to be 71 per cent lower under the 'warm and dry' anomaly A scenario compared with the period from 1965 to 1990. If the extremely short records were ignored, the variability for Q_{95} in Figure 3 due to variability in series length is somewhere between $0.1m^3/s$ and $0.2m^3/s$ (approaching 10 per cent). This means that there will be significant noise in the spatial Q_{95} signal, which reflects variability in the series record and not real changes in flows due to climate change.

Table 6 The sites used for application of the flow factor methodology and regionalisation of the continuous simulation methodology

Site reference	Flow gauge location	Start of record applied to flow factor methodology	End of record applied to flow factor methodology
Rother-New Bridge Lane	Rother-Whittington	08-11-79	31-12-90
Sheaf-Queens Road	Sheaf-Highfield	08-01-81	31-12-90
Blackburn Brook-At A6109	Blackburn Brook-Ashlows Works	08-01-81	07-12-90
Dearne-Adwick-Upon-Dearne	Dearne-Adwick	05-01-76	31-12-90
Calder-Sowerby Bridge	Calder-Mytholmroyd	19-07-89	31-12-90
Aire-U/S Cononley Beck	Aire-Kildwick	29-07-71	31-12-90
Aire-Calverley Bridge	Aire-Armley	01-04-78	31-12-90
Wharfe-Addingham	Wharfe-Addingham	18-12-73	31-12-90
Wharfe-Boston Spa	Wharfe-Flint Mill, Wetherby	24-11-65	31-12-90
Nidd-Pateley Bridge	Nidd-Gouthwaite	16-12-76	31-12-90
Ure-Wensley	Ure-Kilgram, Middleham	29-07-71	31-12-90
Swale-Thornton Bridge	Swale-Crakehill, Topcliffe	29-05-80	31-12-90
Ouse-Nether Poppleton	Ouse-Skelton	18-09-69	31-12-90
Kyle-Newton Upon Ouse	Kyle-Newton-on-Ouse	03-05-79	31-12-90
Rye-Nunnington	Rye-Ness	01-01-82	31-12-90
Costa Beck-Kirby Misperton	Costa Beck-Gatehouses, Pickering	07-08-70	31-12-90
Seven-Barugh Bridge	Seven-Normanby	13-07-77	31-12-90
Dove-Sparrow Hall	Dove-Kirkby Mills	01-01-82	31-12-90
West Beck-Wansford Bridge	West Beck-Snakeholm Lock	07-10-88	31-12-90
Foulness-Major Bridge	Foulness-Holme House Farm	No results	Data start in 1990
Wharfe-Hubberholme	Wharfe-Hubberholme	No results	No data pre-1990

Results from the flow factor methodology are included for illustration and are appropriate for certain types of forecasting. However, the flow factor methodology is not appropriate for assessing the effects of climate change upon river flows in relation to in-stream ecology. Not least because the flow factors are only widely available for the 2020s, a period before climate change signals appear to become statistically significant for both temperature and precipitation.

Figure 3 The estimated flow percentiles obtained under the 'warm and dry' anomaly A scenarios for Flint Mill on the River Wharfe where the calculation begins on the dates at which the other flow records started



Appendix 5 Regionalisation of results: empirical transfer functions

Figure 1 shows the reasons why regionalisation is plausible: correlations between modelled flows at Hubberholme and measured flows at other sites for the period 1990 to 1999 are good (above 0.7) for many of the sites. This is especially true for the Q_{50} and Q_{30} flow percentiles. There also is some regional agreement in the strength of correlation for the very low and very high percentiles: the agreement is greatest for most of the Yorkshire Dales and some of the South Pennines catchments and this almost certainly reflects differing meteorological forcing of flows at the sub-regional scale.

There are some interesting anomalies in the graphs. Particularly poor correlations within the Dales/Pennine regions are found for the south of the region (the Rother, Sheaf, Blackburn Brook and Dearne). This may reflect geographical variations in the catchments in south Yorkshire but may also reflect possible regulation of flow through abstraction and/or compensation. Indeed, it is important to emphasise that sensitivity to climatic variability may be heavily dampened at sites where river regulation and abstraction have dominant impacts upon flow variability.

This aside, these results provide an opportunity to transfer the continuous simulation results for Hubberholme to other Yorkshire sites and to include in the transfer an estimate of the uncertainty associated with the form of the transfer relationships. For each site, an ordinary least squares regression relationship on the measured flow percentiles was parameterised, driven by the flows modelled at Hubberholme. The measure of fit was used to estimate the confidence in each prediction when the transfer functions were applied to continuous simulation results for the 2020s, 2050s and 2080s. It should be emphasised that these transfer functions and the associated uncertainties assume that the current Hubberholme transfer site relationship does not change as a function of climate change. It is quite possible that, given the sub-regionalisation of response to meteorological forcing described above, the form of these relationships will also change. However, this methodology gives a much more reliable indication of future flows for the 2020s than the flow factor methodology, as it is driven directly by future climate scenarios and allows an estimate of flow percentiles for the 2050s and 2080s. Ideally, the methodology should be extended by simulating a wider range of representative sub-catchments, in order to capture the sub-regional variation more fully.

