Climate change uncertainty and natural flow regime variability – implications for environmental flow protection in England

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Sustainable development in the Anthropocene is jeopardised by a multitude of existing and emerging pressures on freshwater ecosystems. The protection of environmental flows represents a key strategy for balancing anthropogenic water demand with the requirements of healthy freshwater habitats.

Using England as a case study, this thesis examines three dimensions of water management pertaining to environmental flow protection. The first dimension is the variability of natural flow regimes and its representation in large-scale environmental flow guidance. A new hydrological framework for classifying natural and modified regimes was developed that distinguishes five river types. Their natural regimes vary most strongly in the magnitude of low, average and high flows, the frequency of high flows, the duration of flow events and the timing of average and high flow events. These hydrological indicators are suggested as new country-scale protection targets and this framework provides decision makers aiming to restore flow regimes and/or develop protection strategies for modified regimes with natural reference conditions.

The second dimension relates to the high climate change uncertainty and its implication for streamflow projections. Two catchments from different regime classes served as case studies for a detailed analysis of climate change impacts on streamflow elements relevant for environmental flow management. Sampling different types of climate model uncertainty across a range of emissions pathways, vastly different streamflow responses are projected. The hydrological response under climate projections sampling climate model parameter settings is substantially stronger and drier than under projections sampling climate model structure. These hydrological projections can guide climate change adaptation, in particular improved abstraction management, in these case study catchments and in similar catchments more widely.

The third dimension relates to policy, governance and social environment of water management. Combining a simple water balance model and stakeholder consultation, environmental flow allocation scenarios were evaluated and the shortcomings of current water management and governance in addressing existing and emerging pressures were identified. Five strategies were outlined for closing adaptation gaps and enhancing water management in a way that improves environmental outcomes and the balance with human water use under climate change.

This thesis informs and contributes to enhanced environmental flow protection and therefore freshwater resilience and sustainable development in the Anthropocene.

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List of Abbreviations

AET Actual Evapotranspiration XI

AI Artificial Intelligence 164

ALS Abstraction Licensing Strategy XXIII

AMP Asset Management Plan 127

ANOVA Analysis of Variance 62

AP Abstraction Point XXIII

API Application Programming Interface 16

ASB Abstraction Sensitivity Band XI

CaBA Catchment Based Approach 129

CAMS Catchment Abstraction Management System 73

CaSTCo Catchment Systems Thinking Cooperative 161

CEH Centre for Ecology & Hydrology 19

CMIP Coupled Model Intercomparison Project 61

CSM Common Standards Monitoring 137

CSO Combined Sewer Overflow 155

Defra Department for Environment, Food and Rural Affairs 127

EA Environment Agency 58

EBA Ecosystem-Based Approach 126

EU European Union 11

eCX euro-CORDEX 57

EFI Environmental Flow Indicator XIV

eFLaG Enhanced Future Flows and Groundwater 136

ELMS Environmental Land Management Schemes 169

ESS Error Sum of Squares XII

euro-CORDEX European Coordinated Regional Climate Downscaling Experiment 8

FAST Fourier Amplitude Sensitivity Testing 74

FDC Flow Duration Curve 80

FEH Flood Estimation Handbook 19

G2G Grid-to-Grid XXII

GCM General Circulation Model 4

GHG Greenhouse Gas 60

GPD Generalised Pareto Distribution . . . . . B xii

GPQM gamma-Pareto Quantile Mapping XVIII

GR4J Génie Rural à 4 paramètres Journalier XXII

GR6J Génie Rural à 6 paramètres Journalier XXII

CSF Catchment Sensitive Farming 173

HM Hydrological Model 4

HMWB Heavily Modified Waterbody 11

HOF Hands-off-Flows 161

HRU Hydrological Response Unit 70

ICM Integrated Catchment Management VIII

IPM Integrated Pest Management 177

ISIMIP Inter-Sectoral Impact Model Intercomparison Project XIX

KGE Kling-Gupta Efficiency 75

LD Linear Discriminant X

LDA Linear Discriminant Analysis X

LS Linear Scaling XIII

MAPE Mean Absolute Percentage Error X

MAR Missing at Random 16

MCAR Missing Completely at Random 16

MME Multi-Model Ensemble 62

NAAS National Agricultural Advisory Service 157

NERC Natural Environment Research Council 160

NFM Natural Flood Management 176

NFW National Framework for Water Resources 128

NAO National Audit Office 163

NGO Non-Governmental Organisation 139

NRFA National River Flow Archive 12

NSE Nash-Sutcliffe Efficiency 75

Ofwat Office of Water Services 127
pbias percent bias 75
PC Principal Component X
PCA Principal Component Analysis XII
PDM Probability Distributed Model XXII
PCP Precipitation XI
PET Potential Evapotranspiration XI
PPE Perturbed Physics Ensemble 57
RCM Regional Climate Model XIII
RCP Representative Concentration Pathway 57
RBMP River Basin Management Plan 128
RMSE Root Mean Square Error X
RSPB Royal Society for the Protection of Birds 129
SDG Sustainable Development Goal 191
SR Surface Runoff 88
SSP Shared Socioeconomic Pathway 61
SuDS Sustainable Urban Drainage System 154
SWAT Soil & Water Assessment Tool 57
UK United Kingdom X
UKBN UK Benchmark Network IX
UKCP18 UK Climate Projections 2018 IX
UN United Nations 1
VE Volumetric Efficiency 75
WFD Water Framework Directive 11
WINEP Water Industry National Environment Programme 128

Chapter 1. Introduction

Earth system functioning and human society are fundamentally dependent on water. Human water security is however often realised without sufficient concern for environmental consequences (Best, 2018; Pahl-Wostl et al., 2013). In the Anthropocene this has led to a myriad of environmental trade-offs, including widespread aquifer depletion (Gleeson et al., 2020) and loss of wetlands (Hu et al., 2017). Freshwater ecosystems are hotspots of biological richness (Strayer and Dudgeon, 2010). Almost 10% of Earth's described animal species including a third of vertebrates rely on freshwater environments for their survival (Balian et al., 2008; Dudgeon et al., 2006). Freshwater species are being lost at a consistently higher rate than those on land and since 1970 their populations have declined by around 83% (WWF, 2022). The pressure on freshwater habitats is projected to increase through population growth and agriculture (particularly irrigation water demand), further endangering these fragile ecosystems (Best, 2018; Boretti and Rosa, 2019; Graaf et al., 2014). Moreover, climate change is a global challenge that affects freshwater systems in a range of ways and is tightly linked to sustainable development (IPCC, 2022). Therefore, water has to be managed in a way that sustains human well-being while addressing acute existing stressors and preparing for emerging pressures (IPCC, 2022; Oberdorff, 2022). Achieving this balance and a resilient freshwater system that thrives under change and maintains coherent function is a central condition for sustainable development (Boltz et al., 2019; Holling, 1973). It is also integral for two of the United Nations (UN) Sustainable Development Goals, 6 – clean water and sanitation and 14 – life below water (UN, 2015).

Evidence-based water policy and regulation are required (Howarth et al., 2020; Lubchenco et al., 2015) to address the high spatio-temporal variability of freshwater systems both in terms of natural hydrology and biodiversity as well as with regards to water management's complex scales of operation (Daniell and Barreteau, 2014; Landres et al., 1999). The cross-scale social (Krause and Strang, 2016; Lund, 2015), economic (Gracia-de-Rentería and Barberán, 2021; Rey et al., 2019), political and societal (Boeuf et al., 2016; Eerd and Wiering, 2022; Robins et al., 2017) dimensions of freshwater use, management and protection need to be integrated. Successful policies that ensure ecosystem integrity and human well-being must reconcile national and local priorities (Rouillard and Spray, 2016; WWAP, 2015).

There is growing recognition that protecting environmental flows represents a key strategy for safeguarding freshwater ecosystems (Arthington et al., 2018a; Boltz et al., 2019). In the Brisbane Declaration, the 10th International River Symposium (2007, p.1) defined environmental flows as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems". This established riparian and aquatic ecosystems as legitimate water users and utilises principles from the natural flow paradigm (Poff et al., 1997). This paradigm promotes the maintenance of flow variability based on magnitude, frequency, duration, timing and rate of change for safeguarding suitable conditions for

instream biota (Arthington et al., 2018b; Poff et al., 1997). The assumption underpinning this theory is that local organisms and community structures have evolved and adjusted in dependence on the natural flow regime characteristics (Lytle and Poff, 2004; Poff and Ward, 1989).

Necessitated by increasing uncertainties from climate change and anthropogenic sources of hydrologic non-stationarity, new (broader) freshwater management approaches are emerging (Milly et al., 2008; Poff, 2017). If resilience shall be achieved in freshwater ecosystems that have to provide a multitude of services at once, flexible strategies for enhancing ecological outcomes need to account for and integrate natural variability (Grantham et al., 2019; Hiers et al., 2016), a range of uncertainties (Kennen et al., 2018; Kundzewicz et al., 2018; Lowe et al., 2017) as well as complex and dynamic human interactions (Carpenter et al., 2019; Xu et al., 2021).

Against this background, this thesis addresses three dimensions of water management pertaining to successful environmental flow protection and therefore freshwater resilience in the Anthropocene. The first dimension is the high variability of natural flow regimes due to complex interactions with the climatic regime, vegetation, soils, geography and topography (Archfield et al., 2014; Kennard et al., 2010b; Poff et al., 1997). This diversity must be reflected in management of both natural and modified regimes. While the natural flow regime is fundamental for understanding ecological response to hydrologic alteration and flow-ecology relationships, shifting hydro-climatic and ecological conditions often render restoration to natural conditions impossible (Poff, 2017). Modified long-term regime-averages have led to baseline shifts (Kopf et al., 2015), transformation of regimes (Folke et al., 2004; Laizé et al., 2017) and novel ecosystems (Hobbs et al., 2009). Moreover, the extent of modifications to ecological conditions often results in a lack of natural reference ecosystems to draw from (Acreman et al., 2014). Limiting flow alteration remains important in relatively pristine areas and/or those with high conservation status (Acreman and Ferguson, 2010). In more modified regimes, managing for variability which facilitates a wide ecological response to shifting conditions (Hiers et al., 2016; Schindler and Hilborn, 2015) and/or managing for resilience sustaining key processes and dependencies for robust and socially valued ecological characteristics (Allen et al., 2011; Poff, 2017) might be the only feasible options. Understanding the natural patterns of hydrologic, geographic and climatic variability is key for informed decision making for all these approaches (García de Jalón et al., 2019; Kennard et al., 2010b).

This thesis uses the term "natural flow regime" to refer to regimes of both natural and modified rivers. If not specifically stated otherwise, in the latter this signifies the natural*ised* flow regime calculated by removing all known water use effects from the observed flow series. Due to complex and often indirect flow modifications, particularly stemming from land use, the natural flow regimes of modified rivers can however rarely be determined with high certainty. Naturalising their flow series is assumed to approximate the river's historic natural conditions even if these cannot be fully restored. In

this thesis the term "environmental flow" is used according to English regulation where it represents the allowable “deviation from natural flow” (Acreman et al., 2008; UKTAG, 2013). Environmental flows are therefore determined based on natural i.e. naturalised flows.

Restoring environmental flows often requires (re-)allocating water from other uses (Skinner and Langford, 2013; Wheeler et al., 2013). While these flow volumes might be small compared to overall water demand increases (George et al., 2011; Kaushal et al., 2019), this is challenging to reconcile with growing populations (Colloff et al., 2019; Vörösmarty et al., 2010). Moreover, difference in (spatial) scales of operation have to be accounted for. Flow-ecology relationships are determined on the reach to basin scale and can be extrapolated and modelled for other similar ecosystems (Klaar et al., 2014; Wheeler et al., 2018) yet their complexity is difficult to represent in national water policy (Cartwright et al., 2017; Daniell and Barreteau, 2014). Natural flow regime classifications are the basis for developing large scale (national) overviews of environmental water needs (Olden et al., 2021; Piniewski, 2017). They simplify spatiotemporal variability and inform extrapolation of established flow-ecology relationships to other regimes (Harris et al., 2000; Pahl-Wostl et al., 2013). They can be a powerful tool to determine where more water might be available and conversely where protection needs to be strengthened (Klaar et al., 2014; Poff et al., 2010). Flow regime classifications therefore present a first step when developing water policy for allocation planning (Acreman et al., 2013; McClain et al., 2013), climate change adaptation (Barrios-Ordóñez et al., 2015; Tonkin et al., 2019) as well as socio-economic development (Dalcin and Fernandes Marques, 2020). However, these classifications usually do not include altered regimes (e.g. Kennard et al., 2010b; Piniewski, 2017; Tavassoli et al., 2014). Flow regime classifications integrating both natural and altered catchments provide a for decision making appropriate for both types of regimes (e.g. management for variability and/or resilience) (Belmar et al., 2011; García de Jalón et al., 2019; UKTAG, 2013). This thesis provides new guidance by developing a hydrological framework for classifying both natural and altered regimes.

Climate change uncertainty and its implication for streamflow projections is the second dimension addressed in this thesis as it represents a central aspect of successful and robust environmental flow protection. Due to climate’s close interaction with the hydrological cycle, some of the most significant impacts of climate change manifest in freshwater systems (Pltonykova et al., 2020; Rodell et al., 2015; Satoh et al., 2022). Freshwater ecosystems’ responses to climate change are multifaceted, dynamic and variable (Capon et al., 2018; John et al., 2021). It has been shown to diminish freshwater habitat conditions, suitability and size (Knouft and Ficklin, 2017). Small changes in climatic drivers can cause large changes in flow regimes (Capon et al., 2021; Donnelly et al., 2017). Furthermore, climate change can affect water quality, exacerbating anthropogenic impacts (Kundzewicz and Krysanova, 2010; Michalak, 2016). Simultaneously, human water demand is increasing under warming climate thus reinforcing existing pressures and further heightening the burden of proof for water managers to justify allocating water to the environment (Boretti and Rosa, 2019; Horne et al., 2017).

Applying models to obtain projections on the hydrological response to climate change has become indispensable to quantify and understand impacts across different scales (Chokkavarapu and Mandla, 2019; Xu et al., 2005). For hydrological climate impact modelling at the spatial scale relevant for environmental flow protection, projections from Regional Climate Models (RCMs) are commonly applied (e.g. Bresney et al., 2020; Givati et al., 2019; Olsson et al., 2015). RCM projections are used to force Hydrological Models (HMs) to simulate climate change impacts across different scales, however there is a wide variety of sources of uncertainty, including climate model structure, associated with this modelling chain (Hattermann et al., 2018; Vetter et al., 2015). Walker et al. (2003) define uncertainty as any departure from perfect knowledge about a system. Robust adaptation relies on identifying and understanding the nature of uncertainty sources (Vetter et al., 2016), increasing confidence in the modelling chain (Kundzewicz et al., 2018) and clearly communicating uncertainty and its interaction with the range of potential outcomes and with the risk level to decision makers (Jones, 2001; Refsgaard et al., 2012). The largest source of uncertainty are the global climate models used to force RCMs (Hattermann et al., 2018; Wang et al., 2020; Wilby and Dessai, 2010). These numerical models, called General Circulation Models (GCMs), simulate the global climate system's response under different socio-economic pathways (Mechoso and Arakawa, 2003). For informing robust environmental flow management, projections of climate change impacts on hydrological variables, such as changes in daily to annual mean streamflow, need to be quantified and the related uncertainty needs to be characterised (e.g. Piniewski et al., 2014). When assessing impacts in modified anthropogenically influenced regimes, human modifications need to be separated from natural variability (Rameshwaran et al., 2021; Terrier et al., 2020). When using hydrological projections to enhance environmental flow protection, the uncertainties introduced by GCMs require decision makers' particular attention (Ghafouri-Azar and Bae, 2019; Joseph et al., 2018; Wang et al., 2020). This thesis addresses this by evaluating modelled streamflow response under a range of socio-economic pathways and climate projections with a focus on GCM uncertainty. The results provide the basis for robust environmental flow protection under a range of potential future pathways.

Environmental flow protection cannot be fully understood isolated from its multidisciplinary context and the major influence of the policy, governance and social setting that water management is operating in (e.g. Arthington, 2012; Pahl-Wostl et al., 2010; Rockström et al., 2014). Extending on and contextualising the first two research aims, the third research dimension this thesis assesses is the dynamic and complex nature of the policy, governance and social operating space of water management and how it governs successful environmental flow protection. The policy environment is important for setting appropriate priorities and designing coherent regulation across sectors that reflect all relevant interests, including that of freshwater ecosystems (Pahl-Wostl et al., 2013; Schaub et al., 2022). The governance system and its institutions carrying out regulations play a central role in improving environmental outcomes for example through shaping how science is translated into impact (Ferré et al., 2022; Gustafsson and Lid-

skog, 2018). The social environment is important as environmental protection pertains to divers interest, relies on local knowledge (Woodhill and Röling, 1998) and its success bases on shared understanding, acceptance and collaboration (Anderson et al., 2019; Pahl-Wostl, 2007). Due to this complex operating space, water management challenges are often referred to as "wicked" (Rittel and Webber, 1973). This means their nature cannot be clearly defined and there are no solutions across all operating scales (Freeman, 2000). A range of concepts for overcoming wicked water management challenges have been developed, most notably ICM (Falkenmark et al., 2004; Fenemor et al., 2011). Relying on participatory and adaptive management processes (Rouillard and Spray, 2016), ICM aims to achieve holistic water management accounting for the environmental, governance, policy and social dimensions (Falkenmark et al., 2004; Savenije and Van der Zaag, 2008). To determine how the best environmental flow protection can be achieved, this thesis aims to uncover the multi-disciplinary barriers across all dimensions relevant to their management. Making reference to ICM and other methodologies for addressing wicked problems, innovative proposals for overcoming these barriers and characteristics of an enabling policy, governance and social environment are outlined.

This thesis addresses these three aspects of water management important for environmental flow protection using England as a case study. English water policy including environmental flow regulation is characterised by the complex, multi-tiered water governance system of the UK (Robins et al., 2017). In England (and Wales) the protection of water for the environment is managed with an EFI that is expressed as deviation from the natural flow regime (Environment Agency, 2013b). The EFI is used to determine where water may be available for new abstraction and to highlight where abstraction pressure may be having an undesirable ecological effect. It is distinguished for three different river types and four flow periods (Acreman and Ferguson, 2010; Environment Agency, 2013b). Instead of relying on quantitative information, thresholds of flow alteration and water quantities "sufficient" for the health of freshwater ecosystems were set based on expert opinion (Acreman et al., 2008).

