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Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice

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ABSTRACT

It is widely accepted that climate change poses severe threats to freshwater ecosystems. Here we examine the scientific basis for adaptively managing vulnerable habitats and species. Our views are shaped by a literature survey of adaptation in practice, and by expert opinion. We assert that adaptation planning is constrained by uncertainty about evolving climatic and non-climatic pressures, by difficulties in predicting species- and ecosystem-level responses to these forces, and by the plasticity of management goals. This implies that adaptation measures will have greatest acceptance when they deliver multiple benefits, including, but not limited to, the amelioration of climate impacts. We suggest that many principles for biodiversity management under climate change are intuitively correct but hard to apply in practice. This view is tested using two commonly assumed doctrines: "increase shading of vulnerable reaches through tree planting" (to reduce water temperatures); and "set hands off flows" (to halt potentially harmful abstractions during low flow episodes). We show that the value of riparian trees for shading, water cooling and other functions is partially understood, but extension of this knowledge to water temperature management is so far lacking. Likewise, there is a long history of environmental flow assessment for allocating water to competing uses, but more research is needed into the effectiveness of ecological objectives based on target flows. We therefore advocate more multi-disciplinary field and model experimentation to test the cost-effectiveness and efficacy of adaptation measures applied at different scales. In particular, there is a need for a major collaborative programme to: examine natural adaptation to climatic variation in freshwater species; identify where existing environmental practice may be insufficient; review the fitness of monitoring networks to detect change; translate existing knowledge into guidance; and implement best practice within existing regulatory frameworks.

1. Introduction

Long-term observations and model projections warn that freshwater ecosystems are highly vulnerable to, and directly affected by climate change (Bates et al., 2008; Fischlin et al., 2007; Meyer et al., 1999; Moss et al., 2009; Scholze et al., 2006). Even with restrictive

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policies on greenhouse gas emissions, there is a strong possibility that the 2 °C global mean warming target of the European Union will be overshot (Allen et al., 2009). However, it is assumed that society and natural systems will have to contend with progressively harmful climate change before this threshold is reached. Furthermore, climate change impacts on freshwaters may be exacerbated by other human pressures including habitat loss, pollution, and invasive species (Millennium Ecosystem Assessment, 2005). This has led some commentators to conclude that policies of adaptation and recovery are urgently required (Parry et al., 2009).

Despite growing calls for action, the science community still has relatively little to say about *how* to adapt freshwater ecosystems to climate change (Ormerod, 2009). To date, most effort, albeit piecemeal, has been invested in gathering evidence of trends in physical drivers and biological impacts. Anticipated changes in thermal and hydrological regimes include higher water temperatures, longer ice free seasons, increased water body stratification, earlier snowmelt, more extreme floods and droughts, increased sediment and nutrient transport, lower dissolved oxygen and increased salinity (Kundzewicz et al., 2007; Whitehead et al., 2009a,b). Biological effects include changes in species' physiology, phenology, dispersal, predation, and ultimately changes in ecosystem structure, productivity, and nutrient cycling (Wilby, 2008). Potential outcomes have been reviewed for groups of organisms such as phytoplankton (Thackeray et al., 2008), invertebrates (Durance and Ormerod, 2007), amphibians (Araújo et al., 2006), macrophytes (Franklin et al., 2008), fish (Graham and Harrod, 2009), and aquatic birds (Poiani, 2006). Others provide useful syntheses of climate impacts for landscape units such as the coastal zone (Richards et al., 2008), wetlands (Harrison et al., 2008), uplands (Orr et al., 2008b), glacier-fed rivers (Milner et al., 2009), lowland rivers (Johnson et al., 2009), lakes (Mooij et al., 2005) and for aquatic ecosystems more generally (Conlan et al., 2007; Eurolimpacs, 2008; Heino et al., 2009; Palmer et al., 2009; Rahel and Olden, 2008; Wade, 2006).

Thorough appraisals of climate drivers and ecological responses are traditionally seen as important first steps towards developing adaptive management strategies for freshwaters. Concerns about the sustainability of some environmental policies have provided further impetus for research (Table 1). Across Europe, there is growing recognition that the objectives and programmes of measures within the EU Water Framework Directive (WFD) and EU Habitats Directive are potentially climate-sensitive (European Environment Agency, 2007; Wilby et al., 2006). Although it is accepted that adapting to climate change involves rejecting basic assumptions about stationary conditions (that have underpinned earlier flood, water and conservation management) opinion is divided on how best to move forwards (Milly et al., 2008). Others are asking more generally *how might biodiversity policies and management practices be modified and implemented to accommodate climate change?* (Sutherland et al., 2006, 2009).

Our aim is to identify specific knowledge gaps that presently hinder adaptation to climate change in practice, and to suggest opportunities for future research. Our premise is that no scientific discipline commands all elements needed to advance best practice guidance. We begin by outlining the constraints on adaptation planning when it is led by climate change impact assessment. Section 3 then explores in more detail the scientific foundations of two accepted "pearls" of wisdom on adaptation (riparian shading, and prescribed environmental flows). Section 4 draws on an amalgam of research options and data needs that was compiled from literature review, expert opinion, and a participatory workshop (see Annex A and B). Finally, we sketch out a programme of research that could tackle these issues. Although our discussion is largely informed by the UK context, it is hoped that the emerging themes will have much broader resonance.

2. Factors hindering scenario-led adaptation

Most policy-makers and scientists accept that a move towards adaptively managing freshwater species and habitats is long overdue (Hulme, 2005). By "adaptation" we mean *adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities* (IPCC, 2007). By "adaptive management" we mean an iterative process that involves observation and continuous learning, in which management actions are followed by targeted monitoring, the results of which inform changes in management actions. In the context of climate change adaptive management involves the consideration of potential climate impacts, the design of management actions that take key risks into account, monitoring of climate-sensitive species and processes to measure management effectiveness, and the redesign and implementation of improved (or new) management actions (West et al., 2009).

The question remains how do we manage such *adjustment* when there is so much uncertainty about the: 1) expression of regional climate variability and change over planning horizons of years to decades; 2) species- and ecosystem-level responses to the combined effect of climatic and non-climatic pressures (such as land use change, channel modification, water withdrawals, point and diffuse pollution as well as any wider measures taken by society to mitigate and/or adapt to climate change); 3) agreed environmental objectives or long-term management goals (Wilby and Dessai, in press).

2.1. Uncertain regional climate change

Considerable effort is being expended worldwide to better *characterise* the components of climate risk and uncertainty at scales relevant to decision-makers. For example, the 2009 UK Climate Projections (UKCP09) offer probabilistic information about changes in climate variables at 25 km resolution (Murphy et al., 2009). By

Table 1
Selected European research programmes addressing aspects of climate change and freshwater ecosystem management.

Acronym	Description	Source
ALARM	Assessing Large scale Risks for biodiversity with tested Methods	http://www.alarmproject.net/alarm/
BRANCH	Biodiversity, spatial planning and climate change	http://www.branchproject.org/
DRIED-UP	Distinguishing the Relative Importance of Environmental Data Underpinning flow Pressure assessment	http://nora.nerc.ac.uk/2257/
EUROLIMPACS	Integrated project to assess the effects of global change on Europe's freshwater ecosystems	http://www.eurolimpacs.ucl.ac.uk/
MACIS	Minimisation of an Adaptation to Climate change Impacts on biodiverSity	http://www.macis-project.net/index.html
MONARCH	Modelling Natural Resource Responses to Climate Change	http://www.eci.ox.ac.uk/research/biodiversity/monarch.php
REFRESH	A process-based evaluation of the specific adaptive measures that might be taken at different scales to minimise the expected adverse consequences of climate change on freshwater quantity, quality and biodiversity	http://www.refresh.ucl.ac.uk/
RegIS	Regional Climate Change Impact and Response Studies in East Anglia and North West England	http://www.cranfield.ac.uk/sas/naturalresources/research/projects/regis.jsp
RUBICODE	Rationalising Biodiversity Conservation in Dynamic Ecosystems	http://www.rubicode.net/rubicode/index.html

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combining different sets of climate model parameters, structures and emission scenarios it was found that mean summer rainfall across SW England could change between −60 and +10% from present by the 2050 s (Fig. 1). When the choice of downscaling method and (hydrological) impact model are added to the mix, the range of uncertainty could expand still further (Wilby and Harris, 2006). Some climate scientists believe that greater investments in climate model (process) resolution and input data will ultimately reduce large-scale uncertainty (Hawkins and Sutton, 2009); others are sceptical that a scenario-led approach to adaptation will ever be feasible beyond alerting managers to the wide range of possible outcomes (Dessai et al., 2005).