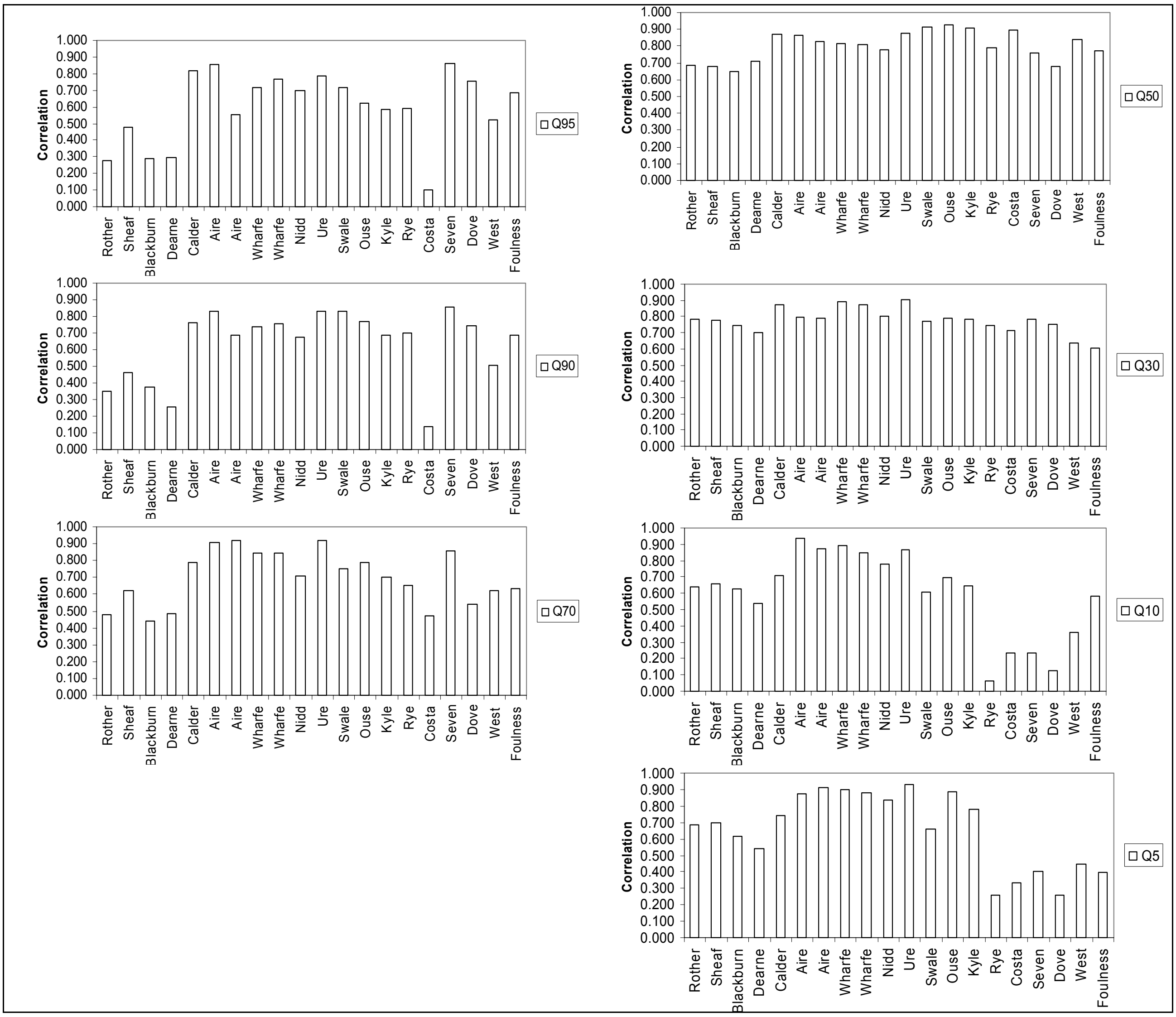


Figure 1 Correlations for the hydrological years 1961–1990 between modelled flow percentiles at Hubberholme and measured flow percentiles at the other Yorkshire sites used in the ecological analysis

Appendix 6 Fisheries habitat modelling

Introduction

In this section, a model for predicting available habitat for two species of fish (*Salmo salar* and *Salmo trutta*) was developed, using a combination of 2D hydrodynamic modelling and fuzzy modelling of the consequent habitat, for three different life-stages (spawning, nursery and rearing). This provided a means of assessing the impacts of future river flows upon in-stream habitat, which may have ecological impacts if those elements of habitat that are modelled (flow velocity and depth) are limiting for any one of the life cycles.