England has a maritime climate that is extremely variable at all scales and its interannual climatic variability is significant (Hulme and Barrow, 1997; Wheeler and Mayes, 1997). Due to its geography and climate, natural flow regimes in England show a high spatio-temporal variability (Bower and Hannah, 2002; Hannaford and Harvey, 2010). While perceived as a water abundant country, the increasing pressures on river ecosystems, stemming from water abstraction, land use (change), damming and pollution pose a substantial challenge for water management and policy (Environment Agency, 2018e; NAO, 2020). Many catchments have been strongly altered from their natural state; in 2020 16% of water bodies were classed as having "poor" or "bad" ecological condition and 48% were classes as having "moderate" ecological status (or potential for heavily modified water bodies) according to the Water Framework Directive requirements (JNCC, 2022). The largest share of water demand stems from public water supply and due to population growth an estimated additional 3,435 million litres of water per day will be required between 2025 to 2050 (Environment Agency, 2020d). Climate change

is a major concern for water managers in England. The climate change signal is much weaker in ocean influenced mid-latitude regions such as the UK; robust long-term climate change signals are therefore more difficult to detect than in continental inland regions (Hannaford, 2015; Wilby, 2006). The most up to date country-specific RCM projections stem from the UKCP18 and outline risks of increasing floods as well as droughts but not necessarily in the same locations (Murphy et al., 2018). If freshwater resilience shall be achieved in England and elsewhere, environmental flow protection has to be enhanced to alleviate existing pressures and brace for emerging pressures.

1.1 Research Objectives and Thesis Structure

Figure 1.1 shows the thesis structure and how the three dimensions, natural flow variability, climate change uncertainty and policy, governance and social operating space of water management fit together.

The aims of the three (data) chapters of this thesis are the following:

Chapter 2: i) To determine large-scale patterns of natural flow, climatic and geographic variability in English catchments and ii) to describe new targets for environmental flow protection and starting points for local-scale assessments in altered regimes.

In order to address these research aims, Chapter 2 develops a new hydrological classification combining both natural and altered catchments. It distinguishes natural hydrological flow regime elements that best separate typical hydrological regimes and represent environmental flow protection end points. Furthermore, it suggests a template for informing extrapolation of flow-ecology relationships and the starting points for case by case decision making on restoration or management for achieving specific outcomes.

Chapter 3: i) To determine climate change impacts on hydrological indicators used in environmental flow management under a range of climate change projections and emissions scenarios and ii) to determine the implications of different types of climate model uncertainty for these projections.

For this purpose, Chapter 3 quantifies how climate change uncertainty translates into streamflow projections for two catchments important for anthropogenic water use. It illustrates the implications of different types of climate change uncertainty for hydrological projections and discusses physical and climatic factors modulating streamflow response to climate change.

Chapter 4: i) To evaluate the performance of environmental flow allocation scenarios under climate change across different types of catchments and ii) to delineate shortcomings of the current water management system and articulate, in a participatory way with stakeholders, opportunities for overcoming the climate change adaptation gap and wicked water management challenges to improve environmental flow protection in England.

To address these research aims, Chapter 4 assesses water availability for environmental protection and demand fulfilment under a range of environmental flow protection scenarios. Based on stakeholder consultation, it delineates main shortcomings of current water management and governance in protecting environmental flows and extends on the other two chapters by highlighting the policy, governance and social dimensions constraining and enabling successful environmental protection and for achieving freshwater resilience more broadly.

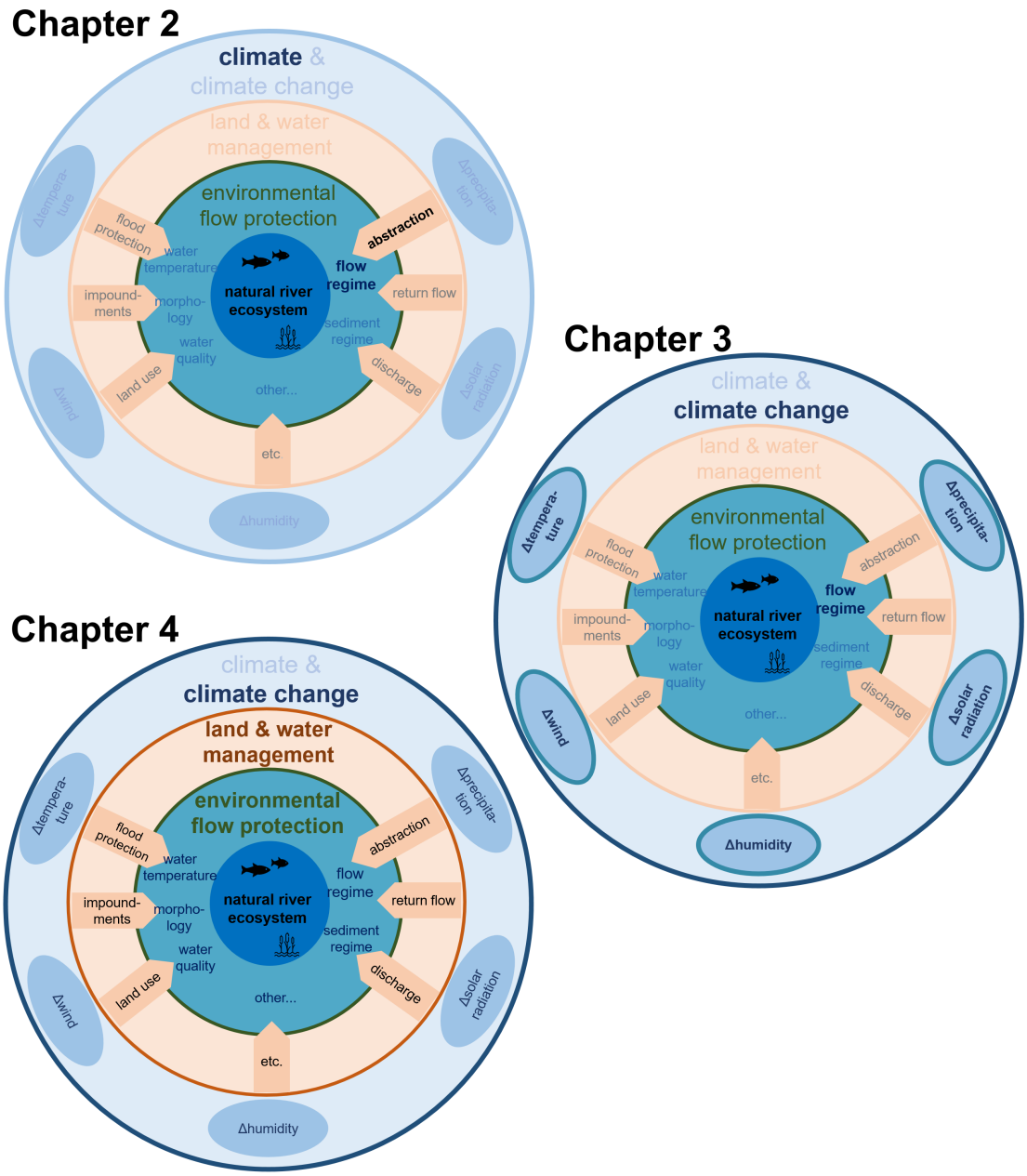


Figure 1.1: Dimensions of water management, climate and climate change relevant for environmental flow protection. Aspects assessed in this thesis in bold.

1.2 Research Strategy

Chapter 2 is a statistical analysis based on mostly publicly available datasets. Using the gauged flow series of 875 catchments, 45 hydrological metrics were calculated and extended by five physical and two climatic descriptors. This total of 52 metrics was assessed with a Principal Component Analysis to reduce redundancy and establish those parameters explaining the highest share of variation within the dataset. A clustering algorithm was applied to determine five natural catchment classes. A set of 749 catchments with altered regimes were then sorted into the catchment classes based on a Linear Discriminant Analysis of the physical and climatic descriptors, that were assumed to be unaffected by human influences.

Chapter 3 is a modelling study and assesses climate impacts in two catchments representative of the classification developed in Chapter 2. The case study approach allows a detailed in-depth analysis of the complex uncertainties in hydrologic response to climate change using real-life examples (Crowe et al., 2011). A hydrological model, the Soil and Water Assessment Tool (SWAT+) (Bieger et al., 2017), was calibrated and validated with observed climate and gauged flows for 2001 to 2017. The models for both catchments were then run with climate projections from UKCP18 (Lowe et al., 2018) and the European Coordinated Regional Climate Downscaling Experiment (euro-CORDEX) project (Jacob et al., 2014) to simulate streamflow until the 2080s. Projected changes for three different time periods were assessed; the near future 2021-2040, the intermediate future 2041-2060 and the far future 2061-2080.

Chapter 4 takes a multi-disciplinary approach combining modelling with qualitative research. This allows to ground-truth purely quantitative analyses and extends on the multi-faceted dimensions relevant for water management (Hargrove and Heyman, 2020; Martin-Ortega et al., 2015; Stoate et al., 2019). The evaluation of different environmental flow scenarios was undertaken with a simple water balance model assessing five case study catchments. Semi-structured interviews with 25 stakeholders working within different organisations in the water sector allowed the mapping the social, policy and governance dimensions of environmental flow protection within England. The interviews were analysing using thematic analysed using structural (DeCuir-Gunby et al., 2011) and open coding of emergent themes (Strauss and Corbin, 1998).

This thesis contributes to the knowledge base on environmental flow protection in the Anthropocene, crucial for achieving both freshwater resilience and sustainable development. It informs environmental policy and water management in England and more widely.

Chapter 2. A framework for classifying natural and anthropogenically modified flow regimes

Abstract

Against the background of increasing demand for water twinned with changes in streamflow due to climate change, it is indispensable to identify the spatio-temporal water availability for both human uses and the environment. To facilitate environmental flow protection across different scales of water management, the water requirements across different hydrological types of rivers need to be systematically determined. A major challenge lies within the strong anthropogenic alteration of most river flow regimes. Ecological baselines have often significantly moved due to degradation of natural regimes and subsequently environmental flow requirements are difficult to determine.

This study developed a broad-scale hydrologic framework upon which flow-ecology relationships can subsequently be established for country-level environmental flow applications across both natural and anthropologically altered rivers. This was achieved in a two-step process by first classifying catchments that are known to be natural or near-natural and then sorting altered regimes into these classes based on indices that are unaffected by human influences. Furthermore, by establishing natural characteristics across flow regime categories for different catchment types, an extension to the currently applied protection of environmental flows based on flow duration curves is suggested.

Applying the methodology to 875 catchments in the UK, five natural flow regime classes representing diverse hydrologic and physical catchment characteristics were identified. This was achieved using Ward's clustering based on five principal components explaining 75.9% of variation across the natural flow regimes. Predictive accuracy of the Linear Discriminant Analysis applied to group altered catchments into the natural flow classes was 67%. The hydrological characteristics suggested as new protection targets are magnitude of low, average and high flows, frequency of high flows, duration of flow events and timing of average and high flow events. The results of this study highlight the immense variability of the UK's flow regimes and emphasize the need for flexible environmental flow allocation accounting for the heterogeneous nature of the country's hydrological regimes.

2.1 Introduction

While covering only around 1% of the world's surface, freshwater ecosystems represent an immensely important habitat (Shiklomanov, 1993). With human population set to rise to 9.7 billion by 2050 (UN, 2019), the protection of freshwater ecosystems from detrimental water withdrawals, discharges, damming and pollution is now more important than ever. Sustainable limits of water consumption and nutrient pollution are being exceeded in more than half of the world's river basins (Hoekstra and Wiedmann, 2014). Humans are responsible for 57 % of the variability in Earth's seasonal surface water storage (Cooley et al., 2021). Finding a balance between the needs of the aquatic and other freshwater-dependent ecosystems and those of human populations who require freshwater for drinking, food production, sanitation as well as economic and cultural activities therefore lies at the heart of sustainable development (UN, 2015; UN Water, 2018).

The establishment of environmental flows that aim to mimic characteristics of natural flow regimes, including their timing, quantity and quality (10th International River Symposium, 2007; Poff et al., 1997) has become the commonly accepted approach to prevent environmental status from (further) deterioration and to provide reliable freshwater supply to growing populations (Acreman and Dunbar, 2004; Arthington et al., 2018a; Pahl-Wostl et al., 2013). Detailed assessments on suitable environmental flows are ideally made based on flow-ecology relationships (e.g. Monk et al. (2006), Poff et al. (2010), Davies et al. (2013), Bradley et al. (2017) and Lathouri et al. (2021)). For country scale decisions, the allocation has to strike the balance between being simple enough for a large number of rivers yet detailed enough to reflect their local to regional sensitivities (Klaar et al., 2014). Classifications provide the frameworks for this principle, allowing flow-ecology relationships to be extended from those rivers where they are known to those that have not been studied thus increasing the empirical evidence of these findings (Poff et al., 2010). Classifications of natural flow regimes, or hydrological 'typologies' allow a comprehensive insight into the spatial distribution and variation of distinctive flow regime types that are expected to have different ecological characteristics. They represent a central step for informing water management and governance mechanisms that balance societal and environmental water requirements (Kennard et al., 2010b; Nel et al., 2007; Pahl-Wostl et al., 2013; Poff et al., 2010).

In regions where most river regimes have been altered from their natural state, a major challenge for developing meaningful classifications of natural flow regimes lies in gauged flows strongly reflecting anthropogenic activities including abstraction (water withdrawals), return flow (discharge), land use and damming (e.g. Champathong et al., 2020; Schinegger et al., 2012). An ideal classification would include information on the degree of anthropogenic influences and how these are reflected in gauged flow (Poff et al., 2010). However, spatially detailed information on the degree of human impacts and its manifestation in gauged flows is rarely available (Abbott et al., 2019; Caldwell et al., 2012). Most studies aimed at classifying natural flow regimes therefore start by running

a flow naturalisation such as a hydrologic simulation (Kim and Wurbs, 2011) or a reconstitution of flow from historical records (Gallant and Gergis, 2011). These approaches are data intensive, their applicability is therefore limited to the local scale and feasible only across a small number of catchments (Terrier et al., 2020). Many studies, particularly climate impact assessments, therefore often resort to classifying as well as basing their analysis on near-natural flow regimes while excluding altered regimes altogether (Brunner and Tallaksen, 2019; Tijdeman et al., 2018; Vlach et al., 2020).

Another consideration that arises when developing hydrological classifications to inform environmental flow management is that many human-induced deviations are irreversible (Downing et al., 2012), meaning restoration might no longer be possible (Kopf et al., 2015). Non-natural, novel or hybrid river ecosystems require the definition of new reference points for restoration as natural habitats are irretrievably lost (Laizé et al., 2017; Seastedt et al., 2008). Instead of restoring and maintaining the natural flow baseline, realising ecological and ecosystem services outcomes, potentially outside the range of their previous natural condition, might be the only viable option (Acreman et al., 2014). Based on environmental, economic and/or societal objectives, managers might formulate specific measurable aims for ecosystem services or ecological outcomes (Barbour et al., 2016; Poff and Schmidt, 2016). Legislation such as the European Union (EU) Water Framework Directive (WFD) Directive 2000/60/EC have recognised this limitation and adopted alternative target objectives for waterbodies that are substantially altered (termed Heavily Modified Waterbodies (HMWBs)) (Acreman and Ferguson, 2010; European Commission, 2000).

2.1.1 Aim of this Study

This study aims to establish how both (near-) natural regimes as well as those subject to anthropogenic disturbances can be represented within the same hydrological framework. Using the United Kingdom as case study, this is achieved in a two-step process by first classifying rivers known to be natural or near-natural and then sorting altered regimes into these classes based on indices that are unaffected by human influences such as physical parameters including the proportion of time that soils are wet and average annual rainfall. Both the dominant pattern of broad scale hydrologic similarities as well as finer hydrologic and physical variability across the country are analysed in detail. Since this methodology overcomes the challenge of data intensive naturalisation it comprises a large number of catchments altered by anthropogenic activities. The natural features outlined for catchment classes provide a template for revising country-scale environmental flow protection beyond simple FDC-based allocation. Characteristic features across flow regime categories have the potential to be used as new protection targets. Furthermore, it establishes a basis for future analyses on the restoration potential of natural habitats in altered regimes. While this chapter focuses on the United Kingdom as a case study location, the methodology has the potential to be applied to other locations with similar data availability.

2.1.2 Case Study - England

Management of freshwater ecosystems in the United Kingdom including England faces the twin challenge of mitigating the effects of centuries of anthropogenic interventions while accommodating for projected increases in water demand and climate change impacts on future water availability (Environment Agency, 2020d; Environment Agency and Ofwat, 2011). Water managers must manage for both resilience to old and emerging pressures as well as for the considerable variability of the UK's river regimes (Charlton and Arnell, 2011; Monk et al., 2006; Watts et al., 2015). Hydrological research within the UK benefits from a dense river gauging network, data from which is available in the National River Flow Archive (NRFA) (Dixon et al., 2013; Hannah et al., 2011). The NRFA provides gauged flow series for around 1400 unique stations. A special subset of these stations is the UKBN which represents a wide and representative selection of catchments with near-natural flow regimes and gauging stations producing high quality data (Bradford and Marsh, 2003; Harrigan et al., 2018). There have been a number of studies classifying English rivers with varying foci and number of considered catchments as outlined in Table 2.1.

Table 2.1: Previous studies classifying the United Kingdom (UK)'s rivers, their main foci, number of rivers considered and number of delineated catchment classes

Study	Number of rivers considered	Considered characteristics	Number of catchment classes
Holmes et al. (1998) and UKTAG (2008)	200 + (1055 + 459)	macrophytic plant communities, sediment, gradient, altitude	10
Cowx et al. (2004)	312	habitat requirements of fish species	8
Acreman et al. (2008)	-	findings by Cowx et al. (2004) and expert opinion	4
Bower et al. (2004)	35	flow magnitude, shape of annual hydrograph	3 magnitude, 4 shape classes
Prudhomme et al. (2013)	154	sensitivity to floods based on response surface	9

Table 2.1 Continued: Previous studies classifying the UK's rivers, their main foci, number of rivers considered and number of delineated catchment classes

Monk et al. (2006)	83	flow magnitude, shape of annual hydrograph	10
Monk et al. (2007)	83	hydrological descriptors, shape of annual hydrograph	3
Chiverton et al. (2014)	116	physical and climatic characteristics, land cover	4

While not a classification study, Coxon et al. (2020) collated the most holistic dataset of UK catchments to date, including 671 catchments and detailed information on meteorological time series, topography, hydrologic signatures, land cover attributes and broad degree of human influences.