2.2. Uncertain responses of freshwater ecosystems

There is a surprising paucity of understanding of the environmental preferences and limits of aquatic biota, even for culturally and economically important species (Solomon, 2008). For example, there are major gaps in knowledge about the consequences of changes in marine temperatures for salmon growth and condition (Todd et al., 2008). Historically, baseline data with wide geographic coverage have not been collected for important groups such as macrophytes. Indeed, the question "what should be done?" is met typically by suggestions that are highly data-dependent (see Annex B). Answers include: more process-based information for model development, including data on growth and grazing rates for algae or the fate of contaminants; more biological, hydrological, morphological and meteorological data collected simultaneously, at comparable resolution and co-located sites, to study whole ecosystem responses to a range of climatic and non-climatic drivers; or more real-time data to evaluate and adjust interventions in response to changing conditions. However, existing monitoring networks were designed with water sector regulation in mind, rather than climate surveillance and targeted research. Provided that users are aware of the limitations of such data, they may still offer some of the longest series available, as well as information for control or relatively pristine sites.

2.3. Uncertain environmental objectives

Adaptation planning may be further constrained by a lack of consensus about the desired outcome(s). Arguably, this is more straightforward for other aspects of water management: standards of protection are defined through cost-benefit analysis for flood control; and standards of service provision are expected for water supplies. However, traditional conservation approaches based on fixed networks of protected areas may be insufficient to accommodate ecosystem response to climate change. Landscape scale habitat restoration, such as the Great Fen Project (http://www.greatfen.org.uk/) could enhance the connectivity of previously isolated protected sites. However, decisions must still be taken about the balance between resisting biotic change, supporting resilience to change, or managing unavoidable change (see West et al., 2009). The nature and time scale of conservation goals will clearly depend on the stakeholder. To the regulator, the (moving) target might be achievement of good ecological status within the reporting cycles of the WFD. To the conservationist, the (short- to medium-term) objective might be to halt or reverse biodiversity loss. To the water manager, the (25-year) challenge is to balance water supply and demand whilst meeting statutory obligations on water quality and the environment. To the general public, the priorities (now) might be more about improving visual amenity and access. To the utilitarian, maintaining ecosystems function not only affords considerable economic value but, through critical services provision, actually has a survival imperative. With such divergent perspectives, some contest that conservation is a social process guided by science, not a scientific process *per se* (Aveling, 2009; Clayton and Myers, 2009).

3. Accepted wisdom on adaptation and underlying science needs

Given deep uncertainty about local climate change projections and anticipated impacts on freshwater ecosystems, there is a strong case for devising adaptation management strategies that yield benefits regardless of the climate outlook (Clark, 2002). Ideally, robust adaptation measures are no regret, reversible, incorporate safety margins, employ 'soft' solutions, are flexible and mindful of actions being taken by others to either mitigate or adapt to climate change (see Hallegatte, 2009). Such principles are implicit to the guidance being issued by a growing number of professional bodies and institutions as they seek to embed climate risk screening and vulnerability assessment in their day-to-day operations (e.g., Defra, 2006; Greater London Authority, 2005). Preparation of guidance typically involves distilling then translating latest scientific knowledge—being mindful of the policy and legal contexts—to formulate workable processes for practitioners. Guidance ranges from very general principles (such as *incorporate more green space in urban designs to reduce heat stress*) through to tables of prescribed allowances for engineers (such as the UK Government's *add a 20% sensitivity allowance* to daily rainfall, peak river flow volumes and urban drainage volumes to account for climate change by 2050).

Some national and international agencies have begun to generate high-level, guiding principles to assist adaptation in freshwater and conservation management (e.g., U.S. Climate Change Science Program West et al., 2009; World Bank, 2008; WWF, 2008). For example, one of the most widely accepted axioms is to *reduce sources of harm not linked to climate* (Hansen et al., 2003; Hopkins et al., 2007). Other advice such as *help species, human communities, and economies move their [geographical] range* (WWF, 2008) is more ambiguous, and value-laden, given that assisted dispersal and translocation of species are so controversial. Table 2 provides examples of anticipated impacts and recommended adaptation responses that are cited widely in the literature. At face value most are intuitively correct, yet on closer inspection it is often found that the underlying evidence of efficacy and/or means of implementation are lacking. In their inventory, Heller and Zavaleta (2009) helpfully make a distinction between "general principle" and "actionable" measure. The following case studies show how further research is still needed to turn two popular adaptation principles into action. These are "increase shading of vulnerable reaches through tree planting" (to reduce water temperatures), and "set hands off flows" (to protect ecosystems by halting potentially harmful abstractions during low flow episodes).

3.1. Proactive management of bank-side shade

River temperature is the master water quality variable that affects physical, chemical and biological processes (Caissie, 2006; Malcolm et al., 2008). It is controlled by dynamic energy (heat) and hydrological fluxes at the air–water and water–riverbed interfaces (Hannah et al., 2008). Land and water management impact on these drivers and, thus, modify river thermal characteristics. There is compelling evidence that climate change is already impacting water temperatures and freshwater ecosystems worldwide (Caissie, 2006; Conlan et al., 2007; Dallas, 2008; EEA, 2007; Kaushal et al., 2010; Langan et al., 2001; Solomon, 2005; Webb and Nobilis, 2007; Webb et al., 2008). In the UK, winter warming over the last 30 years has been most rapid in the surface waters of SW England and Wales (Fig. 2). Higher water temperatures potentially affect species distributions and abundance through changes in metabolic rates, feeding, migration patterns and physiological harm at different life-cycle stages. For example, Atlantic salmon eggs experience high mortality rates at ~12 °C, and at water temperatures of ~20 °C fish will not pass beyond the tidal limit of the River Avon in southern England. At water temperatures of ~23 °C, salmon will not migrate upstream and, in the absence of other stressors, a temperature of ~28 °C is regarded as the 7-day upper