Habitat modelling

The move from one dimensional to two dimensional approaches

The ecologically-available habitat in a river depends on several key physical parameters, notably flow velocity and depth, wetted perimeter, substrate, temperature and pH (see Elso and Giller 2001, Maddock *et al*. 2001, Leclerc 2005). These are often combined into some form of habitat score such as a weighted usable area (WUA) (see Leclerc 2005 for a review). The best known example of this is PHABSIM (see Milhous *et al*. 1984), which is widely used to assess habitat suitability. PHABSIM is based upon a simplified form of the 1D St. Venant equations for width- and depth-averaged flow. It uses a combination of the mass continuity equation and the Manning equation, which is supported by the Bernoulli equation in order to determine the slope of the energy line. Using a diffusion wave approximation of the St. Venant equations (ignoring temporal and spatial accelerations) and specifying a Manning-type friction law gives the mass continuity and Manning equation used by PHABSIM. This approximation limits PHABSIM to situations where flow is uniform or approximately uniform (Milhous *et al*. 1989). Leclerc *et al*. (1995) note that this will not produce reliable results for areas of river less than $10m^2$ in size, limiting its suitability for smaller streams or where spatial variation in habitat is high. This was confirmed by Ghanem *et al*. (1996), who obtained a more accurate representation of spatial patterns of flow velocity with a 2D model than a 1D model. Indeed, the application of PHABSIM at smaller spatial scales appears to lead to an overestimate of the amount of available habitat (Crowder and Diplas 2002).

The main motivation for moving away from a modelling approach like PHABSIM and towards 2D habitat models is that they can deal with the fact that fish are relatively mobile organisms and hence may move over a range of spatial scales. These may include the within-reach scale over a range of time scales, as organisms move between resting and feeding or as external forces (such as river flow) change. Adopting a 2D approach is important, as 1D approaches cannot represent the substantial within-reach variability in hydraulic variables. As such, 2D approaches have been commonplace since the 1990s.

For instance, Leclerc *et al*. (1995, 1996) used a finite element solution of the depth-averaged flow equations, including a wetting and drying treatment and a HSI, to explore habitat changes on the Moisie River, Quebec (Leclerc *et al*. 1995) and the Ashuapmushuan River, Quebec

(Leclerc *et al*. 1996). The HSI was derived from observed vertically-averaged velocity, depth and substrate characteristics for Atlantic salmon fry and parr, using multivariate statistical techniques. The HSIs were driven by the hydraulic model predictions and were used to determine how the percentage usable area varied as a function of discharge. The advantage of using a 2D approach is that it recognises that as some habitat becomes less suitable due to increasing flow depth and/or velocity other habitats become more suitable (if they were originally dry but become wet). This showed that there was a rapid increase in the percentage usable area for both parr and fry habitat up to $50m^3/s$. Above this threshold, the percentage usable area remained relatively constant for fry, but rose more slowly for parr. Most importantly, Leclerc *et al*. noted that the spatial scale of model predictions was similar to that of a known ecological function: salmonids defend territories that rarely exceed $4m^2$.

In a similar study, Tiffan *et al*. (2002) used a depth-averaged model to simulate flow depths and velocities at 36 steady state discharges. The biological model was based upon multivariate logistic regression, in which the probability that sub-yearling fall Chinook salmon were present was predicted by the model from physical habitat parameters. The results showed that estimates of rearing habitat decreased as flows increased and that estimates of the area in which fish could become stranded initially rose, but then fell. However, they noted that even the $16m^2$ resolution was too coarse to characterise adequately the habitat needs of the sub-yearling fish. The biological model in the Tiffan *et al*. study was based upon a habitat probabilistic model (HPI). Guay *et al*. (2000) used a similar approach, but compared it with HSI approaches. They found that the HPI produced better results than the HSI and noted that this may be because of the multivariate nature of the HPI approach. Predictions from the hydraulic models are considered simultaneously rather than independently, thereby dealing with a common criticism of approaches like PHABSIM.

Crowder and Diplas (2000a) extended these approaches to determining energy gradients and 'velocity shelters' or refugia in gravel bed streams. They recognised that point predictions of hydraulic variables may not always provide a sufficient representation of habitat, as spatial variation in those variables is also a crucial requirement for fish (see Hayes and Jowett 1994) and macroinvertebrates (see Lancaster and Hildrew 1993). Crowder and Diplas undertook a higher resolution modelling study, which included mesoscale topographic features (such as boulders) and which generated predictions for input into spatial habitat metrics. These metrics sought to capture the physical habitat difference between two locations with the same velocity but different surrounding velocities in terms of velocity and kinetic energy gradients. For instance, by scaling the spatial change in kinetic energy between two points by the kinetic energy at the point with the smaller velocity, they were able to derive a metric that represents the kinetic energy that must be spent by an organism in order to move from the point of lower velocity to the point of higher velocity. As these are based upon gradients, the determined metrics will depend upon the spatial scale over which calculations are made, and this will need to be evaluated in relation to the spatial resolution of the mesh used in the model and the behavioural aspects of the organism being considered. The research showed that the presence of boulders resulted in a substantially more complex spatial metric, which provided a greater habitat range for fish. Linking this finding to observed fish behaviour, Crowder and Diplas (2002) confirmed that boulders enhanced the potential availability of the right habitat.