These previous studies demonstrate the high variability of hydrological regimes and the intricate sensitivities of aquatic ecosystems. However, other than the ecological study by Holmes et al. (1998), all had a limited coverage focusing on natural and near-natural regimes. They focused on few characteristics and therefore provide classifications for narrow management contexts only. This study takes a different approach. It establishes a holistic picture of the natural variability of hydrology, geography and climate across the country with a particular focus on representing all flow regime categories important for describing hydrologic variability. It includes both modified and natural catchments, thus achieving a wider coverage than previous classification attempts.

When developing management rules for allocating water to environmental flows, the opportunity to consolidate findings of previous studies was missed. Environmental flow protection in England only distinguishes three river classes (Environment Agency, 2020f). The five catchment classes established in this study offer themselves to guide enhanced environmental flow protection in England. The regime categories maximising the groups' separation are suggested as basis for new broad-scale environmental flow allocation rules improving the representation and protection of natural hydrologic variability.

Furthermore, by matching natural with altered regimes a template for establishing the restorability of natural ecology is provided. Decision makers can systematically compare the ecology between modified regimes with that of natural regimes within the same class to determine appropriate conservation and management strategies such as for resilience or variability. While this study requires extension with (broad-scale) ecological

assessments on the environmental flow requirements under different flow regimes and (local-scale) analyses of ecological sensitivities in individual catchments, it provides the most holistic hydrological classification study of UK catchments to date.

2.2 Data

Before detailing the methodological framework applied for classifying natural and altered flow regimes, the following sections outline the selection of catchments and how the quality of the flow series used to classify catchments was assured.

2.2.1 Catchment Selection

From 1400 available sites, gauged daily flows for 875 gauging stations across the UK were selected from the NRFA. The series were split into two sets – a subset of 126 UKBN series (the 'natural' flow set) and a second set of 749 sites with hydrological regimes that are deemed to have anthropogenic influence (subsequently referred to as 'altered set'). The location and coverage of catchments used in this classification is given in Figure 2.1.

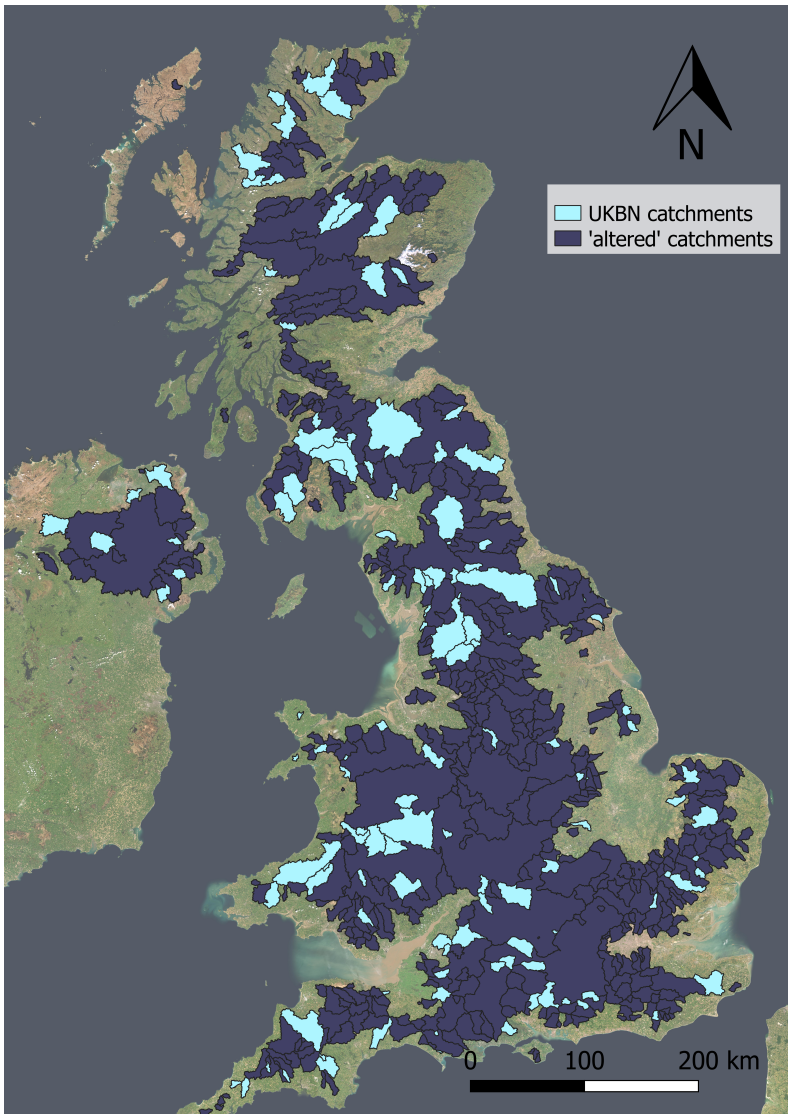


Figure 2.1: Coverage of the UK Benchmark Network (UKBN) (light) and altered catchments (dark) analysed in this study

Data was retrieved from the NRFA using the Application Programming Interface (API) provided through the R package *rnrfa* (Vitolo et al., 2016). All subsequent analyses were completed using R version 4.0.4. Three considerations influenced the choice of these flow series – completeness, representativeness and length of record. To control for metric bias, precision and overall accuracy only those stations providing 20 years of data (1998 - 2017) were considered following the recommendations by Kennard et al. (2010a). Identical start and end dates were used for all gauges to control for potential climatic effects that vary over time (Kennard et al., 2010a; Murphy et al., 2018).

Sites with either more than 10% or a total of 183 days of consecutive missing data were excluded from further analysis as clustering of missing values meant that data infilling methods/imputation would fail and affect the accuracy of the subsequent clustering analysis. A further 6 sites had to be excluded due to a lack of data availability on the NRFA platform. The 875 catchments chosen for this study correspond to 633 unique rivers and provide a wide coverage of the UK including good coverage of western, southern and central areas. Details on the set of benchmark catchments included in the assessment are given in section A.1. Unfortunately, the UKBN dataset's coverage in South Eastern regions is restricted mainly due to larger impacts of water abstractions and discharges (Harrigan et al., 2018). The UKBN are all separate catchments while the altered catchments contain overlapping areas, this means some stations gauge headwaters of other stations.

2.2.2 Data Cleaning

Following the initial selection of sites to be included in the analysis, the gauged flow series were cleaned for further analysis. For 326 of the 875 stations at least one day of logging and up to 7.3 % of data points were missing and required imputation. This is mostly due to spot readings or failures in the measurement equipment, particularly in the extreme flow ranges (Harrigan et al., 2018; Johnston, 1999). Missing values have been shown to decrease the power and precision of statistical analyses (Marsh, 2002; Papageorgiou et al., 2018). Therefore, a simple linear regression was employed to estimate and replace missing data points with the mean of neighbouring points in the time series as suggested by Olden et al. (2012) and outlined in Yang et al. (2017).

To test the goodness of fit of the chosen imputation a two-step analysis was undertaken. In the first step artificially deleted values were introduced in 50 randomly chosen complete flow series. Two missing data mechanisms Missing at Random (MAR) and Missing Completely at Random (MCAR) with 4 different missing data rates (0.5%, 3%, 5.5% and 8%) were tested. As the performance of the imputation also depends on which values were missing, the function was run with 10 different random seeds. In total 80 different runs (10 (different random seeds) * 2 distributions (MCAR, MAR) * 4 missing data rates) for each of the 50 series were included. In a second step the imputation function was applied to the artificially introduced missing values and its performance was analysed with the RMSE (1) and the MAPE (2) metrics.

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{T}(A_t - F_t)^2}{T}} \tag{1}$$

$$\text{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \tag{2}$$

$A_t -$ Actual value

$F_t -$ Imputed value

$T -$ Observation times

The latter is given as a percentage while the former is in the same unit as the assessed variables, in this case $m^3 s^{-1}$. MAPE and RMSE should be assessed in combination. MAPE is inflated when values close to zero are present which is the case in some of the flow series and the RMSE which represents the standard deviation of the unexplained variance is sensitive to outliers (Chai and Draxler, 2014).

2.3 Methods

The methodological process applied in this study consists of two main parts (Figure 2.2). To begin, a hydrological typology based on 126 UKBN catchments that are subject to very little to no anthropogenic influences was developed. The hydrological regimes of these catchments can serve as reference for natural conditions within the overall final catchment classes. To classify the UKBN, a suite of hydrological, climatic and physical metrics were analysed and those with the least redundancy according to a PCA were used in the determination of classes through Ward (1963) clustering algorithm. Typical expressions of the least redundant flow regime categories were described in detail and suggested as improved protection targets for a new way of managing environmental flows.

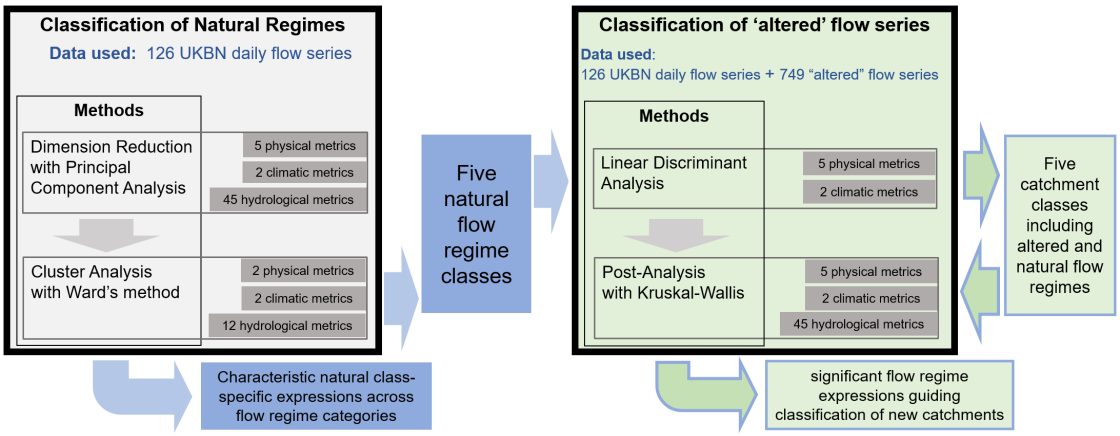


Figure 2.2: Methodological process applied in this study

In the second step, the class memberships of the altered catchments were determined with a Linear Discriminant Analysis (LDA) based on five physical and two climatic metrics. These metrics were chosen as catchments with similarities in key physical and climatic conditions are likely to display similar natural flow regimes (Jin et al., 2017; Roo et al., 2015, cf). In the final step, a post analysis was undertaken. The significant class-specific flow regime characteristics detailed for the final catchment classes (comprising both altered and natural regimes) can guide classification of other "new" catchments not part of this analysis. Once classified the dominant class-specific regime characteristics distinguished for the natural regimes within the same class can guide the development of "novel" environmental flow and/or restoration approaches. This study briefly discusses potential sensitivities to typical human influences.

2.3.1 Classification of Natural Regimes

The following section describes the approach taken to obtain a natural catchment classification using the UKBN catchments. It based on a suite of hydrological, physical and climatic catchment descriptors. After a dimension reduction to lower descriptor redundancy, natural catchments were clustered in five distinctive classes using Ward (1963) clustering algorithm.

2.3.1.1 Catchment Descriptors

A total of 52 physical, climatic and hydrologic descriptors were used to describe the catchments and gauged flow series, as outlined in Appendix section A.3. 45 hydrological metrics first developed by Poff et al. (1997) and Richter et al. (1996) and subsequently refined by Olden and Poff (2003) and exhaustively applied in other studies (Belmar et al., 2011; Dallaire et al., 2019; Piniewski, 2017; Rivers-Moore et al., 2020) across flow regime categories were used. The hydrological metrics were calculated with the R packages *FlowScreen* (Dierauer et al., 2017), *hydrostats* (Bond, 2018) and *EflowStats* (Archfield et al., 2014; Henriksen et al., 2006) or manually.

To represent the major components of the flow regime, care was taken to balance the number of metrics in each category. This was however difficult due to the different number of metrics available to describe each category (e.g. Kennard et al., 2010b); there is a high number of descriptors available for the magnitude of flow but only few for the frequency of flow events and the rate of change. The former was described through measures of the high (hfs1, hfs2) and low flow spell count (lfs1, lfs2) while the latter was expressed through the number (nr) and rate of changes (mrr, mrf) in flow during times when it switches from increase to decrease or vice versa. The frequency of flow events can be characterised through the spell count below or beyond a certain flow percentile value (here Q_{99}, Q_{75} and Q_{10}, Q_{25} respectively). The duration of flow events is expressed as the magnitude of flow during the minimum and maximum annual flow series varying in length (amin7, aminf30, amax7, amax30, anmin) as well as through the time it takes between 50% and 75% of annual flow to have passed (dur). The timing of flow conditions was described using the indicators developed by Colwell (1974) where predictability (pred) describes how closely an event is linked to a season and constancy (const) describes how regularly the event occurs through all seasons. Predictability is either maximised when there is little variation during the year (maximum constancy) or flows across several years are very similar (maximum constancy).

Five physical catchment descriptors – mean catchment slope (slope), station altitude (alt), catchment area (area), baseflow (bfih) and proportion of time when catchment soil moisture deficit is less than 6mm (prop) – were included in the assessment. Furthermore, two climatic descriptors - standard average annual rainfall (saar) and the percentage of rainfall that becomes runoff (shost) were assessed. These are the main physical and climatic descriptors readily available for such a high number of catchments through the databases of the Centre for Ecology & Hydrology (Centre for Ecology & Hydrology (CEH)) and the NRFA. Prop and bfih were obtained from the Flood Estimation Handbook (FEH) and base on modelling of soil typologies and evaporative response (NRFA, 2018). Unlike the hydrological descriptors, these descriptors can be assumed to be independent of anthropogenic influences such as abstractions. Two different baseflow descriptors were included. The bfih was obtained through (NRFA, 2018) and is based on modelling of soil hydrology and runoff response, the baseflow (bf) on the other hand was calculated based on gauged series with the baseflow separation approach.

The two therefore likely yield similar results in benchmark catchments but not in altered catchments as the former is independent of anthropogenic influences while the latter is not (Table A.2; NRFA (2018)).

For several of the metrics the bias for catchment size had to be removed (Johnson and Wichern, 2007). Several approaches were applied to achieve this. Firstly, dimensionless and normalised indicators such as the coefficient in variation (CV) were used (3). CV shows the extent of variability in relation to the mean of a population (Everitt, 1998). Secondly, standardised z-scores were calculated, whereby the raw value of each metric x is converted to the z-score by subtracting the mean of all metrics from it and then dividing this value by the standard deviation of all values (4). The resulting metric dataset has a mean value of zero and a standard deviation of 1 (Monk et al., 2006).

$$CV = \frac{\sigma}{\mu} \tag{3}$$

$$z = \frac{x - \mu}{\sigma} \tag{4}$$

$x -$ single metric observation

$\sigma -$ standard deviation

$\mu -$ mean

2.3.1.2 Dimension Reduction

Before analysing the metrics in more detail, those variables with high correlation with other variables were removed based on the results of a Spearman rank correlation test. To assess if dimension reduction was possible, Levene (1960)'s test of sphericity was run to check for homogenous variances which would render further dimension reduction impossible. To minimise statistical redundancy and reduce the number of metrics, a Principal Component Analysis (PCA) as outlined by Olden and Poff (2003) was then applied. As PCA is highly sensitive to outliers, the optimisation suggested by Rousseeuw and Van Driessen (1999) was used. The decision on which metrics to retain was made based on loadings into the components, cross-loadings between components and with the aim to keep a representative range of regime descriptors through the ten subcategories.

2.3.1.3 Cluster Analysis

To group natural and near-natural streamflow time series with similar characteristics, an agglomerative hierarchical clustering approach, the widely applied Ward (1963)'s minimum-variance algorithm was used across the remaining metrics (Kaufmann and

Rousseeuw, 1990). Agglomeration approaches begin by each gauge in a single cluster and merge clusters until only one is left (Olden et al., 2012). Unlike k-means clustering, this method is not dependent on initialization or local minima (Olden et al., 2012), thus allowing for a more flexible classification that is independent of prioritising similarities or dissimilarities among catchments. This method is commonly used in hydrological research including for hydrological clustering of catchments (e.g. Chiverton et al., 2014; Monk et al., 2006; Ramachandra Rao and Srinivas, 2006; Zhang et al., 2012). Since Ward's is sensitive to differences in the variance of agglomerated data, the metrics with the highest variance having the greatest impact on the identified clusters, the dataset was standardised ((4)). To determine the best number of clusters, similar to Monk et al. (2006) the cluster dendrogram and two agglomeration schedules - scree plots developed by Lebart et al. (2000) and Hubert and Arabie (1985) - were analysed. The Lebart et al. (2000) index is based on intra-cluster inertia which signifies the degree of homogeneity between the data associated with a cluster and the gain on intra-cluster inertia which should be minimized. The algorithm by Hubert and Arabie (1985) is based on the point serial correlation coefficient of two matrices, in this case of two separations of the data, through different number of clusters.

2.3.2 Classification of Altered Flow Series

Once the sites with little to no anthropogenic influence were classified, those with known pressures and alterations were sorted into the distinguished catchment classes using a Linear Discriminant Analysis (LDA). Afterwards, a leave-one-out Cross Validation was run across the natural catchment classes to evaluate the LDA algorithms efficiency. As a last step the classification of all catchments was closer examined and described using the Kruskal and Wallis (1952) and Wilcoxon (1945) analyses. This way significant characteristics across the overall groups were distinguished that provide the basis for classifying "new" (altered) catchments.

2.3.2.1 Linear Discriminant Analysis (LDA)

The LDA used to predict the altered flow series' class memberships relied solely on those catchment descriptors that are assumed to be independent of (direct) anthropogenic effects. These are the metrics describing the baseflow (bfih), the percentage of rainfall that becomes runoff (shost), the catchment size (area), the amount of rainfall (saar), the duration of wetness of soils (prop), the altitude (alt) and the slope (slope). The underlying assumption is that catchments similar in these descriptors will also have similar flow regimes and are alike in (hydrological) metrics.