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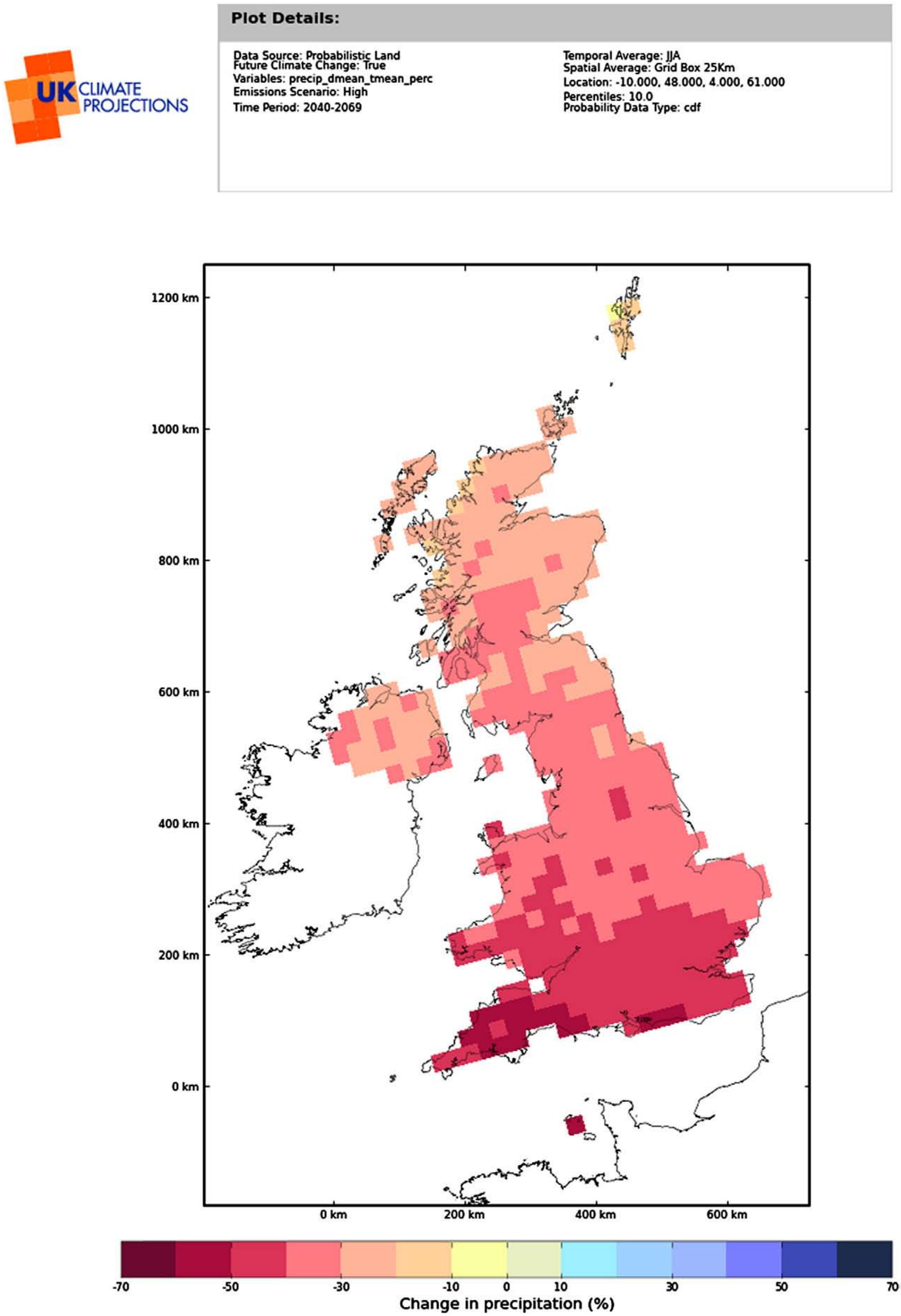

Fig. 1. UKCP09 projected changes in mean summer rainfall totals by the 2050 s under A1FI (left panel, 10th percentile) and B1 (right panel, 90th percentile) emission scenarios. Source: Murphy et al. (2009).

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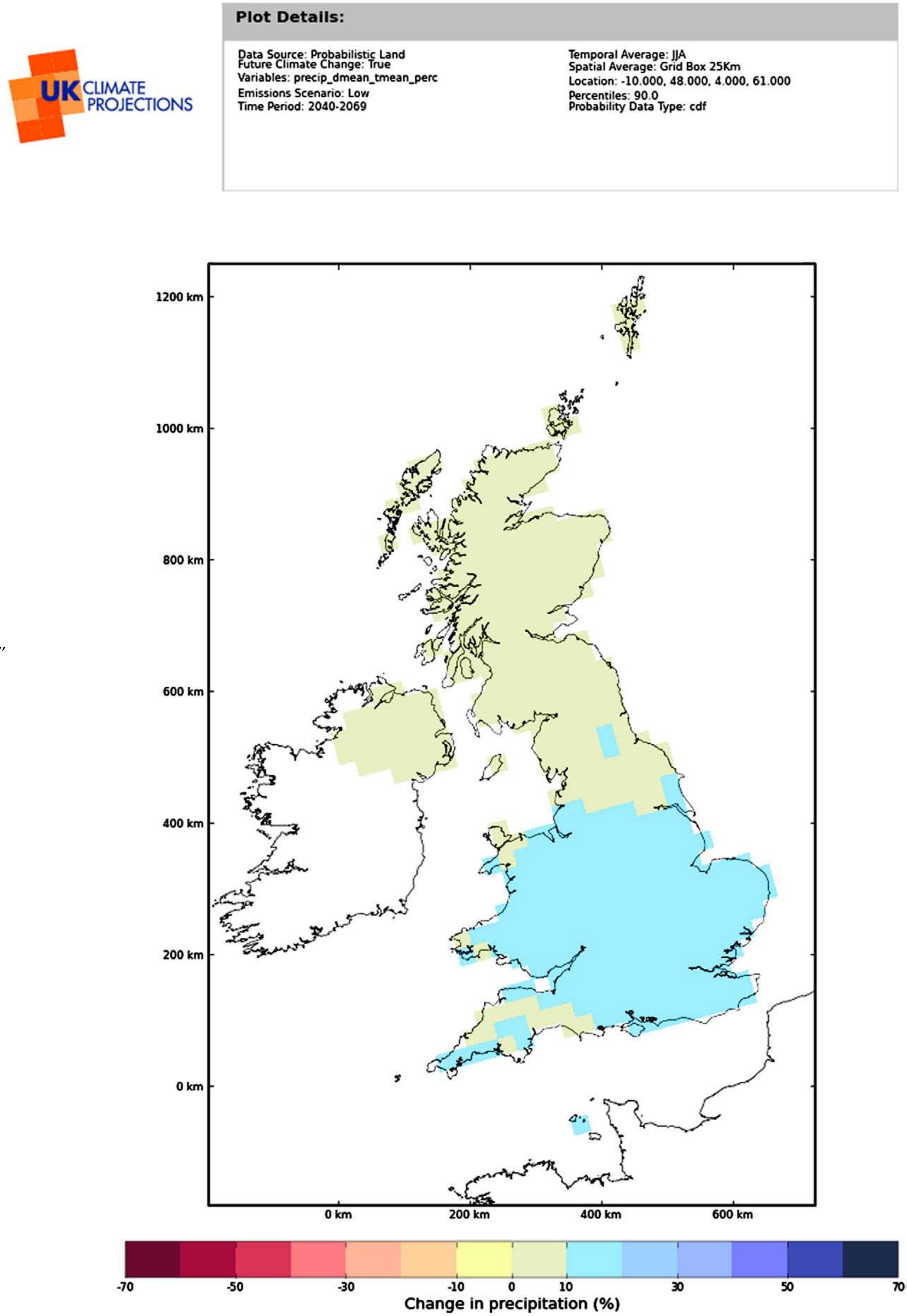

Fig. 1 (*continued*).

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Table 2
Climate change impacts and adaptation responses for freshwater ecosystems.