Why habitat modelling needs to be fuzzy

The above review emphasises that there has been significant development over the past 10 years in habitat modelling approaches using hydrodynamic models. This progress aside, a number of difficult issues remain. Central to these issues is the fact that hydrodynamic models need to be informed by ecological knowledge. Much of this knowledge is traditionally based upon field measurements (such as depth and velocity) at locations where individual organisms have been observed at particular life stages (see Rimmer *et al*. 1983, Heggenes 1990, Heggenes 1991, Heggenes, 1996, Bardonnet and Baglinière 2000, de Crespin de Billy and Usseglio-Polatera 2002, Armstrong *et al*. 2003). Typically, these measurements record a preferred organism preference (where they are living) and not a possible organism preference (where they could live). The latter is a substantially more difficult parameter to estimate, not least because exposure to certain extreme conditions (where an organism could temporarily live) means that certain conditions may only be suitable for a specific period of time, but also because designing experiments to evaluate possible organism habitat is almost impossible. Habitat will only limit organism growth and survival if the densities of fish are sufficiently high relative to the size of the fish (Armstrong *et al*. 2003). If ecological measurements are made when this is not the case, the organism–habitat relationships will partly reflect other processes and hence will be noisy/uncertain with respect to what could be possible habitat.

Fuzzy models are designed to be applied to situations where only imprecise or even ambiguous information is available (Ross 1995). Given the above observation about the noise that will be implicit in ecological preference data, this explains why fuzzy modelling has appeal for habitat modelling. Fuzzy models are particularly valuable for situations where the noise in the knowledge is non-random and not necessarily quantifiable. In other words, where the situation is ambiguous (Ross 1995) rather than uncertain (in the classical statistical sense). Thus, fuzzy analysis commonly maps onto linguistic definitions (good, bad) rather than numerical definitions. The ecological uncertainty surrounding habitat preference, which is both methodological and substantive, means that by developing fuzzy habitat models it is possible to explicitly retain the ambiguity that is implicit in habitat preferences knowledge.

Methodology and approach

The methodology and approach has two key dimensions: i) the development of 2D predictions of flow depth and velocity for shallow gravel bed rivers, using hydrodynamic models; and ii) application of these predictions to a fuzzy habitat model in relation to the species requirements for Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*).

Two dimensional hydrodynamic modelling

The 2D hydrodynamic modelling was based upon FESWMS (Froehlich 1989). This method solves the finite difference form of the depth-integrated conservation equations for mass and momentum. It is not a widely adopted numerical scheme, although it has been used in a similar habitat modelling application by Pasternack *et al.* (2004). Importantly, it allows complex geometries to be represented through use of a finite element mesh, which can include individual habitat-relevant features such as cobbles and boulders. The model does not make a hydrostatic pressure assumption and has a wetting and drying treatment that allows changing discharge to be represented. The model can include both wind-driven and Coriolis stresses, but these are assumed to be negligible in the scales of application used here. The model uses a zero order Boussinesq-type turbulence model with an empirically-specifiable eddy viscosity to deal with the turbulent stresses introduced during depth-averaging (see Lane 1998 for a review). The model uses a Manning-type parameterisation of a quadratic friction law (see also Lane 1998). Taken together, the eddy viscosity and Manning's equation represent the two key calibration parameters available during model simulation. In terms of data requirements, and for application to a reach with a single outflow and inflow, the model requires: i) a stage-discharge relationship as an input to one of the boundaries; ii) stage hydrographs at both boundaries; and iii) a channel geometry. At each model node, the model predicts the depth-averaged velocity and water depth, which are used as inputs to the habitat model. The validation of the hydrodynamic modelling is not reported in this paper. Distributed measurements of water surface elevation and depth-averaged flow velocity were used with very good levels of agreement. Pasternack *et al.* (2004) also report on model validation.

Fuzzy modelling of habitat suitability

The approach to habitat modelling is restricted to considering depth and velocity. As the approach is two dimensional, it implicitly includes consideration of the wetted usable area, as nodes are predicted as wet (depth >0) and/or dry as a function of model solution. This section explains the nature of the fuzzy model.

After verbal consultations with habitat researchers in relation to the depth and velocity requirements of Atlantic salmon and brown trout, both depth and velocity were grouped into three classes – poor, medium and good – and habitat grouped into six classes – unsuitable, very poor, poor, good, very good and excellent. Fuzzy subsets for depth (Di) and velocity (Vi) were used that define the grade of membership of each predicted depth (d) or velocity (v) for each of the i (poor, medium or good) subsets.

$$
\begin{aligned}
D_p &= \{[d, \mu_{Dp}(d)]; d \in D, \mu_{Dp}(d) \in [0,1]\} \\
D_m &= \{[d, \mu_{Dm}(d)]; d \in D, \mu_{Dm}(d) \in [0,1]\} \\
D_g &= \{[d, \mu_{Dg}(d)]; d \in D, \mu_{Dg}(d) \in [0,1]\} \\
V_p &= \{[v, \mu_{Vp}(v)]; v \in V, \mu_{Vp}(v) \in [0,1]\} \\
V_m &= \{[v, \mu_{Vm}(v)]; v \in V, \mu_{Vm}(v) \in [0,1]\} \\
V_g &= \{[v, \mu_{Vg}(v)]; v \in V, \mu_{Vg}(v) \in [0,1]\}
\end{aligned}
\qquad [1]
$$

where: p is poor, m is medium and g is good; and μLi(l) is the grade of membership of the predicted value l(d or v) in Li(Di or Vi), which equals one for at least one value of L for each i. In this scheme, when 0 < μLi(l) < 1, l has a partial membership of Li. This is the sense in which the analysis is fuzzy, with l potentially being a partial member of more than one Li. A fuzzy rule was specified for habitat (Hk) based on two premises (for depth and velocity).