Similar to a PCA, this method relies on linear combinations of the potential predictor variables to allocate group membership (Everitt, 1998). Unlike PCA however, LDA is a supervised algorithm that tries to find linear combinations that maximise the separation between the catchment groups while a PCA's linear combinations shall maximise the variance of the whole dataset. The classification decision for individual catchments is

made based on its respective maximum of so-called posterior probabilities across all classes. LDA determines the posterior distribution of individual catchments across the classes based on the combination of the predictor variables and the prior distribution (Finch et al., 2014). The prior distribution is the probability of randomly selecting an observation belonging to a specific class. Since LDA requires the data to be normally distributed a boxcox transformation (5) was applied first (Box and Cox, 1964) .

$$y^{(\lambda)} = \begin{cases} \frac{y^{\lambda}-1}{\lambda} & \text{if } \lambda \neq 0 \\ log(y) & \text{if } \lambda = 0 \end{cases} \tag{5}$$

$\lambda -$ power to which all data should be raised

$y -$ vector of observations

As LDA is sensitive to outliers those data points were replaced with the mean value (e.g. Alrawashdeh et al., 2018; Todorov and Pires, 2007). Outliers were defined as data values that are more than 1.5 times the interquartile range away from the first or third quartile (Tukey, 1977). The approximate prediction ability of an LDA can be assessed through cross validation. This was done by training the LDA on the whole UKBN dataset except for one data point and then predicting this missing (known) data point. By repeating this leave-one-out cross-validation for several data points a mean success rate was determined. To illustrate the LDA algorithm's uncertainty in assigning altered catchments to the UKBN catchment groups, the cross validation was extended with three classes of classification certainty drawn from the LDA's underlying decision-making tree. The probability of misclassification varies between the classes and is highest for "middle groups" that are equally likely to be misclassified into groups with higher or lower means (Finch and Schneider, 2007). For efficiency reasons, the same and (for the number of classes) conservative cut-off point was chosen at 40% posterior probability (=classification probability) for all groups to distinguish classification certainty. The distance in posterior probability to the next most likely class was also considered.

This yields the following levels of classification certainty:

- "low" - for catchments that were classed into their catchment group with less than 40% probability and where the difference to the next less probable group was less than 10%
- "medium" - for catchments that were classed into their catchment group with either less than 40% probability or where the difference to the next less probable group was less than 10%

- "high" – for those catchments that were classed into their catchment group with more than 40% probability and where the difference between the most likely groups was more than 10%

2.3.3 Post Analysis of the Final Catchment Classification

The last step consists of a post analysis of the catchment classification with the two-fold aim; to determine the effectiveness of the preceding assessment in deriving a classification that separates the dataset well, as shown through significant differences across flow regime classes, physical and climatic parameters. Secondly it allowed to quantify significant differences between the classes. As environmental flow allocation relies on monthly to seasonal metrics, the focus lay on these temporal scales. For these purposes, a Kruskall-Wallis test, (Kruskal and Wallis, 1952) was run across the final catchment groups for all 53 metrics separately and a pairwise Wilcoxon test (α = 0.05) was used to determine which group pairings were significantly different from each other (Wilcoxon, 1945). The distribution of significant metrics across these flow categories guides allows to sort "new" (altered) catchments into the classes. These catchments can then be compared to the natural reference (UKBN) regimes within their respective class to design environmental flow allocation rules and assess feasibility of restoration.

2.4 Results

The results show that a classification with five groups separated the catchments well as shown through statistically significant differences across physical, climatic and hydrological descriptors. These groups allow a detailed insight into the spatial distribution and variation of distinctive flow regimes across the UK. The steps necessary for data cleaning, infilling, dimension reduction through PCA and the clustering algorithm, are outlined first.

2.4.1 Data Cleaning

In total 326 flow series required infilling of missing values, 298 of the altered flow regimes and 28 of the benchmark catchments. 50.2 days were missing on average. In the benchmark catchments the highest rate of missing data was 2% (147 days), however most of the stations had less than 2% of missing data. Two sites with altered flow regimes, the East Glen River in Manthorpe county and the Covey River in Huxley county had 7% or more missing data. Table 2.2 shows the results of the goodness of fit analysis of artificially introduced missing values illustrating the mean and maximum error rate of all runs.

The linear imputation was up to 21 m^3s^{-1} off in one of the series tested (Table 2.2). The large difference between mean and maximum values is due to the random seed; linear imputation cuts off a peak if the missing value(s) fall during an episode of strong increase or decrease of flow. The measurements failing during these episodes is not unlikely due to the reasons outlined above. The mean goodness of fit of 1.6 to 14.9% or 1.28 to 3.5 m^3s^{-1} was nevertheless deemed acceptable. Most of the benchmark flow series that were retained only had a few data points missing. Even if the data should be MAR, strong clusters are therefore unlikely and the mean error introduced through the simple linear infilling method chosen here can be assumed to be closer to the lower end of the range of MAPE and RMSE.

Table 2.2: Mean and maximum values of the goodness of fit (Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE)) of the linear interpolation with Missing at Random (MAR) and with Missing Completely at Random (MCAR). Artificially introduced values for a set of 50 complete stations.

Rate of missing value	**0.5%**		**3%**		**5.5%**		**8%**	
Distribution error metric	mean	max	mean	max	mean	max	mean	max
MAR – MAPE (in %)	0.01	0.04	2.8	7.6	8.3	48.3	14.9	69.9
MCAR – MAPE (in %)	0.01	0.04	0.5	1.9	1.1	4.0	1.6	5.9
MAR – RMSE (in m^3s^{-1})	0.08	0.74	1.65	10.13	2.60	17.22	3.50	21.50
MCAR – RMSE (in m^3s^{-1})	0.07	0.30	0.71	4.17	1.05	5.96	1.28	7.17

2.4.2 Classification of Natural Flow Regimes

The classification of natural flow regimes yielded five catchment classes with distinct spatial distributions and strong variation across hydrological metrics. The delineated classes were named after their dominant characteristics: Group 1 contains “dry, large lowland catchments”, group 2 mainly consists of “small, dry, central catchments”, group 3 of “flashy, coastal catchments”, group 4 of “large, wet, Western catchments” while group 5 is made up of “dry, Southern and Eastern catchments”.

2.4.2.1 Dimension Reduction

Several of the hydrological, physical and climatic metrics calculated for the natural catchments are strongly correlated as shown in Figure 2.3. The lower part of the figure depicts negative correlation and the upper part depicts positive correlations. To retain all major flow regime components, some correlated variables were retained, including the duration of (low flow) events (dlf), the rate of change (mrr) and the timing of low flow conditions (jdmi) leaving 33 metrics remaining for further analysis (Table 2.3). Since the null hypothesis that the variables have equal variances and are therefore unsuitable for structure detection and dimension reduction under Levene’s test could be rejected, the PCA was determined suitable for dimension reduction.

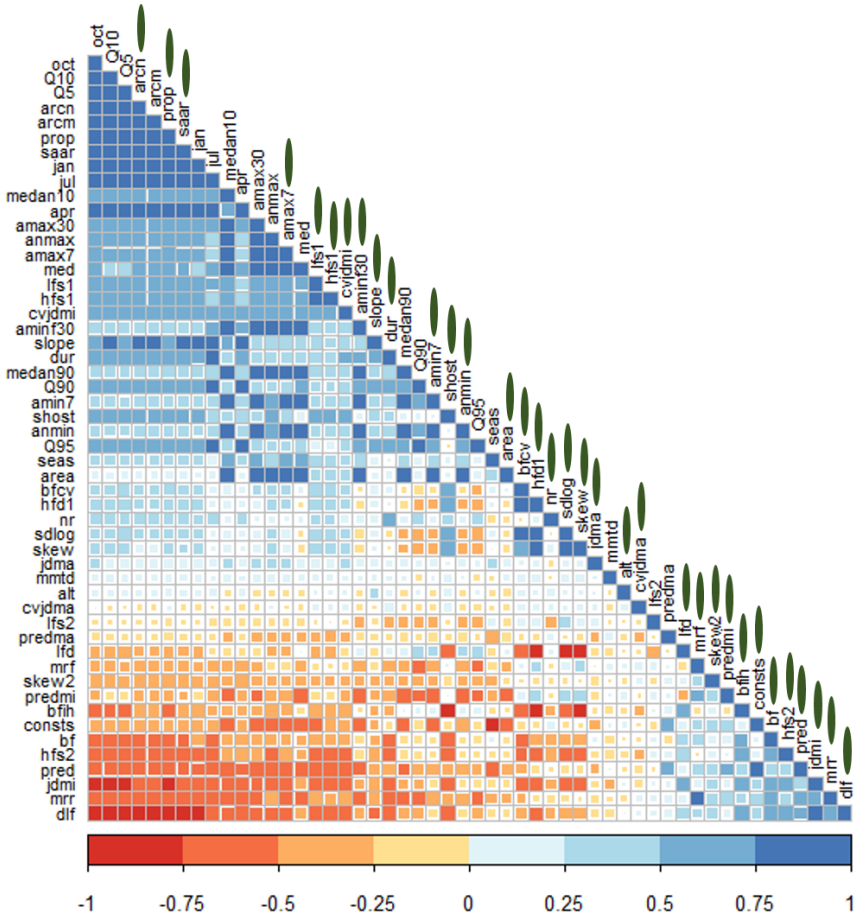


Figure 2.3: Correlation among the 52 metrics according to the Spearman rank test, strong positive correlation is given in blue and strong negative correlation in red retained metrics marked in green

Table 2.3: Metrics considered in the Principal Component Analysis (PCA) (n=33)

Flow Category	Name	Description
Magnitude of flow events average conditions	skew	skewness of daily flow
	arcn	median annual runoff
	sdlog	standard deviation of daily flows
	skew2	skewness in annual flow
Magnitude of flow events low flow conditions	bf	baseflow index (BFI)
	lfd	low flow discharge
	bfcv	coefficient of variation in BFI
Magnitude of flow events high flow conditions	hfd1	high flow discharge
Frequency of flow events low flow conditions	lfs1	low flow event count

Table 2.3 Continued: Metrics considered in the Principal Component Analysis (n=33)

Frequency of flow events high flow conditions	hfs1	high flow event count
	hfs2	coefficient of variation in high flow event count
Duration of flow events	dlf	low flow/drought duration
	aminf30	annual minima of 30 days
	amax7	annual maxima of 7 day means
	anmin	median annual minimum flow
	dur	duration between 25% and 75% of flow
Timing of flow events average conditions	pred	predictability of mean daily flow
	consts	constancy of mean daily flow
Timing of flow events low flow conditions	jdmi	date of annual minimum
	cvjdmi	coefficient of variation in date of annual minimum
	predmi	predictability of min daily flow
Timing of flow events high flow conditions	jdma	date of annual maximum
	cvjdma	coefficient of variation in date of annual maximum
Rate of change in flow events	nr	number of reversals
	mrr	coefficient of variation in rate of rise
	mrf	coefficient of variation in rate of fall
Physical parameters	area	catchment area
	alt	altitude
	slope	mean slope
	prop	proportion of time catchment soils are wet
	bfih	catchment responsiveness
Climatic parameters	shost	percentage of rainfall becoming runoff
	saar	standard average annual rainfall

The PCA resulted in a further reduction to 16 variables that explain a major share of variation in the natural hydrology across the UK. The biplot (Figure 2.4) reflects correlation among the 33 variables through small angles or angles of 180 degree between the loading vectors in Figure 2.4 b). No strong clusters can be distinguished in these first two principal components which is to be expected given the aim to adequately describe the complex hydrology of the UK which can only be attained by a high number of descriptors.

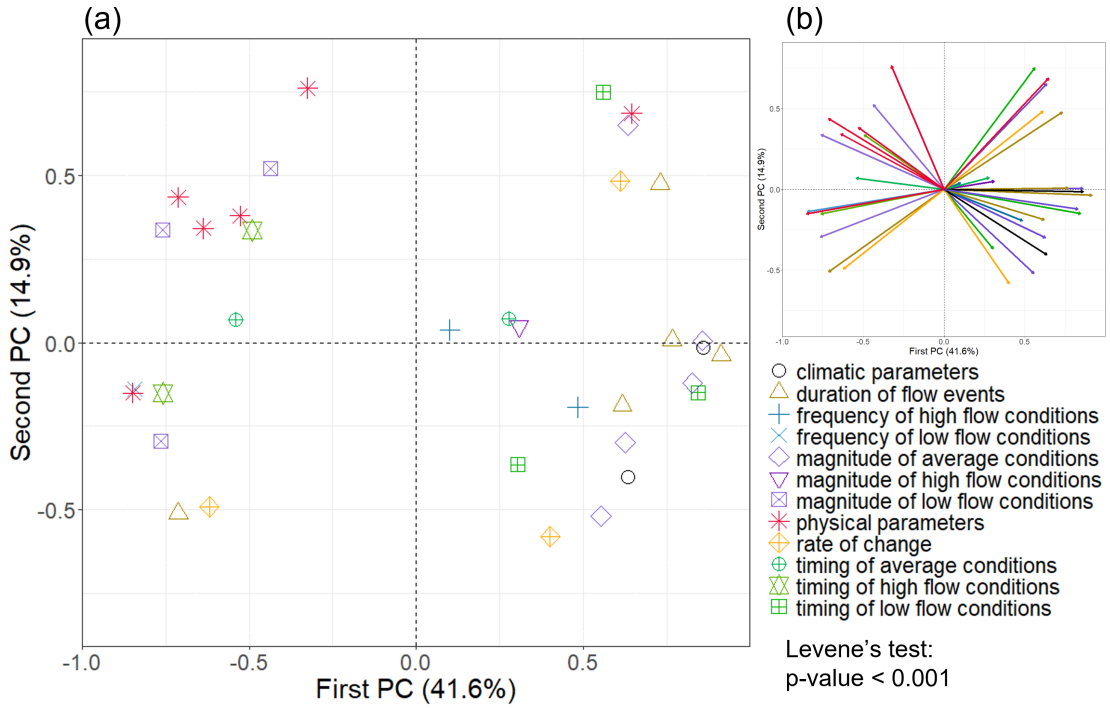


Figure 2.4: Principal Component Analysis (PCA) Biplot of the first two Principal Components (PCs) and flow categories of loadings

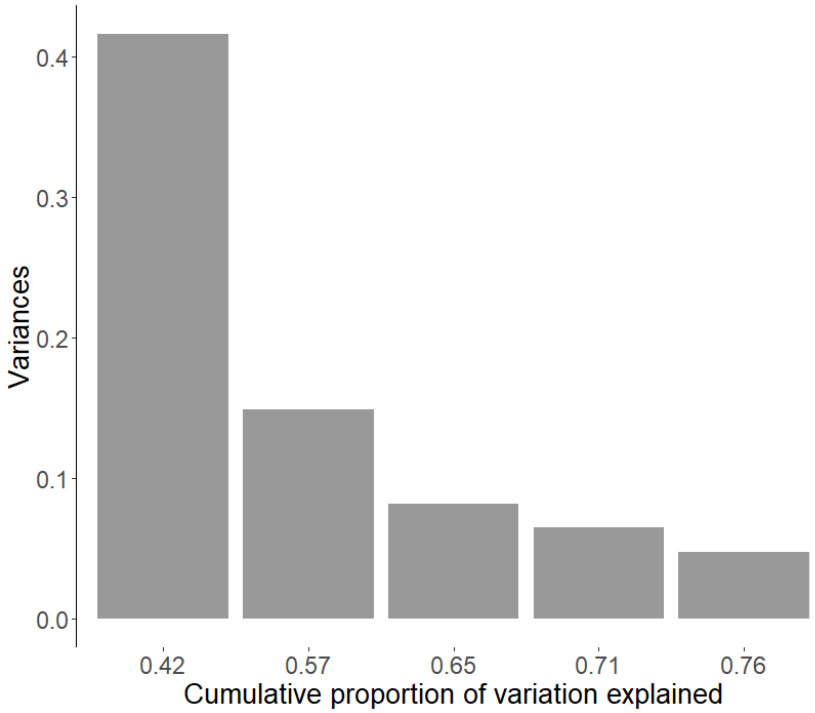


Figure 2.5: Cumulative proportion of variation across the first five Principal Components (PCs)

The decision on which components to retain was made based on the loadings of the individual variables and on the cross-loadings (i.e. when variables load into several components) while also considering the individual metric's flow regime category. Ta-

ble 2.4 reveals that none of the loadings were considerably high. However, there is little consensus as to what constitutes a “high” or “low” factor loading (e.g. Peterson, 2000). The cut-off point for variable loadings to be too small for inclusion in subsequent analysis was selected at |0.3| (Hair et al., 2013). Furthermore, those variables with secondary loadings of more than |0.2| were removed (Wieland et al., 2017) as this might be problematic, especially when the primary loading is not particularly strong (Knekta et al., 2019). As it only loads into one PC, sdlog with a loading of 0.298 was also included. High redundancy among metrics describing natural flow regimes across the country is particularly evident in the rate of change in flow events, the frequency of low flow conditions and the timing of flow events. When deciding whether to use either four or five principal components to classify the groupings, it was noted that three variables which describe important aspects of the flow regime (the temporal invariance of flow (consts) and the predictability of flow (pred) both predict the timing of average flow conditions while the date of the annual maximum flow (jdma) is a measure of the timing of high flow conditions) were only available in the fifth component. It was therefore decided that five PCs would be used in the classification, describing 75.9% of variation (Figure 2.5).

Table 2.4: Principal Components (PCs) and loadings of the variables, excluded for cross loadings (blue), excluded for small loading (grey), metrics that were retained are given in bold

	PC1	PC2	PC3	PC4	PC5
skew		**0.345**		-0.145	
arcn	**0.362**				
sdlog		**0.394**			
skew2	-0.18			-0.211	0.161
bf	-0.224				
lfd		**-0.374**			0.129
bfcv		0.268		-0.102	
hfd1		**0.357**			
lfs1	0.169			-0.107	
hfs1	0.123			-0.119	-0.144
hfs2				**0.33**	
dlf	-0.246	-0.129			
aminf30			**0.459**		
amax7			**0.448**		
anmin		-0.103	**0.469**		
dur	0.21	-0.281		-0.192	
pred					**0.458**
consts				-0.133	**0.447**
jdmi	-0.183			0.183	
cvjdmi				-0.191	-0.119
predmi		0.245	-0.134		0.268
jdma				-0.134	**-0.285**
cvjdma	-0.243	-0.206	-0.182	-0.454	-0.283
nr	0.184	-0.219		-0.304	0.232
mrr	-0.228			-0.175	0.208
mrf	-0.202			-0.27	0.211
area	-0.156		**0.486**		-0.115
alt			-0.228		-0.182
slope	**0.298**				
prop	0.25			-0.1	
bfih		-0.162		0.325	
shost		0.137		**-0.307**	
saar	**0.379**				

Sixteen variables have strong loadings in these five PCs and seven of the ten subcategories are represented, providing a suitable range of hydrological and physical descrip-

Table 2.5: First five Principal Components (PCs) and the characteristics they describe. Metrics suggested for delineation of new environmental flow protection in italic. See also section 2.4.2.3

PC	Described Characteristics & Flow Regime Categories	Metrics
PC 1	water availability & slope	saar arcn slope
PC 2	daily flow magnitude	*skew* *sdlog* *lfd* *hfd1*
PC 3	catchment size & duration of flow events	area *aminf30* *amax7* *anmin*
PC 4	frequency of high flows & responsiveness to rainfall	*hfs2* shost
PC 5	timing of average & high flow conditions	*pred* *consts* *jdma*

tors. Each PC describes different characteristics and Table 2.5 provides an overview of the flow regime, climatic and physical characteristics contained in each of the first five PCs. These flow regime metrics (in italics) and their regime categories suggest themselves as new environmental flow protection targets. Their distribution across the natural catchment classes is described below in section 2.4.2.3.