Pressure	Impacts	Responses
Rising sea levels and surges	Upstream migration of saline water in coastal ditches, grazing marsh, and estuaries; saltwater intrusion into groundwater; consequential changes to freshwater ecology; interruption of abstracted water supplies; damage to sewers and inundation of waste water treatment works	Identify and closely monitor vulnerable sites; provide compensatory habitat; upgrade coastal defences; change target habitat to brackish and modify site management plans accordingly
More sunlight and higher water temperatures	Increased rates of chemical and biological processes; enhanced algal growth and toxic blooms; lower dissolved oxygen concentrations (DOC); loss, northward or vertical migration of species; establishment of invasive species; faster die-off of bacteria; enhanced decay of nitrate in rivers and estuaries	Increase shading of vulnerable reaches through tree planting, particularly in headwaters; in-stream habitat modification to create thermal refugia such as pools; release cooler hypolimnetic water to compensate flows; modify water meadow flooding operations; selective re-introduction or translocation of genetic material from areas with higher temperatures; remove physical barriers to migration and dispersal; manage water levels in water bodies to improve hydrological connectivity
Drier summers and droughts	Higher proportions of effluent in receiving water courses downstream of point discharges; an increased risk of enhanced algal growth including those which may be toxic; increased frequency of fish kills; nitrate flushing at drought termination; transition of perennial to ephemeral systems	Reduce surface and groundwater abstractions through demand management, time limited licensing, compensation schemes, water recycling; enhance aquifer recharge; set hands off flows; manage point and diffuse sources of nutrients, micro-organic compounds, viral and bacterial pathogens
Increased rainfall intensity	More frequent combined sewer overflows; increased sediment loads and allied contaminant metal transport at times of high run-off; increased nitrate, carbon and pesticide leaching from soils; hypoxia (low oxygen) episodes in estuarine waters; more acidic pulses in headwaters; increased mobility of microbiological pathogens; higher suspended sediment loads damage riverine habitats	Upgrade sewage treatment and infrastructure to reduce incidence of uncontrolled discharges; recreate riparian buffer zones, wetlands and active floodplains; restore physical habitats; promote best agricultural practice for husbandry, land and water management; replant hedgerows to trap fine sediments; install sustainable urban drainage systems to manage runoff and water quality
Increased storminess	Increased mixing of lake water column; changes in the timing and assemblage of algal blooms; increased occurrence of acidifying chloride (sea salt) deposition in uplands; tidal surges and waves periodically inundate coastal habitats with salt water	Lake restoration by biological, chemical or sediment treatment; more stringent control of air pollutants; plant tree species with less scavenging of acidifying compounds; upgrade coastal defences

lethal temperature (Solomon, 2008). Other thermal thresholds affect spawning and recruitment (Langan et al., 2001; Solomon, 2005). Synergistic effects with lower volumes of river flow, reduced dissolved oxygen at higher temperatures, or salinity can result in even lower thermal tolerances for salmon (Marshall and Elliot, 1998).

Restoration of riparian vegetation in headwaters has been put forward as a way of increasing shade and countering rising stream temperatures (e.g., Mulholland et al., 1997; Moore et al., 2005). According to Hallegatte's (2009) typology this measure is a *reversible* adaptation strategy that incurs an immediate cost but could be halted if new evidence shows that the intervention is unnecessary, ineffective or harmful. Early field studies showed the impacts of clear-cutting on water temperature (Brown and Krygier, 1970; Swift and Messer, 1971), and the effects of plantations on primary productivity and functional ecology (Clenaghan et al., 1998; Hawkins et al., 1982; Hill et al., 1995; Towns, 1981; Weatherley and Ormerod, 1990). This body of work reveals that post-harvest increases in water temperature are greatest for summer maxima and can attain +13 °C in rain-fed rivers, depending on the area of clear-felling, volume of

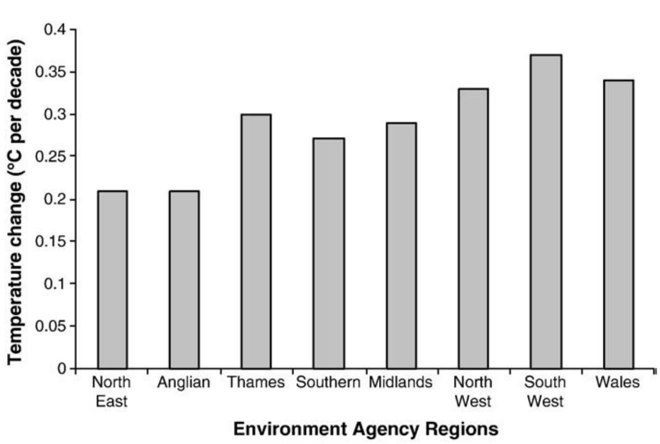

Fig. 2. Decadal rates of change in water temperature across England and Wales shown by Environment Agency regions (after des Clers et al., 2010).

slash left behind, presence of unthinned buffer, rate of vegetation recovery, channel bed material and aspect (Moore et al., 2005). Temperature contrasts of 2 °C (daily mean) and 6 °C (daily maximum) have been reported for NE Scotland depending on whether the land cover is semi-natural forest or moorland (Hannah et al., 2008). However, there is some uncertainty in cooling afforded by forests because of inter-site variations in factors controlling incident solar radiation (catchment topography, channel incision, and channel orientation), heat gains from friction (channel cross-section, roughness and gradient), and thermal exchanges (involving changing ratios of surface and groundwater Malcolm et al., 2004).

Current UK Forest and Water Guidelines recommend that 50% of a river reach should be shaded by riparian trees if salmonids predominate (Forestry Commission, 2003). However, the buffer width, structure, species choice and management plan all determine the extent to which stream temperatures are protected from direct insolation (Broadmeadow and Nisbet, 2004). Early models of the effect of riparian forest cover predicted stream temperatures from buffer length and width (Barton et al., 1985) or from tree height, crown diameter, and stream width (Nakamura and Dokai, 1989). Water temperature simulation on a catchment-scale requires additional information on topographic shading, stream location and orientation (Chen et al., 1998). Others have concentrated on developing low-cost field and image analysis techniques for assessing stream surface shading from digital images (Clarke et al., 2008).

Clearly there is an opportunity to capitalise on accumulated knowledge and build mechanistic models of stream energy balance that can assess different ways of managing climate-driven water temperature increases. Such tools could assist with practical tasks of selecting suitable sites for planting and species mix, as well as with buffer design and management. However, some components of the river water and energy balance—such as groundwater temperature—remain relatively poorly understood. It will also be important to monitor the long-term effects of thermal buffering and shading on managed ecosystems compared with control sites (Gomi et al., 2006). Similarly, the long-term efficacy of the shading should be assessed with respect to other actions (such as creation of thermal refugia via channel modification or cool water discharges from hypolimnon or

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groundwater), set in the context of catchment-wide changes in land cover and hydrological regimes.

Some researchers are calling for long-term empirical research on riparian microclimate and stream energy balance to provide transferable, mechanistic understanding (Hannah et al., 2008). Preliminary studies suggest that field-based and modelling research could lead to workable guidance for site managers on *what*, *where* and *how much cover* to install, as well as the expected benefits for sensitive organisms (see for example, Broadmeadow et al., 2009). It is expected that the value of shading with deciduous trees will be greatest during leaf growth periods and when incoming direct solar radiation is strongest; winter water temperatures (which are very important for incubation and timing of emergence) are controlled less effectively. Other multi-functional benefits of bank-side vegetation should not be overlooked, including: buffer zones for water quality restoration (Osborne and Kovacic, 1993), increased shading to prevent algal blooms (Hill et al., 2001), improved retention of sediments (Larsen et al., 2009), habitat for the adult stages of aquatic insects (Petersen et al., 2004), promoting ecological resilience both within and beyond riparian zones (Seavy et al., 2009) and enhanced energy subsidies to the river (Ormerod and Tyler, 1991). Conversely, it will be necessary to assess possible adverse effects of riparian trees such as increased transpiration losses, shed leaves affecting local water quality and food chains, or woody debris exacerbating downstream flooding.

3.2. Proactive management of river flows

Regardless of climate change, the natural flow regimes of the world's major rivers have already been modified by agricultural, domestic and industrial water withdrawals, effluent returns, impoundment, urban drainage, vegetation removal, water transfers, channelization and flood control. Accompanying changes in water quality and decoupling of rivers from their floodplains have impacted freshwater biodiversity in many ways. For example, loss of wetland habitat, changed environmental cues for life cycle stages, patterns of dispersal, and success of invasive species, are resulting in population decline and range reduction (Bunn and Arthington, 2002; Dudgeon et al., 2006). Climate change is expected to place additional pressure on both pristine and stressed freshwater systems (Bates et al., 2008; Xenopoulos et al., 2005; Xenopoulos and Lodge, 2006). Past efforts to protect freshwater ecosystems have tended to focus on managing water quality or minimum flows. However, the importance of restoring and/or maintaining hydrological variability is now recognised as central to sustaining ecological integrity (Monk et al., 2008; Petts et al., 1995; Poff et al., 1997; Richter et al., 1997). This would be a challenging task even under stable climate conditions.