$$\text{If } Di \otimes Vj \text{ then } Hk, \text{ for } K \text{ values of } k \qquad [2]$$

where: K is the number of habitat classes, i is the subset of depth and j is the subset of velocity. In this case (i = j = 3), there are nine rules and potentially nine values of k. In order to capture the fuzziness of the analysis, membership of Di and Vj is expressed as a grade that can vary between zero and one. Thus, a product operation rule (Wang 1994) was used to define the degree of fulfilment of a particular habitat class.

$$\mu_{Hk} = \mu_{Hk,Di(d)}\mu_{Hk,Vj(v)} \qquad [3]$$

where: μHk is the degree of fulfilment of habitat class k, as defined by each possible combination of Di and Vj (from (2)), given the predicted values of d and v.

The nine rules that come from (2) could be used to provide nine habitat classes. However, a symmetrical habitat classification that weights depth and velocity equally was used to determine habitat suitability, using the scores in Table 1. This can be made more sophisticated by changing the weightings to reflect the known importance of velocity and depth in contributing to a particular habitat class. The process can also be informed by field data or traditional habitat suitability analyses, or calibrated onto measured relationships between habitat and productivity for a specific reach or set of reaches. This possibility is not explored here.

Table 1 The (symmetrical) definition of habitat classes in relation to the rule set defined in (2)

Symmetrical	Velocity poor (presence rarely found)	Velocity medium (presence sometimes found)	Velocity good (presence often found)
Depth poor (presence rarely found)	Unsuitable habitat 0	Very poor habitat 1	Poor habitat 2
Depth medium (presence sometimes found)	Very poor habitat 1	Good habitat 3	Very good habitat 4
Depth good (presence often found)	Poor habitat 2	Very good habitat 4	Excellent habitat 5

The analysis so far provides nine outcomes, which indicate the degree of fulfilment of each rule. If there was no fuzziness in the system, then there would only be a single outcome. As the level of fuzziness increases, so the number of outcomes increases to the maximum of nine. In order to provide a single HSI, the analysis was 'de-fuzzified' to produce a single 'crisp' number. This can be done in a number of ways. Here, the total degree of membership of all classes was scaled into one, and then the weightings shown in Table 1 were introduced.

Salmo salar and *Salmo trutta* habitat preferences

The main additional data source required to run the habitat model relates to habitat preferences. On the basis of available data (such as Rimmer *et al*. 1983, Heggenes 1990, Heggenes 1991, Heggenes 1996, Bardonnet and Baglinière 2000, de Crespin de Billy and Usseglio-Polatera 2002, Armstrong *et al*. 2003), habitat preferences were mapped onto the following set memberships. A precision that defines the fuzziness was set as per Table 2.

Table 2 Habitat preferences

	Poor (presence rarely found)	Medium (presence sometimes found)	Good (presence often found)
***Salmo salar* (Atlantic Salmon)**			
Spawning, velocity *Precision*: 0.20m/s	<0.20m/s >0.80m/s	0.20–0.40m/s 0.54–0.80m/s	0.40–0.54m/s
Spawning, depth *Precision*: 0.10m	<0.17m >0.76m	0.17–0.25m 0.38–0.76m	0.25–0.38m
Nursery, velocity	<0.15m/s >1.00m/s	0.10–0.30m/s 0.40–0.10m/s	0.20–0.40m/s
Nursery, depth	<0.10m >0.50m	0.10–0.20m 0.40–0.50m	0.20–0.40m
Rearing, velocity	<0.20m/s >1.20m/s	0.20–0.50m/s 0.60–1.20m/s	0.25–0.60m/s
Rearing, depth	<0.20m >0.70m	0.15–0.30m 0.60–0.70m	0.25–0.60m
***Salmo trutta* (Brown Trout)**			
Spawning, velocity *Precision*: 0.20m/s	<0.11m/s >0.80m/s	0.11–0.35m/s 0.50–0.80m/s	0.35–0.50m/s
Spawning, depth *Precision*: 0.10m	<0.06m >0.82m	0.06–0.25m 0.40–0.82m	0.25–0.40m
Nursery, velocity	<0.05m/s >0.20m/s	0.05–0.15m/s	0.15–0.20m/s
Nursery, depth	<0.05m >0.35m	0.05–0.20m 0.30–0.35m	0.20–0.30m
Rearing, velocity	<0.05m/s >0.70m/s	0.05–0.10m/s 0.40–0.70m/s	0.20–0.40m/s
Rearing, depth	< 0.05m >1.22m	0.05–0.50m 0.75–1.22m	0.50–0.75m

Assessing future climate change impacts

To assess the effects of future climate change, the impacts of estimated changes in low flow regime due to climate change were explored. The output of CAS-Hydro was taken from the start of the baseline period (1960) to 2069 and then applied to a distributed continuous simulation model of hydrological response. The model was calibrated on measured flows for the 1990s and early 2000s. Model output allowed annual flow duration curves over the full 109-year period to be determined. These were then used to determine characteristic drought period Q_{95} flow percentiles for the baseline period and for the 2050s ($0.106 m^3/s$ and $0.078 m^3/s$, respectively). The modelled site comprised a weakly curved reach with a riffle at the downstream end (Figure 1).