2.4.2.2 Cluster Analysis and Classification

The significant knee in the Lebart et al. (2000) and Hubert and Arabie (1985) indices in Figure 2.6 indicate the optimal number of clusters in the Ward (1963) algorithm. This knee corresponds to a significant decrease of the first differences of clustering gain for the Lebart et al. (2000) index and a significant increase in second differences between the point serial correlation coefficient of two matrices in the algorithm by Hubert and Arabie (1985). Both algorithms indicate an optimal number of five clusters for separating the dataset.

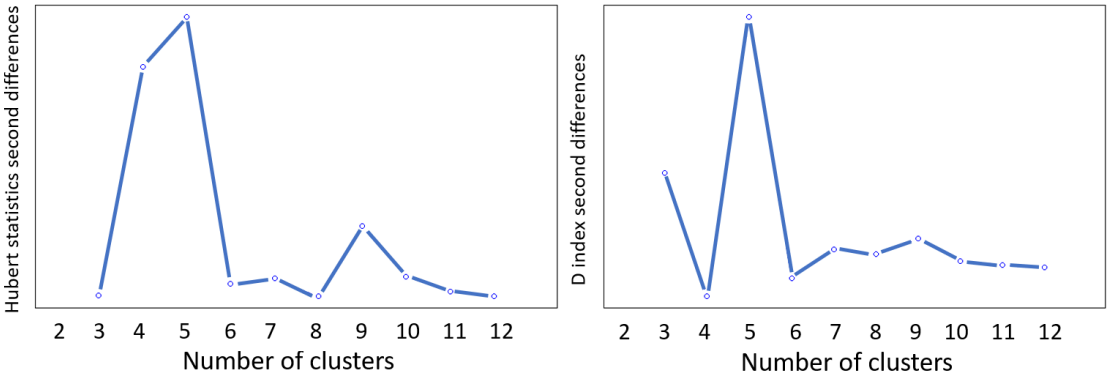


Figure 2.6: Second differences plots of the graphical methods by Lebart et al. (2000) and Hubert and Arabie (1985)

Ward's clustering determined an ESS across all stations of 12.3 (Figure 2.7). Half of this space is taken up by two groups 3 and 4 that have a combined within-cluster ESS of 6.4. A clustering of five groups lead to group 3 being the largest and group 1 the smallest and the most different from the others shown in the highest merging in the dendrogram.

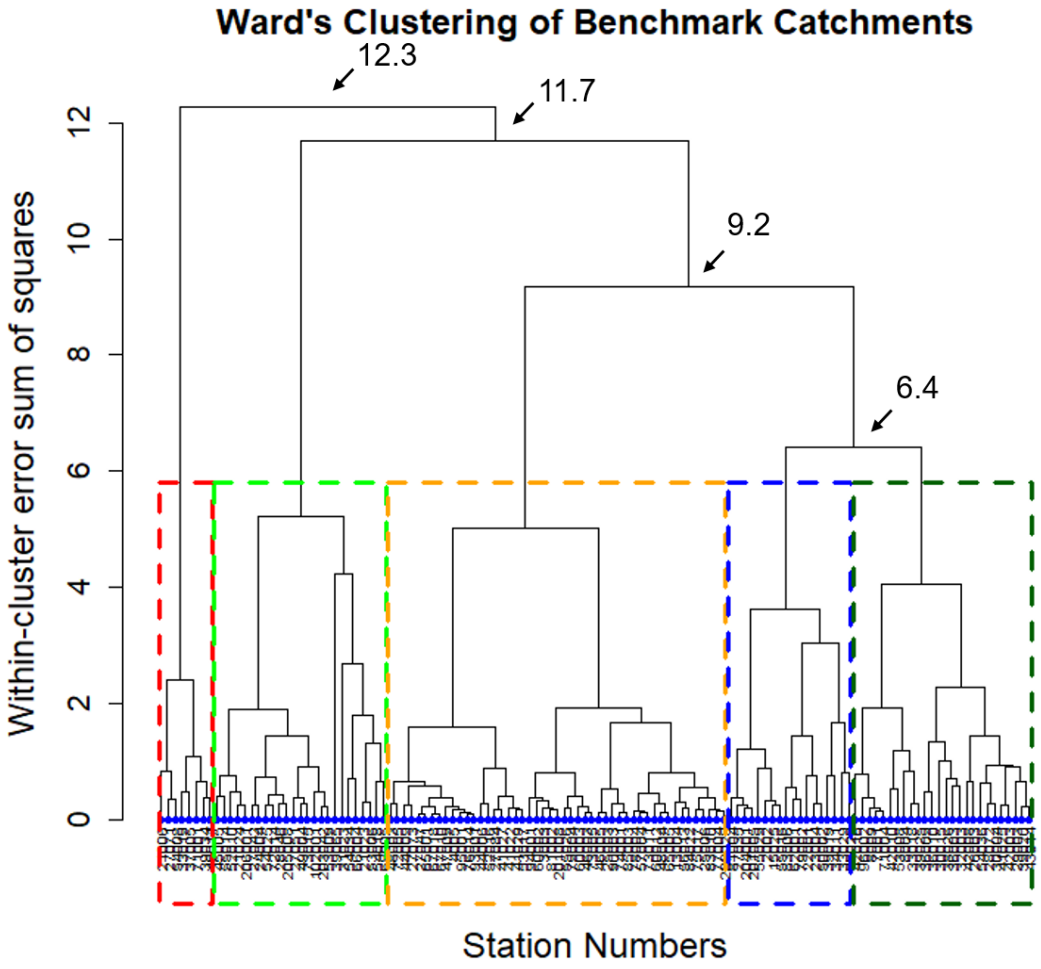


Figure 2.7: Dendrogram of the Wards clustering algorithm for the 126 UK Benchmark Network (UKBN) stations, according to 16 variables and a choice of five groups, Error Sum of Squares (ESS) at cluster merge points

2.4.2.3 Natural Regime Characteristics

Three types of annual hydrographs for the five natural catchment classes were assessed. The first shows the individual catchments' flows calculated as z-scores according to Equation 4 (Figure 2.8). Another way of presenting and comparing the different catchments used by Olden et al. (2021) relies on calculating daily mean discharge of the five groups by averaging for each calendar day, the daily discharge across all gauges in the individual catchment group (Figure 2.9 (a)) and by calculating the 10th and 90th percentile of standardised daily discharge which is the average daily discharge normalised through mean annual discharge of all years and gauges for each catchment group (Figure 2.9 (b)).

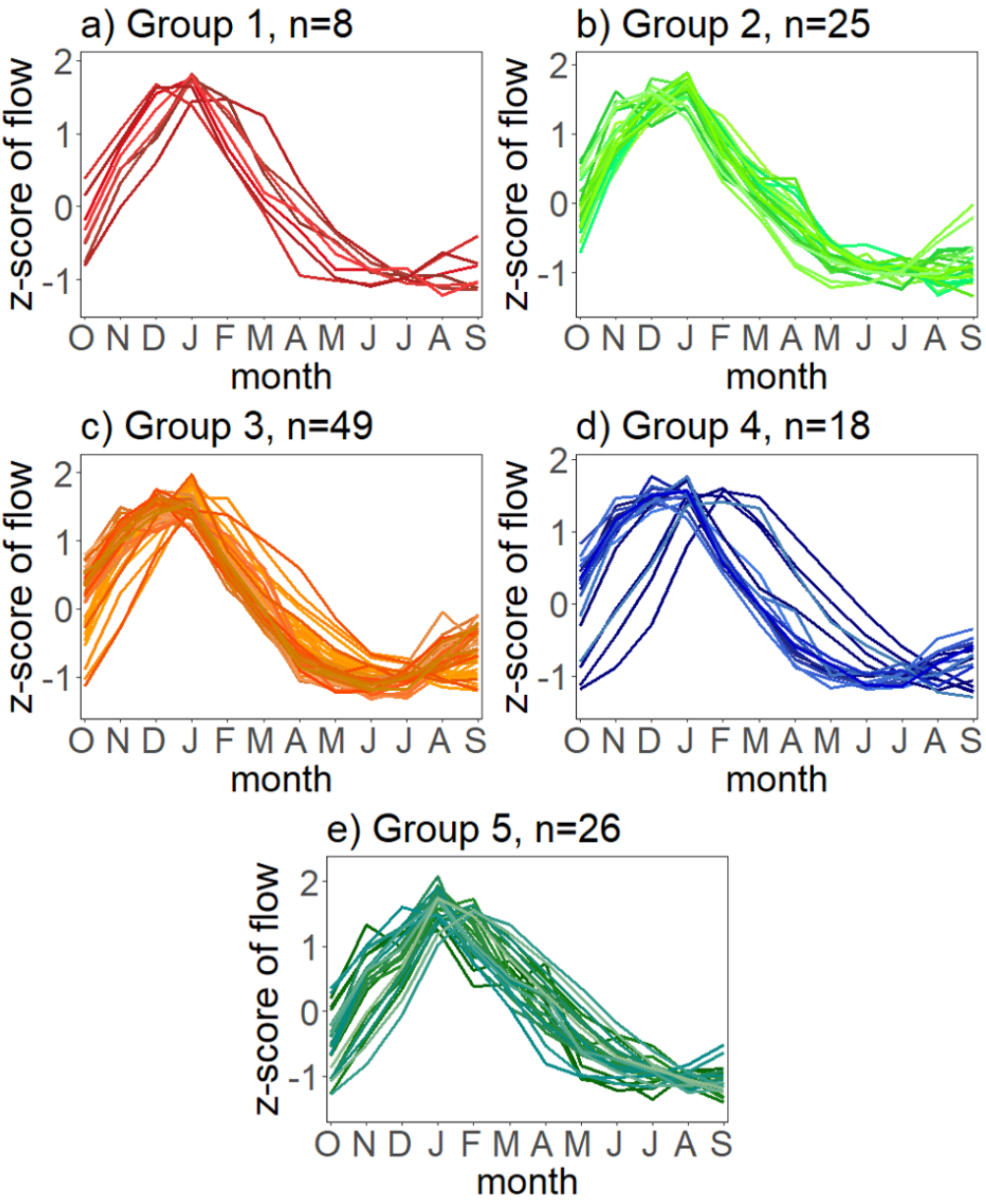


Figure 2.8: Annual standardised Hydrographs of the Catchment Groups, basis water years = 1998-2017

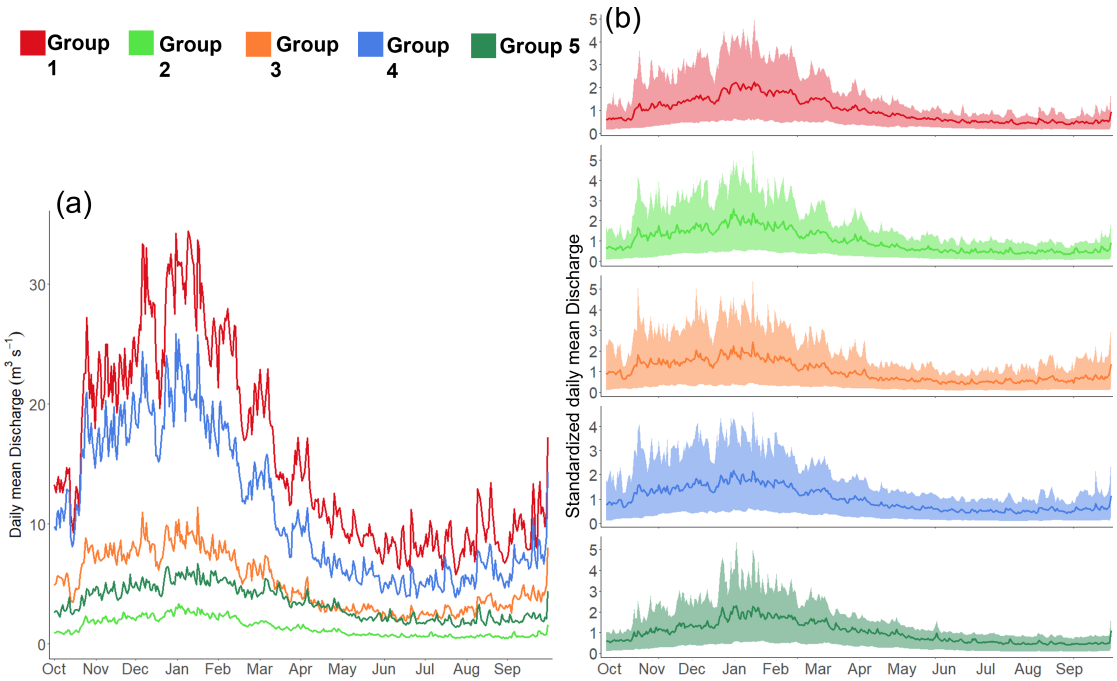


Figure 2.9: Annual hydrographs for each of the five Catchment Groups. (a) Daily mean discharge was calculated by averaging for each calendar day (x axis), the daily discharge across all gauges for each class. (b) Standardized daily mean discharge was calculated by first dividing each daily discharge record by the mean annual flow of that year and then averaging these normalized values across all years and gauges for each class. Solid lines represent average daily values, while the shading represents the 10th (lower limit of shading) and 90th (upper limit of shading) percentiles of the daily discharge for that day of the year across all stream gauges and years of data. basis water years = 1998-2017

The location of the five catchment classes is shown in Figure 2.10. The description of the five catchment classes below focuses on the metrics that were considered in the clustering algorithm (Table 2.5) and on the annual hydrographs (Figure 2.9). The distribution of these metrics is given in Figure 2.11, they are water availability and slope (saar, arcn, slope) (PC1), *flow magnitude* (*skew, sdlog, lfd, hfd1*)(PC2), catchment size and *duration of flow events*(area, *aminf30, amax7, anmin*) (PC3), *frequency of high flows* and responsiveness to rainfall (hfs2, shost) (PC4) as well as *timing of average and high flow conditions* (*pred, consts, jdma*) (PC5). Since the hydrological metrics (in italic) considered in the classification separate the natural catchments well, they are suggested for refining environmental flow protection targets. The distribution of the remaining metrics across the five natural catchment classes is given in the appendix section A.4.1.

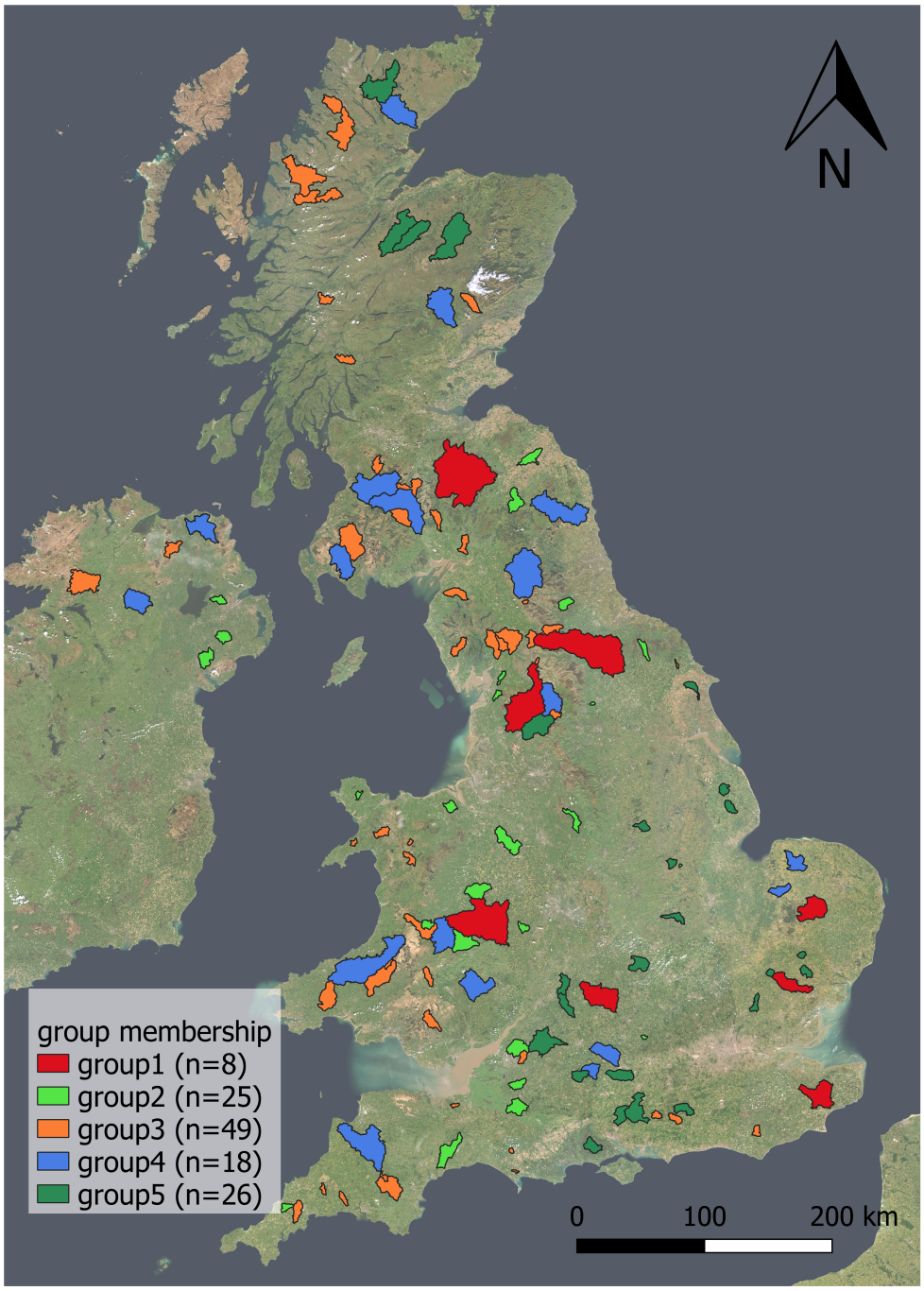


Figure 2.10: Location of the five benchmark catchment groups (n=126)

Group 1. Dry, large, lowland catchments: The first group of benchmark catchments comprises eight large, low elevation catchments (red in Figure 2.10) between 238 and 1500 km^2 in size. Most of them are located in the lowlands with only two stations beyond 100 m above sea level. With rainfall rates of on average 78 mm/month (saar inFigure 2.11) of which on average less than 35% contributes to runoff generation (shost) these are dry catchments. The median annual runoff is on average 453 mm/day (arcn). Six of them have the highest flows in January. They are mostly underlain by highly respon-

sive aquifers (section A.2) and, sustained by a considerable baseflow component, low flows at Q_{90} are comparably high compared to those at Q_{50} (lfd). Accordingly, at 1.6, the skewness (skew) of daily flows is lowest in catchments of group 1 and mean variability of daily flows (sdlog) is low, its median only slightly higher than in group 5. The magnitudes of the 7- and 30-day annual minimum flow series (anmin, aminf30) are however low compared to other groups as is the magnitude of 7-day annual maximum flow series (amax7). While high flows are not particularly pronounced (hfd1) in this group, their frequency is quite variable in this catchment group (hfs2). Due to the strong seasonal differences reflected in the hydrographs in Figure 2.8 a) and Figure 2.9, constancy (const) of flow is low as is predictability (pred) (ranging from 0.26 to 0.36). The date of the annual maximum flow is variable across catchments.