The science of environmental flow assessment seeks to determine the quantity and quality of water required to achieve specific predefined ecological, social or economic objectives (Petts, 2009). In some regions, objectives may be specified by international law. This is the case for Good Ecological Status—defined with respect to the fauna and flora communities at reference sites—under the EU WFD. Alternatively, flow targets may be negotiated through trade-off and scenario-analysis of water allocation amongst different uses. There are literally hundreds of methodologies for calculating the environmental flow requirement, but most can be grouped into one of four main categories (Acreman and Dunbar, 2004; Tharme, 2003). First, look-up tables are based on simple rules-of-thumb and include percentages of the mean flow or an exceedance percentile (such as the Q95) taken from the flow duration curve (FDC). Second, desk top analyses such as the Range of Variability Approach (RVA) set hydrological targets for the whole river flow regime, including peak, average and low flows, to achieve environmental objectives. Third, functional analyses such as the Building Block Methodology (BBM) are based on the premise that the flow regime can be disaggregated into units with specific functions such as habitat maintenance, channel flushing, minimum flows for migration, and so forth (e.g., Acreman et al., 2009). Finally, physical habitat analysis and modelling techniques establish functional relationships between simple indices of usable physical habitat and the properties of flow volume, depth and velocity via rating curves (e.g., Parasiewicz and Dunbar, 2001).

All environmental flow assessments require information about the time-varying hydrological and geomorphological conditions required by individual species or communities to survive. Unfortunately, supporting data are patchy (in space and time) or even absent for some groups of species, and scientific understanding of the complex interactions between these elements is incomplete. In some cases, a relatively low ability to accurately assess the flow requirements means there is a danger that groups such as macrophytes may be disadvantaged when water resources are allocated (Franklin et al., 2008; Wade et al., 2002; Wilby et al., 1998). Holistic approaches try to counter these concerns by considering the needs of the whole ecosystem via a mix of quantitative and qualitative expert review (e.g., Acreman et al., 2008; Acreman and Ferguson, 2009; Cottingham et al., 2002). Such efforts are being supported by systematic cataloguing and meta-analysis of the environmental preferences of taxa, as well as by information on physical habitat (e.g., Orr et al., 2008a).

Even if it is assumed that river flow will remain the "master" water variable affecting freshwater ecosystem integrity, climate change raises several awkward issues about the methods used in restoration ecology. First, the shape of the FDC—an ingredient of many environmental flow assessments—could alter in response to projected changes in catchment water balance. Changes in the incidence of peak-flows could have either positive or negative consequences for ecosystem health depending on the season: summer spates, accompanied by uncontrolled sewer outflows, can severely impact water quality whereas winter spates may favour the recovery of benthic and hyporheic macroinvertebrates following drought (Stubbington et al., 2009). In the near-term (2020 s) it is possible to envisage scenarios in which climate change could more than off-set any gains in low flows arising from reduced abstraction (compare NAT HIGH with NAT ABS in Fig. 3). Under these circumstances, the hands off flow would become a more frequent event, in-stream total physical habitat area would decline, decreasing physical habitat availability for some taxa (e.g., salmonids) but increasing for others. Allowable abstractions pegged to critical segments of the historic FDC might then have to be revised downwards. However, even the historic FDC is uncertain because of decadal variations in rainfall-runoff leading to clustering of flood- and drought-rich episodes (see: Jones et al., 2006).

The ecological basis for the standards is also sensitive to climate change. Individual species at the southern limit of their range may be

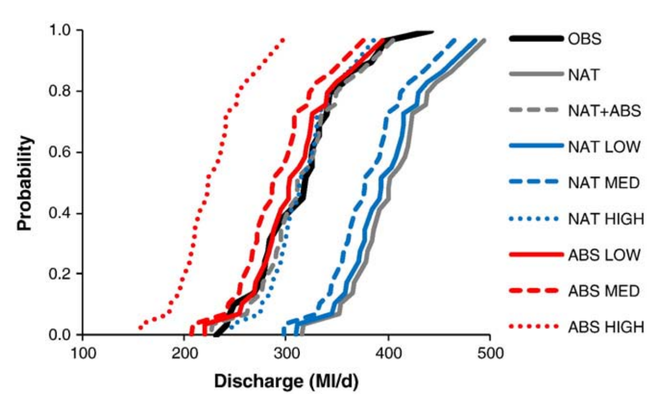

Fig. 3. Sensitivity of naturalised (NAT) September mean flows of the River Itchen at Allbrook and Highbridge to historic abstraction (ABS) combined with LOW, MEDIAN and HIGH climate change for the 2020 s. All scenarios are compared with respect to observed (OBS) 1961–1990 flows. The climate change scenarios are respectively the 5th, 50th and 95th percentiles of the climate model ensemble used in the 2009 England and Wales water company plans.

extirpated (e.g., salmonids, amphibians, glacial relict species, and freshwater bryophytes), or vulnerable aquatic habitats may migrate or be lost (e.g., coastal ditches, freshwater fen/coastal grazing marsh close to the tidal limit, and spring-heads). For example, 10 out of 11 studied populations of Arctic charr (*Salvelinus alpines*) have suffered recent decline in the UK (Winfield et al., 2010). In such cases, rising water temperature or geomorphological responses to catchment-wide climatic and non-climatic pressures may pose greater threats to the ecology than an altered flow regime (Poole and Berman, 2001). Variations in river flow may also have indirect consequences through reduced dilution of nutrients, organic contaminants and disease agents. Changes in ecological communities at reference sites mean that without a system for regularly reviewing ecological objectives, the initial set of environmental standards could be rendered obsolete (Wilby, 2004).

Proactive and adaptive management of river flows to resist the effects of climate change will, therefore, require scientifically defensible conservation targets and unambiguous measures of success (Nel et al., 2009). At the moment the burden of proof is on demonstrating that damage occurs to ecosystems when the flow falls beneath a critical threshold (e.g., Exley, 2006; Fung et al., 2009). As with ecological restoration, this can involve undertaking fully transparent before and after assessment (Palmer et al., 2009). Alternatively, response curves may be used to predict target species' abundance under changed environmental conditions. Detailed monitoring and reporting of whole ecosystem response will be required for test cases, and any lessons fed back into revised guidance. High-level screening could help to identify potential "hot spot" sites (i.e., those that are already close to a tipping point between different habitats or assemblages thanks to climatic and/or social pressures). For example, the UK Government's Public Service Agreement for climate adaptation refers to catchments that are already over abstracted.

However, it will continue to be difficult to detect and (statistically) test the value of any adaptation measures against a background of confounding factors and natural variability. Integrated hydro-ecological models of high-value or high-risk systems can assist cost-benefit analysis of alternative adaptations including manipulation of flows, nutrients loads and physical habitat under a range of climate change scenarios (as in Whitehead et al., 2006). Until such experiments are performed, it will remain unclear whether limited resources are best invested in revoking abstraction licences, improving water treatment, restoring degraded habitats, or a combination of all three. In the meantime, it makes sense to implement low regret policies to enhance water efficiency and thus reduce demand in areas that are already under significant water stress.