Figure 1 Climate change impacts on low flows

Model geometry and mesh

Model geometry was determined using high density field survey with Total Stations. This yielded data files with point spacings of better than 1 point per square metre. The density was varied to reflect the topographic structure of the river bed and individual boulders and cobbles were mapped where it was clear that these were having (or would have) a substantial impact upon the associated flow characteristics. These topographic data were mapped directly onto the finite element mesh, locally interpolating nodes where the local rate of topographic change necessitated a higher node spacing. Achieving mesh independence in a study like this is not straightforward: as mesh resolution is progressively made finer, the model starts to resolve aspects of the topography that are a consequence of data point spacing and topographic data interpolation rather than the real topography (Lane *et al.* 2004). This necessitates the exploration of different approaches to topographic data representation in models of this kind. Methods for doing this are reported elsewhere (Lane *et al.* 2004, Lane 2005, Hardy *et al.* 2005), but this is beyond the scope of this application.

Appendix 7
Generation of future climate scenarios

The SDSM model was used to project future daily average air temperatures for use as inputs to the CLIO macroinvertebrate modelling.

Available measured daily maximum and daily minimum air temperature data at selected meteorological stations for the period 1960–1989 were used to provide daily maximum temperatures and daily temperature ranges for model input. The High Mowthorpe meteorological station (NGR: SE888685; 175m AOD) in Yorkshire was used, as it was considered representative of regional air temperature variations. The Tregaron meteorological station (NGR: SN241521; 70m AOD) was the most suitable local station to the upper Tywi stream sites.

SDSM model calibration identified the following key factors at each meteorological station.

High Mowthorpe	Tregaron
Mean sea level pressure 500hPa geopotential height 850hPa geopotential height Wind direction at the 850hPa geopotential height Near surface specific humidity Mean temperature	Divergence at the 500hPa geopotential height Divergence at the 850hPa geopotential height Relative humidity at 850hPa height Near-surface specific humidity Mean temperature

High Mowthorpe is in the north-east regional grid and Tregaron is in the Wales grid[1].

Twenty SDSM model runs were undertaken; a representative 'typical' run was selected and the daily average temperatures were calculated. These daily average temperatures were aggregated into monthly means and further aggregated into 30-year time blocks: 1970s, 2020s, 2050s and 2080s. The modelled daily average air temperature aggregated to monthly means for the 1970s is shown in Table 1 for High Mowthorpe and Table 2 for Tregaron. The 1970s are used as representative of pre-climate change. The average daily air temperature increase from the 1970s to the 2020s has been calculated, as well as the 2020s to 2050s and 2050s to 2080s. For example, the average daily air temperature at High Mowthorpe in March was modelled as 4.4ºC for the 1970s, increasing by 0.4ºC to a daily average of 4.8ºC in the 2020s.

Table 1 Modelled daily average air temperature (ºC), aggregated to monthly means for the 1970s and increases for the 2020s, 2050s and 2080s for HadCM3 A2 at High Mowthorpe

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970s	3.4	3.7	5.4	7.6	10.3	12.8	14.6	14.2	12.3	9.7	6.4	4.6
Increase 1970s–2020s	0.0	0.5	0.5	0.7	0.5	0.5	0.2	0.0	0.6	0.7	0.4	0.1
Increase 1970s–2050s	1.1	1.6	1.3	0.6	0.8	0.9	1.0	1.4	1.2	1.5	1.5	0.8
Increase 1970s–2080s	1.6	2.8	2.2	1.8	2.1	2.0	2.3	2.7	1.9	2.5	3.0	2.0

[1] Wilby, R.L. and Dawson, C.W., 2004. *Using SDSM version 3.1 – a decision support tool for the assessment of regional climate change impacts: user manual*.

Table 2 **Modelled daily average air temperature (ºC), aggregated to monthly means for the 1970s and increases for the 2020s, 2050s and 2080s for HadCM3 A2 at Tregaron**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970s	3.4	3.7	5.4	7.6	10.3	12.8	14.6	14.2	12.3	9.7	6.4	4.6
Increase 1970s–2020s	0.0	0.5	0.5	0.7	0.5	0.5	0.2	0.0	0.6	0.7	0.4	0.1
Increase 1970s–2050s	1.1	1.6	1.3	0.6	0.8	0.9	1.0	1.4	1.2	1.5	1.5	0.8
Increase 1970s–2080s	1.6	2.8	2.2	1.8	2.1	2.0	2.3	2.7	1.9	2.5	3.0	2.0

Appendix 8 Predicted future flows for Hubberholme: continuous simulation

Figure 1 shows a selection of annual flow percentiles. This emphasises that there remains considerable inter-annual variability due to natural variability in the weather, but that this is superimposed upon a negative trend and, possibly, greater variability. Figure 2 tests the statistical significance of trends in annual percentiles as a function of time.