Group 2. Small, dry, central catchments: The second group consists of 25 small catchments with an average size of 87 km^2 located in the Midlands, Northern Ireland and along the border with Wales (light green in Figure 2.10) and are characterised as having mostly flat terrain (27 m/km to 161 m/km). The extreme flow ranges are a distinct feature of this group, with Q_{10} on average 4.5 times as large as Q_{90} (hfd1) and Q_{90} being on average only 30% as high as Q_{50} (lfd). The variability of daily flows (sdlog) is highest of all groups ranging from 0.6 to 1.6. Furthermore, these catchments are characterised by the highest skew of daily flows with mean daily flows on average more than twice as high as median daily flows (skew). At on average 82 mm rainfall is slightly higher than in catchments of group 1 and at on average 34% the share of rainfall that becomes runoff (shost) is very similar. Accordingly, the median annual runoff is 40 mm higher, on average 493 mm/day. During the 7- and 30-day annual minimum flows (anmin, aminf30) however, magnitudes of flow are lowest of all groups. With a mean of 7.4 mm/day the 7-day maximum flow series is not particularly high (amax7). Several catchments display a secondary peak in November and high April flows (Figure 2.8 b)). The frequency of high flow events shows a lower spread than in group 1 (hfs2), the notable outlier is the very small Ewelme Brook catchment, a chalk stream where at 146% the variability of high events counts over Q_{25} is considerable. Annual maximum flow (jdma) occurs late on average at the end of November in all but one catchment and with on average 0.33 and 0.12 respectively predictability and constancy of daily flows are high (pred, consts).

Group 3. Flashy coastal catchments: The largest group contains 49 catchments (orange in Figure 2.10) with an average size of 107 km^2. These sites are mainly found on the western side of the country with the highest levels of rainfall of all groups (saar) of up to 266 mm per month (Nevis catchment in Scotland). Accordingly, these catchments display the largest median annual flow of on average 1340 mm/day (arcn). Furthermore, these catchments are defined by the steepest slopes of on average 143m/km. The regimes in this group are very flashy and 41% of rainfall does on average contribute to runoff generation (shost). Both low flows (lfd) and high flows (hfd1) are pronounced as compared to median flows in these catchments, low flows are on average 31% the size of median flows while high flows are up to 7.8 times as large. Accordingly, the variability of daily flows (sdlog) is relatively high at >0.62 for all catchments, as is the skewness at

1.9 (skew). The high flow events count is most constant across all groups at 24 (hfs2). The 7- and 30-day annual minimum flow series (anmin, amif30) have the highest magnitudes of all groups as does the 7 day annual maximum series (amax7). The flashiness also reflects in a low constancy of events across seasons (const) of only 0.1 while a mean predictability (pred) of 0.3 indicates that events are not linked to seasons. The date with annual maximum flows is very variable (jdma).

Group 4. Medium and large, wet, Western catchments: The fourth group consists of eighteen medium sized catchments with average sizes of around 423 km^2 (blue in Figure 2.10) and mean slopes of 87 m/km. Most of them are coastal. With the second highest rainfall rates (saar) and an average of 701 mm/day the median annual flow (arcn) is high in these sites. On average 36% of rainfall contributes to runoff generation in these catchments (shost). The high flow events count shows no particularly high variation at 32 (hfs2). As shown in the hydrographs (Figure 2.8 d) and Figure 2.9), several of the catchments in Group 4 have comparably high spring flows and the flow peak is shifted to the middle of the year. The variability (sdlog) and skewness (skew) of daily flows as well as low flow discharge (lfd) and high flow discharge (hfd) are in the midrange of all groups. With 9.2 mm/day the 7-day maximum flow series is second highest while the low flow series are very similar to the other groups (aminf30, anmin). The timing of flow events is the major distinguishing category for their flow regimes showing a high seasonality (Figure 2.9); their predictability (pred) is lowest at between 0.23 to 0.37, driven by the low constancy (const) ranging from 0.03 to 0.16. The date of maximum flow (jdma) is after October for most catchments in this group.

Group 5. Dry Southern and Eastern catchments: The last group consists of small lowland and some larger catchments in the North ranging from 26 up to 542 km^2 (dark green in Figure 2.10), mostly found in the west. They have the lowest average elevation with mean slopes of 62 m/km and the driest with mean rainfall of 73 mm per month (saar). Accordingly, the mean annual median flow is only 425 mm/day while the skewness and variability of daily flows (skew, sdlog) are also at the lower end. Only on average 32% of rainfall contributes to runoff generation (shost), group 5 catchments are however underlain by responsive aquifers (section A.2). Their hydrographs are variable, especially in the larger catchments the flow curves are shifted to the middle of the year due to snowmelt processes. Several catchments' high flow is in February and some have secondary peaks in March or April. This goes hand in hand with catchments in Group 5 displaying the least pronounced low flows as compared to median flows (lfd) at 0.4 and the least pronounced high flows as compared to median flows (hfd1) at on average 3.8. Their dryness reflects in the duration of flow events with the 7 day maximum series (amax7) which is equally low as in group 1 and the 7 and 30 day minimum series (anmin, aminf30) which are only slightly higher than those in group 1. The frequency of high flow events (hfs2) is considerably variable across many of the catchments in this group – on average 40. Catchments in Group 5 furthermore display the second highest constancy (consts) ranging from 0.05 to 0.33 and the highest predictability (pred) of daily flows of between 0.24 and 0.53. Unlike in the other groups, all of group five's

catchments annual maximum flow is early in the year (jdma), on average on the 21st of January but before mid-March for all catchments.

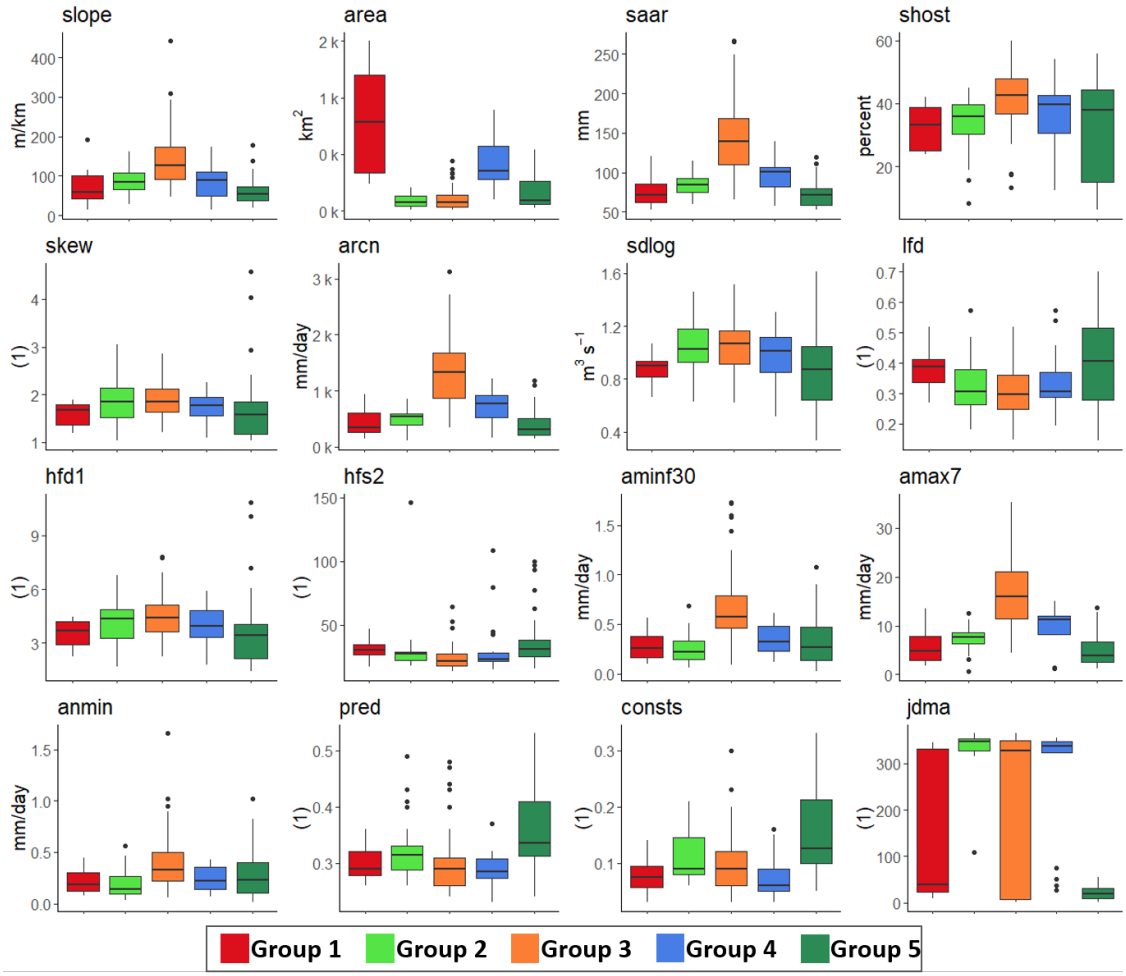


Figure 2.11: Distribution of the two physical (slope, area) and two climatic (saar, shost) and 12 hydrological metrics across seven flow regime categories (magnitude of average flow: skew, arcn, sdlog; magnitude of low flows: lfd; magnitude of high flows: hfd1; frequency of high flow events: hfs2; duration of flow events: aminf30, amax7, anmin; timing of average flow events: pred, const; timing of high flow events: jdma) included in the clustering of natural flow series in the natural flow regime classification (n=126). For acronyms see Table A.2.

2.4.3 Classification of Altered Flow Regimes

After establishing the natural flow regime classification, the remaining, altered, catchments were sorted into the natural catchment groups using a LDA. The spatial distribution of the catchment groups in the final classification is depicted in Figure 2.12. After cross validating the success of the LDA, section 2.4.4 provides a detailed analysis of the catchment groups and their characteristic hydrological parameters.

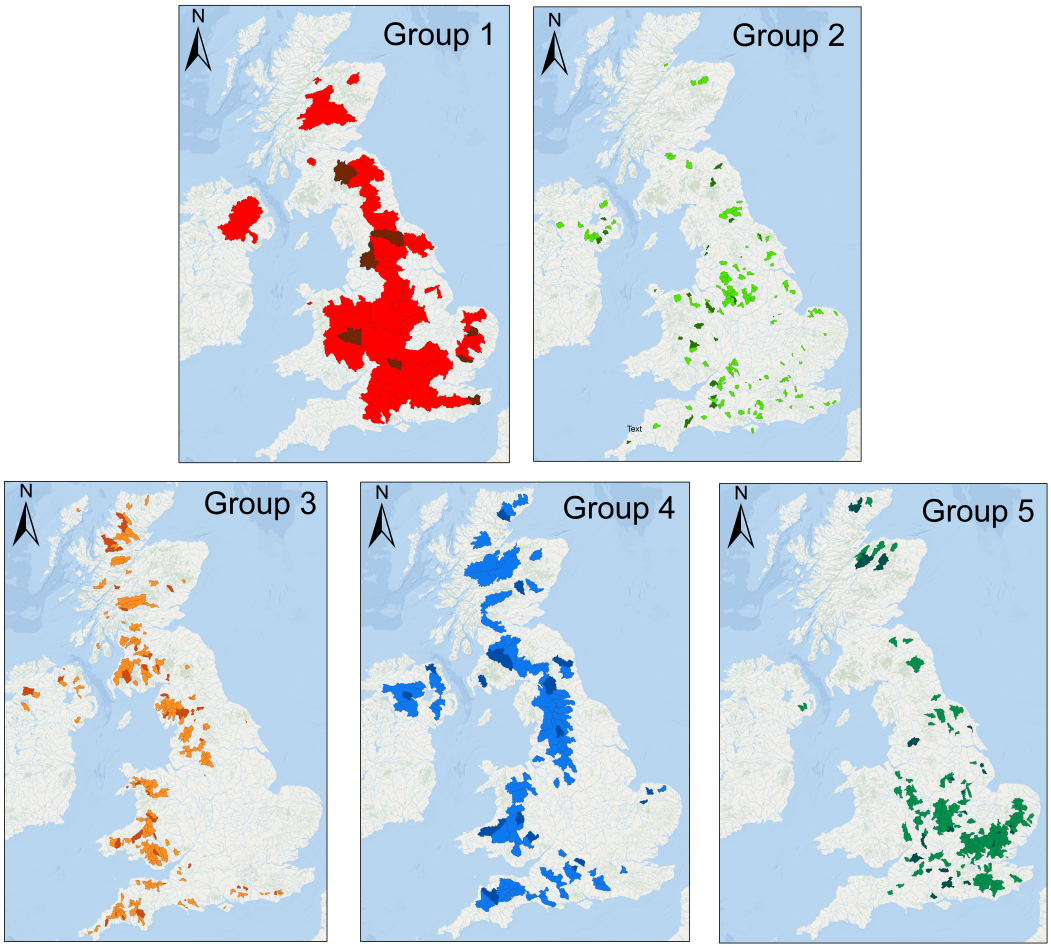


Figure 2.12: Distribution of the final catchment classes, UK Benchmark Network (UKBN) catchments highlighted in dark (n=875)

2.4.3.1 Linear Discriminant Analysis

The class membership of the altered catchments was determined through an LDA that was run across five physical and two climatic descriptors to sort altered catchments into the benchmark catchment classes. The loadings of the four LDs given in Table 2.6 show that variables describing the area and rainfall explain the highest loading into the first two components. Shost is the third most important variable loading strongly into the third component.

Table 2.6: Predictor Variables and loadings into the Linear Discriminants (LDs)

	LD1	**LD2**	**LD3**	**LD4**
bfih	-0.09	0.13	1.28	-0.12
slope	0.16	0.31	-0.20	1.28
prop	0.37	0.33	-0.98	-1.59
shost	-0.42	0.40	1.94	-0.20
alt	-0.25	0.17	0.05	-0.49
area	-1.63	-1.32	-0.11	0.01
saar	1.38	-1.32	0.93	0.63

The leave one out cross validation (Table 2.7) demonstrated that the overall success rate in predicting the correct group membership within the UKBN dataset was 66.67%. Prediction accuracy was highest for group 3 and lowest for group 4.

Table 2.7: Confusion Matrix of the leave one out cross validation for the Linear Discriminant Analysis (LDA), number of classified catchments

		Actual Group				
		group1	**group2**	**group3**	**group4**	**group5**
Predicted Group	group1	3	0	0	4	1
	group2	0	13	6	1	5
	group3	0	5	42	1	1
	group4	2	0	2	8	6
	group5	1	2	0	5	18
	success	0.50	0.65	0.84	0.42	0.58

LDA relies on probabilities for sorting catchments into the classes and quantifies each catchment's probability to be part of either group. The highest probability corresponds to the final membership. To improve the quantitative understanding of classification certainty, three classes of certainty, distinguished based on the highest probability and the difference in probability to the next class, were calculated (Figure 2.13). Most catchments, 638, were classed with high certainty. The "medium" certainty applied for 66 catchments, 56 of which had less than 40% probability in their resulting class and 10 had < 10% difference between the two most likely class memberships. For 45 catchments the results on group membership were in the "low" certainty class due to the probability of their defined class membership being < 40% and the probability for the next class having < 10% probability difference. Aligning with the results of the cross validation, group 4 is classified with the lowest certainty - 13 (12%) catchments are in the low certainty class and 19 (17.6%) in the medium certainty class. In group 3, the most clearly delineated group, 207 out of 218 catchments fall in the high certainty class.

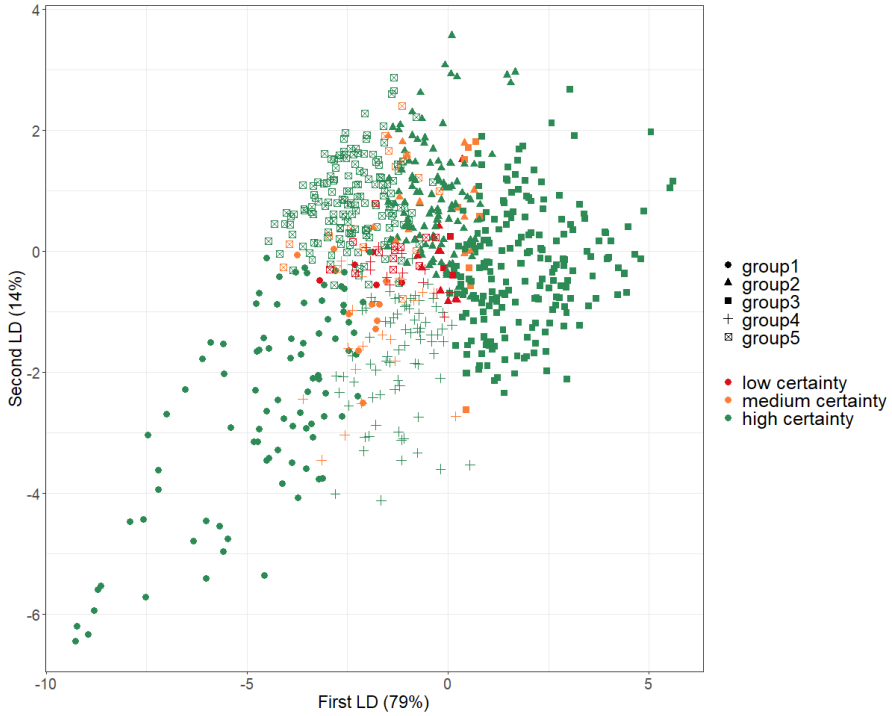


Figure 2.13: Linear Discriminant Analysis (LDA) prediction uncertainty

To understand the reasons for these differences in prediction accuracy the projections of the predicted catchment classes on the first two LDs (Figure 2.14) and the mean values of the predictor variables across the five groups were more closely examined (Table 2.8).