4. Discussion of broader evidence needs

So far we have explored just two adaptation options amongst hundreds on offer. Heller and Zavaleta (2009) assert that ~70% of the recommended actions for biodiversity management under climate change are classified as "general principles". This suggests that most are remote from the sharp end of site-scale conservation, leaving managers with few alternatives to "business as usual" or "buying time" by reducing pressures that are not linked to climate change (Hansen et al., 2003). Measures such as more intelligent monitoring and reporting of species distributions are valuable under any climate change outlook, but research programmes should now be testing specific aspects of adaptation to provide a firmer evidence base for regional planning and site management. This means designing experiments and long-term (>5 years) field campaigns that can test the efficacy of adaptation interventions (Fig. 4).

The following sections synthesize findings from individual questionnaires submitted by experts. The survey was designed by the Environment Agency with a view to building consensus about the

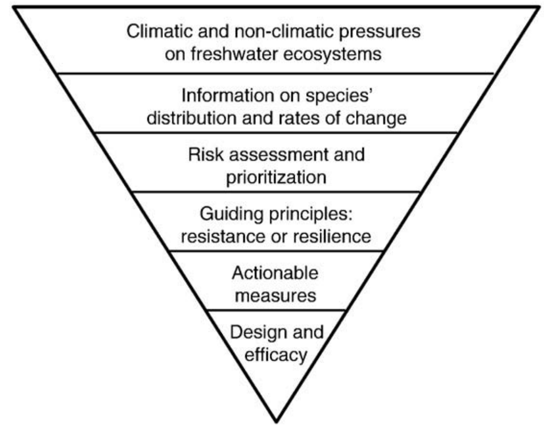

Fig. 4. Drilling down to the evidence needed to underpin actionable adaptation.

present state and gaps in knowledge for a cross-section of freshwater species and habitat types (Annex A). Respondents were targeted with research expertise in one or more major taxonomic groups plus a good understanding of the UK regulatory context. Experts included heads of relevant section within government agencies/research centres such as the Environment Agency, Natural England, Centre for Ecology and Hydrology, Scottish Fisheries Agency, as well as independent consultants (frequently called upon by the agencies to undertake work and/or audit research programmes), and academics recognised in the field for their active engagement with the management community.

The feedback was used to collate understanding of anticipated climate change vulnerabilities and impacts (questions 1 to 5), existing management practices (6–7), and evidence needed to support adaptation (8–9). This information seeded group discussions in a participatory workshop attended by the same experts alongside invited UK water managers and environment policy-makers. The brief was to highlight barriers to adaptation and gaps in evidence needed to implement adaptation in practice. From these discussions it became apparent that collective interest was greatest in the two areas discussed above (i.e., water temperature and environmental flow assessment). Questionnaire responses and workshop outputs were subsequently organised by scale of management: spanning ecosystem, protected area, and administrative region. These are discussed in turn below.

4.1. Evidence of ecosystem responses to climate variability and change

Studies are needed to identify the most vulnerable taxa and associated risks to ecosystem goods and services. This requires integrated monitoring systems that can track changes in species-level life-history, population dynamics, community composition, species interactions and ecological processes, from molecular to continental scales. For example, understanding of the natural resistance and resilience of (salmonid) populations to climate change is being advanced by measuring genetic variation (and rates of straying) as an evolutionary response to changing flows and habitat (McClure et al., 2008). Likewise, the adaptability of semi-ubiquitous species assessed through detailed studies of life histories in different places. *In situ* measurements of the flow/temperature conditions experienced by individuals could be collected by tagging and telemetry to improve understanding of behavioural responses to environmental cues. Some under-represented groups of species (e.g., macrophytes) and habitats (e.g., modified channels) require basic information simply to benchmark their present distribution and status. Thermal imaging technologies can help locate refugia during low flows (e.g., Hedger et al., 2006; Marcus and Fonstad, 2008;

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Torgersen et al., 2001); bathymetric LIDAR and aerial photography can map fluvial grain size, water depths, habitats and barriers to species dispersal at reach to catchment scales (Fig. 5). Even so, LIDAR may not be applicable in the case of heavily shaded channels.

An important ancillary task should be systematic review of the "fitness" of freshwater monitoring networks to detect and attribute ecosystem change. Unfortunately, the networks operated by regulatory bodies tend to be project-based (i.e., concentrating on individual

Fig. 5. Quantitative mapping of salmon habitat in the South Tyne achieved through the integration of known habitat preferences with aerial surveys of grain size and water depth. Source: Keith Hendry (*pers. comm.*).

species, or issues) rather than providing long-term, homogenous records at species-level. One way of rationalising the monitoring burden might be to bring together or upgrade existing sentinel sites (as in the UK's Environmental Change Network). Data recovery and digitization can also help to extend observational records and thereby characterise the true extent of natural variability of systems over several decades. More robust predictions of species' distributions and ecosystem processes will depend on field data to better define model parameters representing life history, predation, dispersal, and habitat. The sensitivities of fundamental hydrological processes such as evapotranspiration and groundwater recharge are still poorly understood despite their significance to future river flow and water levels. Finally, geo-referenced national and international data holdings could be pooled to enable analysis of transboundary range shifts, and to compile look-up tables of the environmental requirements of southern counterpart species.

4.2. Evidence for protected area management

Managers of protected areas and water bodies are immediately confronted by the choice of trying to build resistance or resilience to climatic change (Hansen et al., 2003). Management responses may also be reactive or proactive (Palmer et al., 2009). These are not necessarily mutually exclusive, but managers have to consider a range of practical issues, not least the cost-effectiveness and sustainability of each adaptation option. In the short- to medium-term, measures also have to work within existing policy, planning and regulatory frameworks (Orr et al., 2008b). Furthermore, there has to be realism about what can actually be achieved. For example, local efforts to protect species such as salmon might ultimately be thwarted by increased mortality at sea (Todd et al., 2008).

We have already suggested that management of riparian vegetation and in-stream flows to retard the consequences of climate change will be most effective if firmly based on scientific understanding. Other local measures include removal of invasive species, habitat restoration, upgrade of coastal defences, removal of physical barriers to migration, treatment of point and diffuse pollution sources, control of bank-side erosion, and artificial mixing of lake waters (Table 2). Detailed process modelling of habitat suitability and population dynamics can help identify vulnerable rivers (Walsh and Kilsby, 2007) and those that might respond positively to interventions. For example, models of Chinook salmon in a Pacific Northwest river basin suggest that recovery plans that enhance lower-elevation habitats are likely to yield greater benefits than those targeting higher elevation sites which are already relatively pristine (Battin et al., 2007). Likewise, models of phytoplankton community can test the relative sensitivity of responses to a range of co-stressors and hence the benefit of managing nutrient loads, lake stratification, and water levels under higher temperatures (e.g., Elliott and May, 2008).

Most conservation policy and legislation is aimed at maintaining species and ecosystems that are representative of historically-defined communities for a given biome or ecosystem, as well as the preceding stages of succession. Hence, the legal requirement may be to resist climate (or indeed any other) change. The widely held assumption that high-quality ("natural") freshwaters are more resilient than degraded systems remains largely untested (Clark, 2009) but some progress is being made in this area. For example, Dunbar et al. (2010) showed that less modified channels offer a greater diversity of habitats and hence refugia for invertebrates during extreme high and low flow. If resilience is to be promoted, conservation managers and stakeholders may need to adjust expectations of what is an acceptable ecosystem state (or indeed type) as new assemblages are formed. Notwithstanding the philosophical issues, major uncertainty surrounds the outcome of assisted gene flow and species translocation. For example, translocation experiments with butterflies show that poleward migration is hindered by a lack of host plants (Pelini et al., 2009). Some glacial relict fish (Vendace *Coregonus albula*) are already part of translocation experiments to refuge sites (Winfield et al., 2008). It remains to be seen if such experiments will be successful; but the message is clear that broader inter-species and habitat linkages need to be understood before such actions are taken.