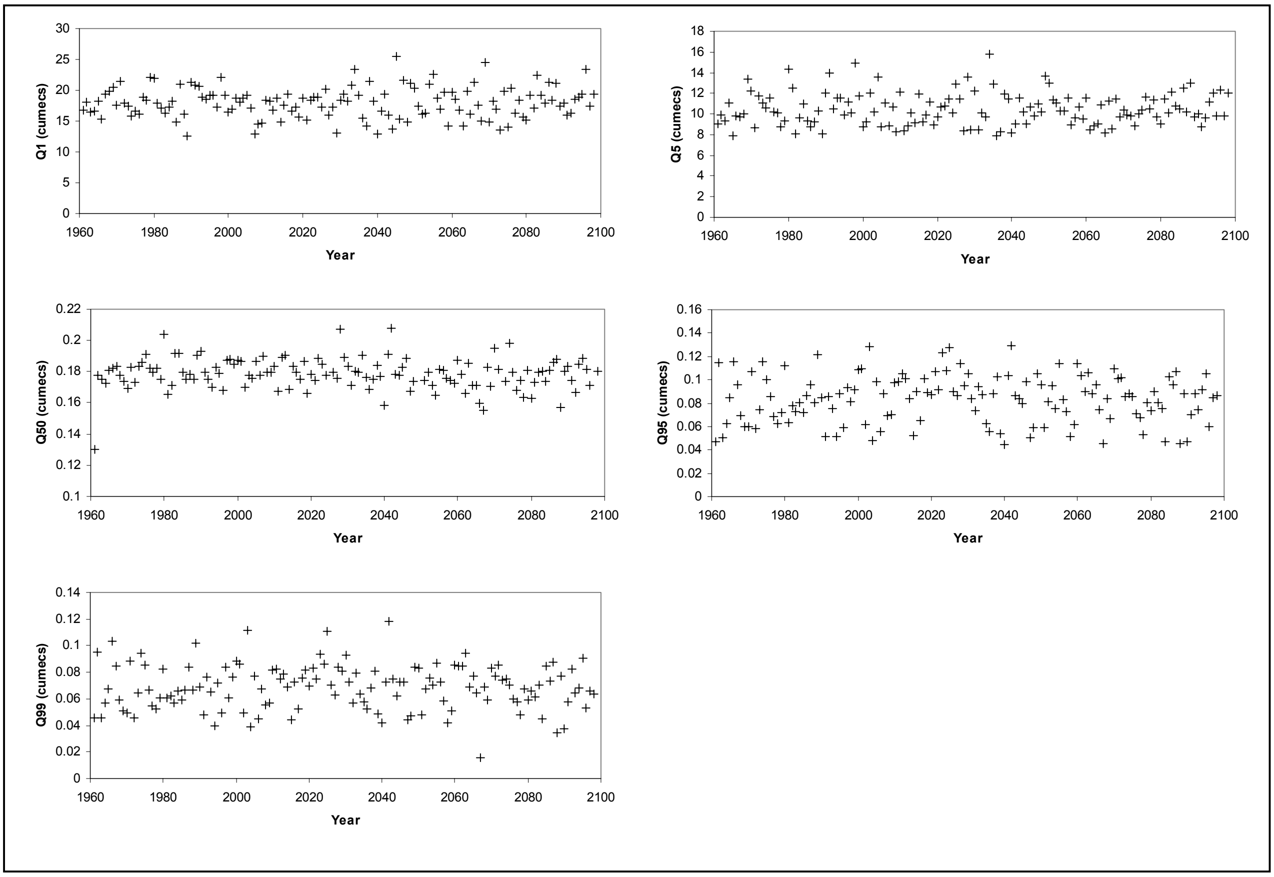


Figure 1 Annual predictions by hydrological year for Q_{99} (a low flow index), Q_{95}, Q_{50}, Q_5 and Q_1 (a high flow index)