The reason for the low classification certainty for catchments in class 4 lies in its similarities to groups 1 and 5 in some of the descriptors as depicted in Table 2.8. LD 1 and LD 2 are strongly determined through area and saar. While catchments in group 4 tend to be wetter, wet for longer and steeper than those in group 1, some of the (larger, drier) catchments of group 4 occupy a similar space (Figure 2.14) as catchments in group 1 partly because they are often sub catchments of group 1 (Figure 2.12). The similarities between catchments of group 4 and 5 are clear in shost, bfih and altitude (Table 2.8). However, their pronounced differences in area and rainfall and the high loading of these metrics in the first two LDs justifies their separation in two groups. Groups 2 and 3 occupy a very close space across the first two LDs (Figure 2.14) but are well separated through LD 3.

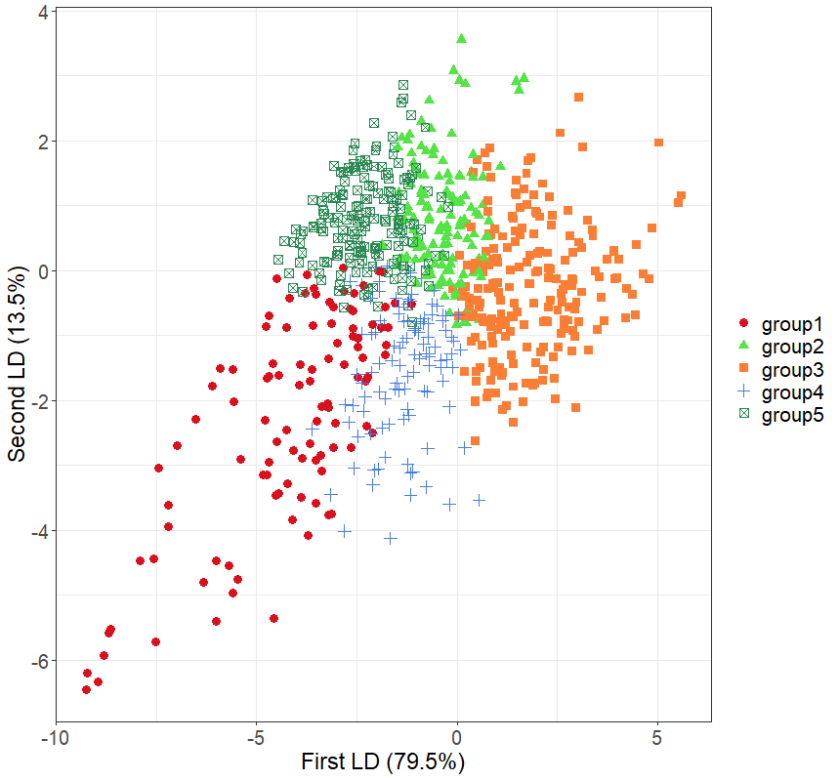


Figure 2.14: Projection of the predicted catchment groups on the first two Linear Discriminants (LDs)

Table 2.8: Mean values and standard deviation (in parentheses) of the predictor values in the five groups, (n=126)

	saar (mm/year)	**alt** (m)	**bfih** (%)	**shost** (%)	**area** (km^2)	**slope** (m/km)	**prop** (%)
group1	78 (25)	32 (32)	57 (13)	33 (8)	332 (79)	76 (57)	39 (12)
group2	82 (15)	56(46)	49 (11)	35 (8)	88 (63)	83 (39)	44 (11)
group3	134 (37)	50 (48)	43 (11)	42 (10)	108 (104)	124 (47)	60 (14)
group4	97 (22)	44(42)	52 (19)	38 (12)	322 (149)	87 (46)	50 (14)
group5	73 (19)	45 (37)	52 (17)	39 (11)	164 (150)	62 (38)	37 (14)

2.4.4 Post Analysis of the Catchment Classification

The Kruskall-Wallis test sought to find significant differences between the groups and identify the variables that separate the groups best. It determined which flow categories contained the variables describing the strongest variation and the most group-pairing with significant differences in variables means. The distribution of significant metrics across these flow categories are given in figure Figure 2.15. While this cannot replace naturalisation of gauged flows as undertaken in Chapter 3, Table 2.9 and Table 2.10 to Table 2.14 can guide sorting of "new" catchments into the respective classes by detailing the distribution and gradients in the main hydrological variables across the five groups. Clearest differences among the catchment groups were found for variables describing

the magnitude of flow during average conditions and during high flow conditions, the duration of flow events and the timing of low flow conditions. The latter is calculated based on daily variables but was nevertheless included. Since influences from abstractions and impoundments reflect most strongly in daily gaugings, these variables might be (more) affected by anthropogenic activities (than monthly to seasonal descriptors). Due to the importance of low flows for water management and environmental protection, it is however included in the description below. Details on the results of the Wilcoxon test are provided in Table A.3.

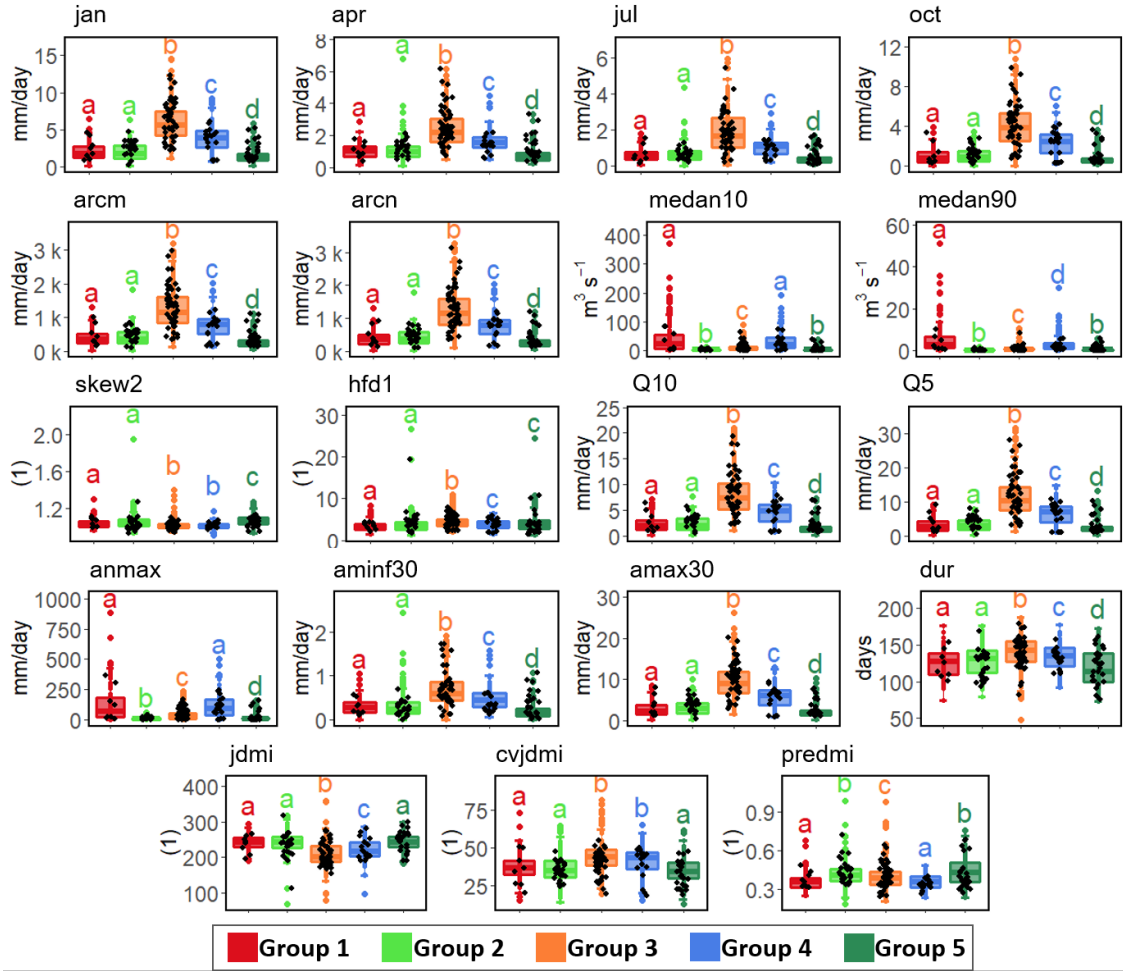


Figure 2.15: Distribution of the metrics describing the magnitude of flow during average conditions (jan, apr, jul, oct, arcm, arcn, medan10, medan90, skew2) and during high flow conditions (hfd1, Q_{10}, Q_5, anmax), the duration of flow events (aminf30, amax30, dur) and the timing of low flow conditions (jdmi, cvjdmi, predmi) across the final catchment classifications. Benchmark catchments are given in black. Groups sharing the same letter are not significantly different according to the Wilcoxon signed-rank test by Wilcoxon (1945), (n=875). For acronyms see Table A.2.

The magnitude of flow during average conditions can be distinguished in absolute flow (medan90, medan10) which is largest in group 1 and smallest in group 2 and relative flow volumes which are highest in group 3 and smallest in group 5 (Table 2.9). The wet catchments of group 3 display significantly higher flows per catchment area than

the other groups followed by groups 4, 2, 1 and 5 close together. Relative high flow magnitudes follow similar gradients. High flow discharge (Q_{10} and Q_5) is highest in group 3 and lowest in group 5 while absolute high flow magnitudes is highest in the large catchments of group 1 and lowest in group 2. The ratio of Q_{10} and Q_{50} (hfd1) reveals how pronounced high flows are in relation to median flows. Group 3 is highest in this category with closely followed by group 5, a group that is otherwise very different. Catchments in both groups are quite responsive to high rainfall events. This ratio is smallest in the lowland catchments of group 1 that are characterised by stable flows and high base flow components. The duration of flow events across the catchment classes follows the same gradient as relative magnitudes. Flows during the 30 day maximum and 30 day minimum series are highest in group 3 and significantly lower in the other groups that are more similar to each other. The duration between 50 and 75% of annual flow is also highest in group 3 and shortest in group 5. The date of annual minimum flows is similarly late in groups 1, 2 and 5 and generally earliest in group 3 with group 4 falling in between. The predictability is highest in the dry Southern and Eastern catchments of group 5 and lowest in the large wet catchments of group 4.

Table 2.9: Mean descriptor values (in parentheses) and gradient from high to low in the three dominant flow categories across five catchment groups; red - group 1, light green - group 2, orange - group 3, blue - group 4, dark green - group 5 (* measured on daily scale).

Flow Category	**Magnitude of flow events – average conditions**						**Magnitude of flow events - high flow conditions**			
variable	jan/apr/jul/oct	arcm	arcn	medan10	medan90	skew2	hfd1	Q_{10}	Q_5	anmax
unit	$mmday^{-1}$			m^3s^{-1}			-	$mmday^{-1}$		m^3s^{-1}
higher	3 (6.0/2.4/1.9/4.0)	3 (1257)	3 (1250)	1 (47.7)	1 (5.8)	5 (1.06)	3 (4.4)	3 (8.0)	3 (11.4)	1 (130.3)
	4 (3.9/1.6/1.1/2.3)	4 (772)	4 (768)	4 (32.5)	4 (3.2)	2 (1.05)	5 (4.2)	4 (4.7)	4 (6.6)	4 (115.8)
	2 (2.0/1.1/0.7/1.1)	2 (422)	2 (407)	3 (10.0)	3 (0.8)	1 (1.04)	4 (3.8)	2 (2.4)	2 (3.4)	3 (37.6)
	1 (2.0/1.0/0.7/1.0)	1 (398)	1 (388)	5 (3.0)	5 (0.4)	3 (1.02)	2 (3.7)	1 (2.3)	1 (3.2)	5 (15.6)
lower	5 (1.5/0.7/0.4/0.6)	5 (281)	5 (268)	2 (2.3)	2 (0.3)	4 (1.01)	1 (3.3)	5 (1.6)	5 (2.5)	2 (10.2)

Flow Category	**Duration of flow events**			**Timing of low flow conditions**		
variable	aminf30	amax30	dur	jdmi*	predmi*	cvjdmi*
unit	$mmday^{-1}$		days	-		
higher	3 (0.7)	3 (9.5)	3 (140)	5 (242)	5 (0.4)	3 (44.1)
	4 (0.5)	4 (5.9)	4 (134)	2 (242)	2 (0.4)	4 (41.1)
	2 (0.3)	2 (3.1)	2 (128)	1 (241)	3 (0.4)	1 (37.4)
	1 (0.3)	1 (2.9)	1 (124)	4 (220)	1 (0.3)	2 (36.0)
lower	5 (0.2)	5 (2.3)	5 (118)	3 (209)	4 (0.3)	5 (35.6)

Table 2.10: Description of catchments in class 1, their distinguishing hydrological features, physical and climatic characteristics and location of natural catchments in this group, standard deviation in brackets

Name	Location	Typical Hydrology				Typical Physical and Climatic Characteristics (mean values)
		Average Flow Magnitude	High Flow Magnitude	Typical Duration of Flow Events	Typical Timing of Low Flow Conditions	
1. Dry, large, lowland Catchments	**Eastern regions & English Lowlands**	Relative discharge (in $mmday^{-1}$): jan: 2.0 (1.1) apr: 1.0 (0.4) jul: 0.6 (0.3) oct: 1.0 (0.7) arcm: 398.7 (219.6) arcn: 388.5 (221.5) Absolute discharge (in m^3s^{-1}): medan10: 47.7 (64.2) medan90: 5.8 (8.1)	anmax (in m^3s^{-1}): 130.3 (154.3) Relative high flow discharge: Q_{10}: 2.3 (1.4) Q_5: 3.2 (1.9) hfd1: 3.3 (1.2)	flows of the 30 day flow series (in $mmday^{-1}$): amax30: 2.9 (1.7) aminf30: 0.3 (0.2) dur: 124 (20) days	jdmi: 29^{th} of August (21) predmi: 0.37 (0.07) cvjdmi: 37.4 (9.0)	altitude: 24 m area: 1640 km^2 prop: 35% saar: 73 base flow: 0.57 slope: 64 m/km

Table 2.11: Description of catchments in class 2, their distinguishing hydrological features, physical and climatic characteristics and location of natural catchments in this group, standard deviation in brackets

Name	Location	Typical Hydrology				Typical Physical and Climatic Characteristics (mean values)
		Average Flow Magnitude	High Flow Magnitude	Typical Duration of Flow Events	Typical Timing of Low Flow Conditions	
2. Small, dry, Central Catchments	**mostly central**	Relative discharge (in $mmday^{-1}$): jan: 2.0 (1.1) apr: 1.1 (0.7) jul: 0.7 (0.5) oct: 1.1 (0,8) arcm: 422.3 (244.3) arcn: 407.7 (242.5) Absolute discharge (in m^3s^{-1}): medan10: 2.3 (2.5) medan90: 0.3 (0.3)	anmax (in m^3s^{-1}): 10.2 (11.7) Relative high flow discharge: Q_{10}: 2.4 (1.4) Q_5: 3.4 (2.0) hfd1: 3.7 (2.6)	flows of the 30 day flow series (in $mmday^{-1}$): amax30: 3.1 (1.8) aminf30: 0.3 (0.3) dur: 128 (21) days	jdmi: 30^{th} of August (31) predmi: 0.43 (0.11) cvjdmi: 36.0 (9.6)	altitude: 55 m area: 76 km^2 prop: 40% saar: 75 base flow: 0.6 slope: 68 m/km

Table 2.12: Description of catchments in class 3, their distinguishing hydrological features, physical and climatic characteristics and location of natural catchments in this group, standard deviation in brackets

Name	Location	Typical Hydrology				Typical Physical and Climatic Characteristics (mean values)
		Average Flow Magnitude	High Flow Magnitude	Typical Duration of Flow Events	Typical Timing of Low Flow Conditions	
3. Flashy, Coastal Catchments	**Western Coastal Regions**	Relative discharge (in $mmday^{-1}$): jan: 6.0 (2.5) apr: 2.4 (1.1) jul: 1.9 (1.1) oct: 4.0 (2.2) arcm: 1257.5 (605.3) arcn: 1250.3 (619) Absolute discharge (in m^3s^{-1}): medan10: 10 (11.5) medan90: (1.2)	anmax (in m^3s^{-1}): 37.6 (37.9) Relative high flow discharge: Q_{10}: 8 (4.1) Q_5: 11.4 (5.8) hfd1: 4.4 (1.4)	flows of the 30 day flow series (in $mmday^{-1}$): amax30: 9.5 (4.1) aminf30: 0.7 (0.4) dur: 140 (23) days	jdmi: 28^{th} of July (35) predmi: 0.40 (0.10) cvjdmi: 44.1 (10)	altitude: 82 m area: 104 km^2 prop: 58 % saar: 146 mm base flow: 0.44 mean slope: 143 m/km

Table 2.13: Description of catchments in class 4, their distinguishing hydrological features, physical and climatic characteristics and location of natural catchments in this group, standard deviation in brackets