4.3. Evidence for regional policy and conservation planning

Planners are being encouraged to re-instate hydrological connectivity between river channels and floodplain wetlands, to incorporate the upstream-downstream continuum, and to create more/larger protected area networks in order to enable species' dispersal and safeguard refugia (Clark, 2009; Erwin, 2009; Nel et al., 2009). In practice, this means that reliable evidence is needed on the potential risks and options for managing invasive species, recognising that definitions of what is native and what is invasive may need to change (Willis and Birks, 2006). Continental-scale bioclimatic modelling can help to identify future biodiversity hotspots or conversely locations where colonization is unlikely *for specified regional climate change scenarios* (Vos et al., 2008). Maps of climatically suitable habitat can then inform the design of climate corridors and shortlist areas that might be acquired for reserves or wetland re-creation. However, it is acknowledged that there are large uncertainties inherent to bioclimatic modelling and that even the suitability of existing protected area networks remains an open question (Araujo et al, 2004). Furthermore, most studies focus on terrestrial (plant) species; freshwater organisms have been largely neglected by bioclimatic modellers.

Conservation planners must also take into account the possibility of habitat loss due to other policy imperatives for flood and coastal management, food security, renewable energy production, and urban development (see: Defra, 2008, 2009). This includes managing an array of unintended or indirect consequences (Table 3) of climate adaptation and mitigation measures being taken by other water-dependent sectors (Berry, 2009; Lopez et al., 2009; Paterson et al., 2008; Poiani, 2006; Ratcliffe et al., 2005). There are water quality risks to manage too, including the possibility that higher water temperatures could combine with endocrine disruptors and result in catastrophic population declines (Williams et al., 2009). Many of these decisions could be serviced by high-level meta-modelling (e.g., Harrison et al., 2008).

Table 3
Examples of indirect pressures and unintended consequences of climate mitigation or adaptation strategies on freshwaters.

Pressures	Impacts
Reduced nitrogen emissions to air	Smaller area of acidic deposition and area of ecosystems adversely affected by excessive nitrogen (eutrophication)
Increased bio-fuel production	Increased groundwater acidification caused by enhanced acid deposition to forestry and removal of soil cations during harvesting
Increased water supply and storage	Higher concentrations of conservative pollutants due to water re-use; river regulation and inter-basin transfers change thermal and chemical composition of downstream waters
Changing growing seasons and land management	Changing cropping patterns, agricultural pesticide and fertilizer use; changes in soil tillage; diffuse runoff quality
Changing fire regime	Increased frequency and severity of fires in headwaters; contamination of groundwater resources; increased export of organic carbon, sediments and toxics; higher water treatment costs, even closure of works
Measures to reduce flood risk	Improved urban water quality linked to introduction of sustainable urban drainage systems; upgrading and retro-fit of sewerage systems to cope with higher rainfall intensity

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Greater levels of interdisciplinary collaboration will be needed to tackle the above regional-scale issues. Fortunately, these new ways of working are being reflected in the make-up of international research teams (Table 1). For example, the INTERREG III BRANCH project brought together ecologists and spatial planners to evaluate existing policies and develop new tools to improve conditions for species dispersal across NW Europe. Models were used to evaluate the robustness of the Natura 2000 network and to identify where wetlands might be created or restored. Landscape approaches to land and water management are already enshrined within integrated river basin management, however, further research is needed to test the effectiveness and design of buffer zones between surface waters and surrounding matrix of potentially damaging land uses (Harrison et al., 2008).

5. Concluding remarks and recommendations

Freshwater ecosystems of today are the legacy of centuries of modification; freshwaters of tomorrow will be altered by the combined effects of climatic and non-climatic pressures. So conservation managers are facing difficult choices about what if any direct action should be taken to restore past losses, maintain the *status quo* or build flexibility in the face of large uncertainty about future impacts. The climate change literature abounds with adaptation principles, but is less forthcoming about how they might be applied in practice. Therefore, we have made the case for smarter monitoring, modelling, and experimentation that directly addresses the questions raised by managers. These are typically: *what*, *where*, *when*, and *how much action to take?* There are potentially large sums of money involved in adaptation, so there has to be confidence that measures will be cost-effective and sustainable. Options should be evaluated in a systematic way through field trial, use of long-term data, and sensitivity testing then the outcomes shared through best practice guidance and demonstration projects. Much of what has been discussed falls outside the scope of individual scientific disciplines.

Given the deep uncertainty, adaptation to climate change should involve solutions that are low-regret, evidence-based and synergistic with responses to other pressures on freshwater ecosystems. This means implementing measures that have multiple benefits, for example by limiting diffuse pollution or providing habitat, *alongside* climate adaptation. However, not all solutions will be equally appropriate in all locations. There is also recognition of the need to manage protected area networks within a broader matrix of off-site pressures. Furthermore, the adaptation and mitigation actions being taken by others could create opportunities or cause further harm to freshwater ecosystems. The river basin provides a rational basis for adaptively managing ecosystem change given that it is a fundamental unit for legislation, data collection and appraisal. Integrated modelling techniques could also be used to assess the cost-benefit of controlling different pressures so that resources are allocated in defensible ways. Ultimately, all these depend on open access to data to reveal fundamental species–ecosystem–environment relationships. Routine monitoring and reporting are also needed to constantly review and test adaptive management strategies.

Some contest that "managing for change"—when there is imminent risk of loss of a species or habitat—represents a special case (West et al., 2009). This may require application of tools and knowledge that already exist. In such cases, researchers should be prepared to work directly with catchment managers to identify feasible solutions, and monitor the outcomes of interventions (such as assisted species translocation, gene flow, regeneration, or successional change). We have already identified specific research activities that would support such practices (Annex B). However, in other cases, unavoidable ecosystem shifts may require realignment of management goals or even a triage approach to priority-setting. In the future, such decisions would be well served by targeted research into societal values, public expectations and willingness to pay, all within the constraints set by legislative and institutional frameworks.

We believe that in the medium term, ecosystem adaptation could be assisted by establishing a thematic programme. This would bring together researchers from many disciplines, governmental and non-governmental bodies, landowners, and the private sector, to build a shared evidence base for adaptively managing freshwater ecosystems in the 21st century. The programme would have to confront fundamental scientific questions about the intrinsic resilience of freshwaters, to establish what (if any) additional interventions might be needed, or even feasible. Annex B lists topics for research, including the recurrent call to build data assets. In addition, a systematic review of monitoring and reporting systems should be undertaken to determine the fitness of existing networks to detect ecosystem change at different scales. Without appropriate real-time information it will be impossible to adaptively manage emergent risks. Meanwhile, different adaptation measures should be subject to field trials on a scale last seen during the upland forestry and acid rain research campaigns. Expert working groups should be tasked with translating the results into best practice guidance, beginning with water temperature and flow management. Ideally, work programme outputs would be harmonized with the time-table of the WFD to help secure environmental objectives by 2015, and beyond.

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Annex A. Questions asked of species and habitat researchers

1. Is the impact of climate change on your given species, taxa or habitat known, partially, fully or not at all?
2. What changes are expected, for example range change, phenological change, indirect impacts (e.g. predators, disease, and competitors), extinction, habitat loss (e.g. wetland drying)?
3. Does the sensitivity of your species, taxa or habitat vary with location?
4. Is your species, taxa or habitat likely to be able to adapt without additional intervention?
5. What sort of climate change would be dangerous for your species, taxa?
6. Would the reduction of other specific pressures e.g. habitat modification or diffuse pollution make any difference to the long-term success of your given species, taxa or habitat or would it merely buy some time?
7. What single or combination of adaptation strategies would be most appropriate, over what timescales, and what level of evidence is available to support them?
8. Could we have greater understanding of how your given species, taxa or habitat might respond to future climate?
    a. What would be needed in the short term (1–3 years)?
    b. What steps would be needed in the medium term (2–4 years)?
    c. What would form the basis of a longer-term research programme (>3 years)?