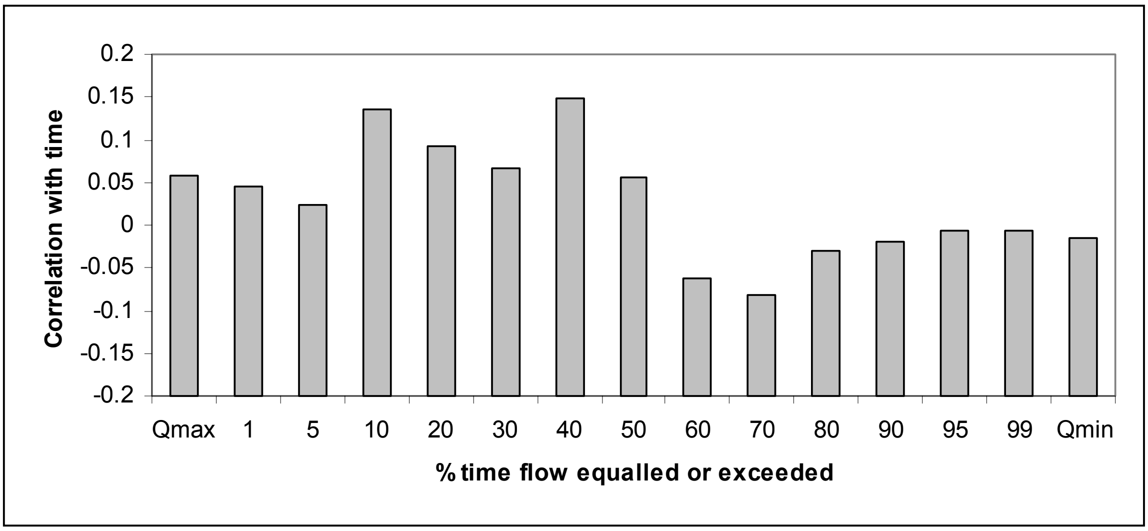


Figure 2 Correlation of annual flow percentiles with time, from baseline period through until 2099

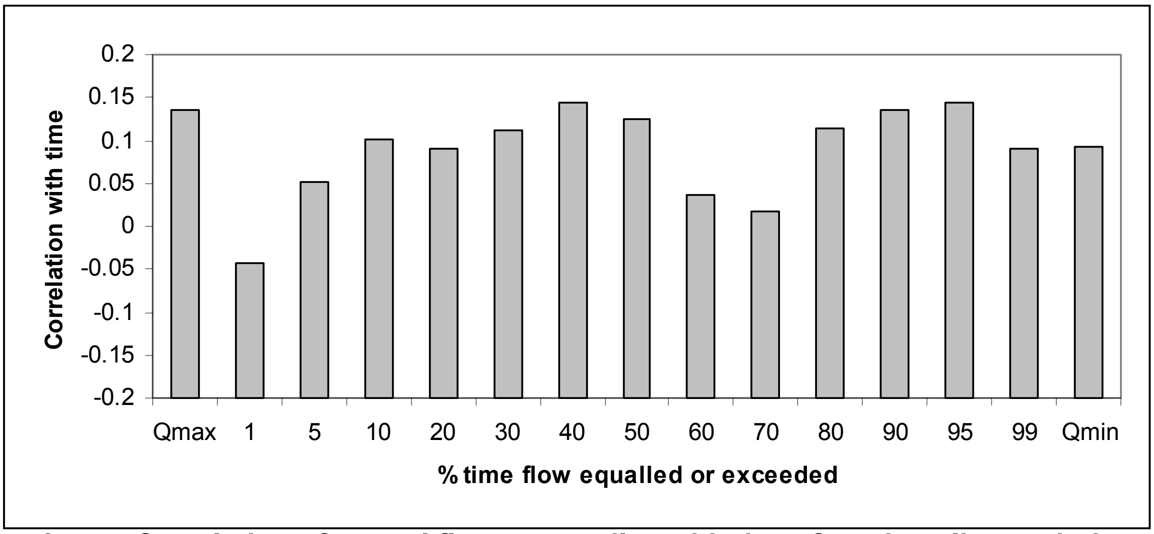


Figure 3 Correlation of annual flow percentiles with time, from baseline period through until 2029

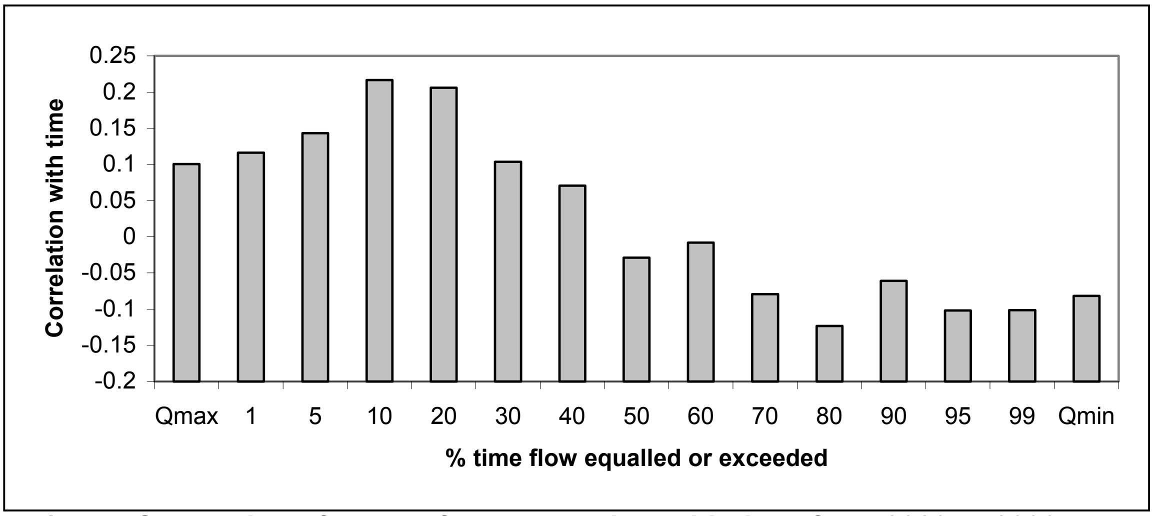


Figure 4 Correlation of annual flow percentiles with time, from 2029 to 2099

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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