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9. Could targeted research help identify appropriate adaptation strategies to help reduce the impacts of climate change?
   a. What would be needed in the short term (1–3 years)?
   b. What steps would be needed in the medium term (2–4 years)?
   c. What would form the basis of a longer-term research programme (>3 years)

Annex B. Building the evidence base for adaptation

Expert and policy-maker responses are grouped into six activities that support adaptation in practice: detecting climate change impacts; managing multiple anthropogenic pressures; restoring riparian vegetation; assessing and protecting environmental flows; managing transitions to new ecosystem states; integrating and appraising adaptation options.

Detecting climate change impacts

i. Monitor and report changes across networks of data-rich or sentinel sites/ hot spots/ indicators/ taxa (e.g., spring-heads, headwater streams, downstream migration of habitats, coastal ditches, freshwater fen/coastal grazing marsh close to tidal limit, wet heath land, amphibians, habitat specialists, glacial relict species, dragonflies, juvenile salmonids, roach and trout [for endocrine disruption], aquatic bryophytes, shallow eutrophic and mesotrophic lakes, and process-based indicators);
ii. Monitor across a range of spatial scales to improve understanding of macro-scale linkages between climate change, fluvial geomorphology and habitat availability;
iii. Undertake data archaeology campaigns to catalogue and digitize paper archives;
iv. Automate trapping and record emergence patterns and timing of aquatic insects (including small streams and standing waters);
v. Normalize (short) observational records (e.g., eel, salmon, trout, invertebrate populations) for multi-annual and multi-decadal variability linked to large-scale ocean (SSTs, AMO) and atmospheric changes (NAO) across NW Europe;
vi. Undertake meta-analysis of data-holdings (by location), centralise and share key temporal and geographical data sets across Europe, plus develop tools to visualize relationships within and between rich data sets;
vii. Review “fitness” of national monitoring and reporting programmes for detecting and attributing climate change impacts (in terms of indices used, spatial/habitat coverage, and temporal sampling regime);
viii. Design harmonized monitoring programmes for research, management and regulation to achieve closer integration and efficiency gains.

Managing multiple anthropogenic pressures

i. Co-locate meteorological, environmental and ecological monitoring to track whole ecosystem/community change (at patch, microcosm, river basin scales), including phenology (e.g., timing and duration of salmonid egg and early life stage development, and emergence mismatch), predation, pathogens, and invasive competitors in relation to climate change and other anthropogenic stressors;
ii. Assess risks from synergies between endocrine disruption and temperature-determined gender modification, or remobilisation/ re-deposition/bio-accumulation of toxics substances with more hydrological extreme events;
iii. Assess the consequences of flood and coastal management for freshwaters (fish stocking, floodplain biodiversity, and provision of compensatory habitat);
iv. Model future distributions of invasive species to evaluate different control strategies;
v. Assess risks posed by tidal stream or wave power structures to (eel and salmonid) fisheries;
vi. Determine relative risks posed by oceanic and freshwater changes to diadromous (e.g., eel larvae) and anadromous species (e.g., salmon growth stage) to assess limits to adaptation.

Restoring riparian vegetation to manage water temperature

i. Establish catchment studies to monitor and model the effectiveness of different configurations of riparian vegetation to control rising water temperature;
ii. Use technologies such as bathymetric LIDAR and aerial photography to map whole catchment fluvial grain size, depths, habitats, barriers (to fish migration or sediment transport) and thermal imaging of low flows (to locate potential sites for plantation of vegetation, thermal refugia within streams);
iii. Collate data and model climate change impacts on groundwater temperature;
iv. Assess the sensitivity of phytoplankton community to temperature change and co-stressors (such as nutrient loads, lake stratification, and flushing rate);
v. Review lessons learnt from analogues of climate change (e.g., ecological and habitat responses to temperature regulation by impoundments; reach effects of thermal discharges from power stations; and removal of upland riparian tree cover);
vi. Develop decision-support and regulatory framework for water temperature management based on the above.

Assessing and protecting environmental flows

i. Undertake *in situ* measurement of real-time environmental (flow and temperature) conditions experienced by taxa using tagging and telemetry;
ii. Develop national evidence base to define critical flow thresholds and habitat quality for target species (or ecosystems);
iii. Collate evidence of the relative efficacy (or detrimental effects) of river flow, water quality and habitat restoration practices in different locations;
iv. Quantify potential impacts of changes in evapotranspiration and CO_2 fertilization on minimum river flows and water-table fluctuation in wetlands;
v. Conduct field and laboratory experiments to calibrate uncertain model parameters and processes (e.g., growth and grazing rates of algae);
vi. Model system behaviour to benchmark impacts, then evaluate adaptation options (e.g., bank-side habitat management, compensation flows to maintain habitats and low flows, artificial mixing to reduce Cyanobacteria blooms versus nutrient control, wetland creation, etc);
vii. Model freshwater species and propagule dispersion to evaluate options for improving hydrological connectivity and/or species translocation.

Managing transitions to new ecosystem states

i. Apply molecular biological techniques to improve understanding of genetic variation (including role of “straying”) as an evolutionary response to direct climate change stressors and habitat changes;
ii. Undertake systematic cataloguing/meta-analysis of the thermal and environmental limits of particular (key-stone) taxa;
iii. Evaluate semi-ubiquitous species' (e.g., mayfly) adaptability through detailed study of their life histories in different places;
iv. Use models to test the assumption that systems with greater heterogeneity and lower levels of habitat disturbance will have greater resilience to climate change (e.g., ecology of ‘natural’ versus engineered channels);

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v. Use bioclimatic envelope modelling to identify potential sites for new or re-created freshwater and wetland habitats (as under the Wetland Vision);
vi. Determine societal values, public expectations and willingness to pay when confronted with imminent species and/or habitat loss (e.g., freshwater floodplain fen to brackish fen; and salmonid to non-salmonid river);
vii. Develop visualization tools to convey relative risks arising from climate change and other anthropogenic pressures on the freshwater environment (e.g., new urban and infrastructure development, over-abstraction, saline intrusion, diffuse runoff, uncontrolled waste water discharges, and habitat degradation);
viii. Assess social acceptability of triage for prioritising those species and habitats considered most worthy of conservation.

Integrating and appraising adaptation options

i. Develop meta-analysis techniques for up-scaling intensively studied sites, river reaches (fluvial geomorphology/ecology) and experimental catchments to regional and national effects;
ii. Integrate mechanistic and bio-climatic space models (by incorporating life history, inter- and intra-specific density dependence, predation, ability to colonise, ecological response to variability and extremes, socio-economic drivers of change, habitat rather than species change, etc);
iii. Conduct field trials for managing water levels, reinstating hydrological connectivity, permeable landscapes, and refuges in ways that limit the spread of invasive species or disease (as in the Usk Valley pilot);
iv. Model conjunctive use of land and water to predict outcomes of best practice forestry, agricultural methods to limit sediment and pollutant delivery, and spatial planning;
v. Use integrated assessment tools to evaluate possible conflicts and synergies between different adaptation policies (e.g., food security, habitat conservation, and ecosystem service provision);
vi. Use models to assess cost-benefit of habitat restoration, improved water treatment, reduction of agricultural pollution and/or maintenance of flow to prevent exceedance of chemical thresholds (for nutrients and micro-organic compounds);
vii. Use integrated assessment tools to evaluate multi-sectoral trade-offs between adaptation–mitigation–biodiversity (e.g., re-creation of wetlands to manage floods, increase biodiversity and sequester carbon; and low-head hydropower or tidal power affecting emigrating silver eels);
viii. Assess impacts of national food and energy security strategies for freshwaters (such as increased domestic production of fruit and vegetables);
ix. Establish demonstration sites to share best practice, in particular adaptation measures that yield multiple benefits.

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