Name	Location	Typical Hydrology				Typical Physical and Climatic Characteristics (mean values)
		Average Flow Magnitude	High Flow Magnitude	Typical Duration of Flow Events	Typical Timing of Low Flow Conditions	
4. Medium & Large, wet Western catchments	**Highland Britain, Wales, Coastal regions**	Relative discharge (in $mmday^{-1}$): jan: 3.8 (1.7) apr: 1.6 (0.6) jul: 1.1 (0.5) oct: 2.3 (1.3) arcm: 772.8 (353.1) arcn: 768.9 (359) Absolute discharge (in m^3s^{-1}): medan10: 32.5 (34.6) medan90: 3.2 (4.1)	anmax (in m^3s^{-1}): 115.8 (104.1) Relative high flow discharge: Q_{10}: 4.7 (2.3) Q_5: 6.6 (3.1) hfd1: 3.8 (1.1)	flows of the 30 day flow series (in $mmday^{-1}$): amax30: 5.9 (2.7) aminf30: 0.5 (0.3) dur: 134 (17) days	jdmi: 8^{th} of August (30) predmi: 0.36 (0.05) cvjdmi: 41.1 (9.5)	altitude: 48 m area: 505 km^2 prop: 51 % saar: 104 mm base flow: 0.5 mean slope: 96 m/km

Table 2.14: Description of catchments in class 5, their distinguishing hydrological features, physical and climatic characteristics and location of natural catchments in this group, standard deviation in brackets

Name	Location	Typical Hydrology				Typical Physical and Climatic Characteristics (mean values)
		Average Flow Magnitude	High Flow Magnitude	Typical Duration of Flow Events	Typical Timing of Low Flow Conditions	
5. Dry, Southern & Eastern catchments	**Eastern Coastal Regions & East-English Lowlands**	Relative discharge (in $mmday^{-1}$): jan: 1.5 (1.0) apr: 0.7 (0.5) jul: 0.4 (0.3) oct: 0.6 (0.6) arcm: 281.6 (180.5) arcn: 268.2 (180.6) Absolute discharge (in m^3s^{-1}): medan10: 3.0 (4.9) medan90: 0.4 (0.6)	anmax (in m^3s^{-1}): 15.6 (22.7) Relative high flow discharge: Q_{10}: 1.6 (1.2) Q_5: 2.5 (1.9) hfd1: 4.2 (2.4)	flows of the 30 day flow series (in $mmday^{-1}$): amax30: 2.3 (1.6) aminf30: 0.2 (0.2) dur: 118 (24) days	jdmi: 30^{th} of August (22) predmi: 0.44 (0.10) cvjdmi: 35.6 (8.7)	altitude: 41 m area: 140 km^2 prop: 32 % saar: 63 mm base flow: 0.51 mean slope: 44 m/km

2.5 Discussion

Hydrologic classifications represent the basis for developing regulatory tools required for protecting distinctively different flow regimes (Belmar et al., 2011; Kennard et al., 2010b). These classifications (and subsequent regulation) should be flexible enough to facilitate (broad) environmental flow protection across a high number of regimes and systematically safeguard ecosystems depending on a suite of specific flow regime features (Bunn and Arthington, 2002; Poff et al., 1997). They should be implemented in a way that accommodates possible refinement on the reach to basin scale to allow for stricter or more lenient allocation of flows once flow-ecology relationships have been established (Poff et al., 2010). Classifications like that developed in this study that match natural with altered regimes provide the template for closer assessments of the degree of alteration. In those rivers where capacity for restoring and conservation of natural flow regimes might no longer be possible (e.g. in HMWBs as defined in the WFD (2000/60/EC) European Commission (2000)) environmental flows are allocated to achieve specific ecologic or ecosystem service outcomes (Acreman et al., 2014). Designing new "novel" baselines can maximise the outcomes for both human uses and environmental objectives (Kopf et al., 2015; Poff et al., 2010; Thompson et al., 2018). The exact degree of alteration is however hard to establish for regimes that have been affected by humans, sometimes for centuries and not only directly through impoundments or abstractions but also indirectly through changes in land cover and land use (Garg et al., 2019; Wang et al., 2014). With many regions facing increasing water demand through growing populations and most rivers having been altered from their natural state (Best, 2018; Grill et al., 2019), classifications represent the first step in outlining hydrologic variability and overcome this data constraint (Olden et al., 2012; Poff et al., 2010).

Unlike previous studies (such as Bower and Hannah (2002), Acreman et al. (2008) and Bower and Hannah (2002)), this study combined physical and climatic catchment metrics with hydrological descriptors of the whole flow regime spectrum, therefore yielding a holistic depiction capturing a high degree of complexity for a large number of catchments. The typology developed here stands out through two aspects in particular – the clustering of natural flow regime classes based on metrics representing major flow regime categories and the sorting mechanism relying on five physical and two climatic descriptors. The latter aspect facilitated the inclusion of a high number of catchments that have not been part of previous classification efforts. This work represents an alternative to approaches relying on elaborate and often times costly naturalisation of gauged flows (Terrier et al., 2020). This chapter has shown that a limited number of metrics is enough to distinguish natural regimes in a meaningful way while most (hydrological) indices are too variable and noisy (Bailey, 2012) hampering statistically sound separation of catchment classes (Piniewski, 2017). Five flow regime, physical and climatic categories (annual water availability, daily flow magnitude, duration of flow events, frequency of high flows, timing of average and high flow conditions, responsiveness to rainfall, catchment size and slope) facilitate the identification of broad patterns of large-scale differences between the catchment classes.

Applying the framework to the UK, five natural catchment classes were identified that provide a detailed overview of the spatial distribution and variation of river flow regimes. When examining the hydrology of natural flow regimes across the country, particularly those metrics describing the rate of change in flow events, the frequency of low flow conditions and the timing of flow events showed high redundancy with other metrics. The metrics underlying the natural classification explain 75.9% of total variation across all descriptors. Since the number of metrics available to describe some flow categories are limited (e.g. Kennard et al., 2010a), slight correlations among variables used in the clustering algorithm were deemed acceptable (Kennard et al., 2010b). Improving redundancy of metrics and separation of catchments would require reducing the number of flow regime categories represented however the focus of this study was to reflect all elements of natural regimes required for appropriate natural flow protection. The cross-validation of the LDA used to sort altered catchments into the natural flow classes based on these physical and climatic descriptors yielded a prediction accuracy of 67%.

Major hydrological differences between the final catchment classes were found to lie in flow magnitude during average and high flow conditions, and the duration and timing of low flow events. Since each group contains natural flow regimes with little to no flow alterations through streamflow abstractions or impoundments different classes' typical natural hydrological features were described in detail. The most relevant characteristics across natural flow regime categories that suggest themselves as (new) protection targets are the magnitude and duration of flows, the frequency of high flows, the duration of flow and the timing of average and high flow events. For protection along these hydrological regime elements to become operational and to facilitate a transition from the currently applied approach (based on three river types and four flow conditions), more work is needed. The importance of the individual regime features for the natural ecology across the catchment classes needs to be determined. The different regime features' roles in the ecology (for example in ecological life stages) within different classes need to be evaluated and the allowable deviation from these natural features needs to be determined (e.g. through hydro-ecological modelling). Environmental flow requirements and changes from current protection can then be systematically determined.

The benchmark catchments in each class can also serve as template for matching altered with natural reference flow regimes for guiding restoration. These characteristic natural features shall briefly be evaluated as to their sensitivity to common human activities. The natural regimes within the first class of catchments suggest distinctive natural flow regime features that might require improved protection through environmental flow allocation rules as a result of their characteristic strong seasonality, lack of pronounced high flows and high flow spells and comparably high low flows. Particularly the latter two characteristics imply that abstraction during low flows (Boddy et al., 2020; Brooks and Haeusler, 2016; Saha and Quinn, 2020) and high intensity discharges might potentially be harmful to the natural ecology of these regimes. The magnitude of flood events has been shown to be correlated with reductions in invertebrate densities (Piniewski et al., 2017; Suren and Jowett, 2006) and due to decreases in habitat diversity, invertebrate

richness commonly decreases with decreases in low flows (Dewson et al., 2007). Characteristic elements of the natural regimes of catchments of the second group include pronounced high and low flows, a considerable skewness with mean daily flows on average more than twice as high as median flows, high April flows, no strong seasonality and pronounced low flows for some longer periods. Activities that affect the extreme flow ranges of these regimes including flood reduction (Tonkin et al., 2018) and discharges during times of drought (Leigh and Datry, 2017) therefore require water managements' particular attention in group 2 catchments. High flow conditions have been shown to strongly influence benthic invertebrate species (Clausen and Biggs, 1997; Suren and Jowett, 2006). Due to its importance in substrate mobilisation, reduced peak flows have been shown to negatively affect in-channel habitats (Bestgen et al., 2020; Grams et al., 2020). The natural regimes of group 3 exhibit flashiness with pronounced low and high flows, pronounced high flow events as well as week-long pronounced high flows as characteristic natural flow elements. Human activities that pose the largest threats are likely similar to those in group 2. Next to a high seasonality, characteristics related to high flows identify natural regimes in class 4 including high spring flows, pronounced high flows and week-long high flow spells. Those activities affecting the pronounced seasonality such as discharges during times of low flows or high abstraction rates during high flows might be harmful for these regimes (Singh and Basu, 2022). The natural regimes within group 5 were found to show little seasonality, stable flows yet high responsiveness to rainfall, early high flows and no pronounced high flow spells. Activities with the largest potentially harmful effects on natural flow regimes in this group include infrequent large water discharges or releases from dams (Kuriqi et al., 2021) as well as high rates of groundwater abstraction that reduces connectivity to baseflow providing groundwater (Lewandowski et al., 2020; Middleton and Allen, 2017). Baseflow connectivity is important for spawning habitats (Goodman et al., 2018), recruitment and thermal regimes (Hare et al., 2021; Horne et al., 2004).

The UKBN network provides a good basis for hydrologic climate impact and trend analyses (e.g. Bradford and Marsh, 2003; Hannaford and Marsh, 2006) and facilitated the development of a natural catchment classification. The coverage of the South East is however limited (Harrigan et al., 2018) and (previously) natural regimes of these regions are therefore potentially underrepresented in this study. This limitation in coverage has been a challenge for previous studies looking into past and future climate impacts on hydrology (Smith et al., 2019). Decision making in strongly altered catchments such as for for climate-smart environmental flow allocation requires flow naturalisation using detailed local information on the scope of human influences (BGS, 2017; Soley et al., 2012) which is performed as part of the next chapter for two case study catchments that are representative of catchment groups 1 and 4.

Roo et al. (2015) found that climate indices show stronger relationship with streamflow than physiographic characteristics. Climate represents a fundamental determinant that influences streamflow at a range of scales (McGregor, 2019). The five most relevant climate indices Roo et al. (2015) found were aridity index, precipitation seasonality, trans-

formed mean annual precipitation, potential evapotranspiration seasonality and mean annual potential evaporation. The limited availability of such detailed climate information for such a large area meant that this study relied on standard average annual rainfall and the share of precipitation that becomes runoff. The latter metric being derived from extensive modelling efforts for the FEH project(NRFA, 2018). The power of the LDA would likely improve through incorporating more climate variables.

While the natural flow paradigm remains relevant to understanding ecological response to hydrologic alteration (Richter et al., 1996), and flow-ecology relationships (Poff et al., 2010), the trajectories of greenhouse gas emissions frequently tend to point to the high-end climate change scenarios (England et al., 2015). Climate sensitive water management has to be revised for shifting hydro-climatic and ecological baselines which require an extension and adaptation of the assumptions underlying environmental flow protection (Acreman et al., 2014; Arthington et al., 2018a; Poff, 2017). For refining the classification developed here to reflect different catchments' climate sensitivity, it could be extended with metrics such as those found by Roo et al. (2015). For the case of the UK, particularly the recently published CAMELS dataset (Coxon et al., 2020) provides the necessary information on climatic indicators with a large coverage. However, as outlined within the climate impact analysis of the next chapter, streamflow response to climate change is highly uncertain and decision making support is best attained through analyses on smaller (i.e. catchment) scale.

The analyses undertaken here furthermore cannot replace local-scale assessments of sensitivity to abstraction and of flow-ecology relationships (e.g. Lathouri et al. (2021), Klaar et al. (2014), Davies et al. (2013)). However, this classification provides a template to match altered and unaltered regimes and represents a broad-scale hydrologic framework to characterise a high number of catchments in a systematic and holistic way. It makes suggestions on how FDC-based environmental flow protection can be improved through protecting for characteristic natural flow regime categories. Further assessments should focus on the degree of alteration in highly managed catchments and on the priorities in future (conservation) management. Particular attention should lie on the inclusion of different regimes' and their ecological communities' sensitivity to climate change to support robust yet flexible country-level environmental flows applications (Horne et al., 2019). This classification provided the basis for the choice of case study catchments for the following two chapters.

2.6 Conclusion

A major conclusion that can be drawn from the findings of this study is that environmental flow protection approaches relying on only a few river types and sensitivities to deviations from natural flows (such as the EFI in England that only distinguishes three sensitivity classes) are too simple. In most countries rivers are highly variable and complex ecosystems. This study presented a methodology for a holistic typology of the UK's catchments including both natural and altered regimes across 875 individual river flow series and three different types of descriptors. The main elements distinguishing natural flow regimes are overall wetness, high flow and low flow magnitude, duration of flow events, frequency of high flows and responsiveness to rainfall and the timing of average flow conditions. Against the background of growing pressures on often strongly altered river systems, finding the balance between the needs of the environment and those of human populations requires flexible environmental flow allocation that allow anthropogenic demand to be fulfilled when environmental goals cannot be achieved. Country-scale environmental flow allocation rules can provide important guiding frameworks and should provide local-scale decision makers with flexible tools required to adequately manage a wide range of regimes. While this study cannot replace detailed site-specific assessments of flow-ecology relationships and flow sensitivities, it provides a template matching altered regimes with natural reference regimes and suggests flow characteristics that require decision makers' particular attention.

Chapter 3. Hydrological climate change impacts under regional projections; sampling climate model uncertainty

Abstract

The priority catchment project in England focuses on developing innovative solutions to environmental protection and ensuring a clean and plentiful supply of water. It provides a unique opportunity to model the impacts of climate change on streamflow to support the development of resilient management solutions. GCMs represent the largest source of uncertainty for hydrological climate impact modelling and therefore require particular consideration.

The latest 12-member dynamically downscaled Perturbed Physics Ensemble (PPE) of regional climate model projections from the UKCP18 samples GCM parameter uncertainty. In this study it was extended with projections from 18 members available of the euro-CORDEX (eCX) initiative sampling GCM structural uncertainty. Both ensembles are available for emissions pathway Representative Concentration Pathway (RCP) 8.5. To cover a broad range of scenarios, they were extended by lower emissions (RCP4.5 & RCP2.6) eCX projections. Future changes in streamflow in two contrasting priority catchments were analysed with the new, revised version of the Soil & Water Assessment Tool (SWAT). Both catchments are influenced by high rates of freshwater withdrawals. One is a wet coastal catchment with steep slopes while the other is a dry lowland catchment. Modelled impacts were analysed for natural monthly to annual flows and flow duration statistics until the 2080s.

SWAT+ performed well in simulating natural flows during the validation period. The projections under UKCP18 are consistently drier than those under eCX. Under high emissions, streamflow in the coastal catchment was projected to increase in seasonality with higher winter and lower summer flows, while streamflow in the dry lowland catchment was projected to decrease across all months apart from February. RCP2.6 and RCP4.5 represented a mixed result with rarely beyond 10% change and more months with increasing trends than under RCP8.5. The different emissions pathways largely agreed on increasing high flows and decreasing low flows in the coastal catchment. For the lowland catchment both ensembles driven by RCP8.5 projected decreases across the whole flow duration curve while RCP2.6 and 4.5 projected medium to high flows to increase and low flows at Q_{70} and Q_{95} to stay the same. This study suggests the need to adapt environmental flow protection to decreasing streamflow across the whole year in the lowland catchment and to pronounced changes in streamflow timing in the coastal catchment. The parameter uncertainty sampled through UKCP18 translated into a strong hydrological response, in particular streamflow decreases while the eCX outlined some considerably wetter future pathways. This study provides insights into the challenges that water managers may face when enhancing abstraction management and environmental protection in the priority catchments and more widely.

3.1 Introduction

Freshwater management needs to strike a balance – supplying water to increasing populations while safeguarding aquatic ecosystem health from the combined pressures of climate change and anthropogenic water use (Capon et al., 2018; Dudgeon, 2019; Springmann et al., 2018). Climate change represents a major concern for water management because as an essential part of the climate system, the hydrological cycle is very responsive to climatic variability and changes (IPCC, 2022). Research has shown that small variations in climate may lead to significant changes in hydrological processes including magnitude, timing and seasonal distribution of streamflow (Donnelly et al., 2017; Krysanova and Hattermann, 2017; Lobanova et al., 2018). The main drivers of change in the spatial and temporal distribution of river flows are air temperature, evaporation and precipitation (Chiew, 2006; Gerten et al., 2013; Milliman et al., 2008).

The protection of environmental flows, defined as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human wellbeing that depends on these ecosystems, faces unprecedented challenges (10th International River Symposium, 2007; Pastor et al., 2019). Particularly within catchments important for anthropogenic water supply, where freshwater ecosystem health is declining, a solid understanding of both the current state of water resources as well as of possible future trends is therefore crucial to adopt no/low regret adaptation measures (Döll et al., 2014; Jägermeyr et al., 2017; Wilby and Dessai, 2010). No/low regret adaption strikes a balance between environmental and societal water needs and minimises trade-offs between long-term water security (Gunda et al., 2019; Srinivasan et al., 2017) and environmental flow requirements (Pastor et al., 2019). Relevant indicators useful for informing decision making under climate change include changes in daily to annual streamflow magnitude and variability and in flow quantiles. Robust estimates for these indicators are consistent in sign across different hydrological climate projections and allow to determine future water availability and guide water allocation among different uses (Knutti and Sedláček, 2013; Phung et al., 2022).

While perceived as a water abundant country, the UK is facing unprecedented difficulties in safeguarding its water resources while securing supply to increasing populations (Environment Agency, 2020d). Due to pressures from water abstractions predominantly required for public water supply, many regions face decreasing freshwater ecosystem health and one in five surface water bodies is considered as over-abstracted (Environment Agency, 2019a). In these catchments, freshwater withdrawals are tapping into flows required for the environment as allocated through the Environmental Flow Indicator (EFI) (Environment Agency, 2018b). The EFI represents the allowable percentage deviation from the natural flow. Several plans and strategies to restore sustainable abstractions (Defra, 2020) and to ensure a clean and plentiful supply (Environment Act, 2021) have been introduced. For example as part of the Water Abstraction Plan (Defra, 2020), the Environment Agency (EA), the regulator responsible for safeguarding English river systems, has initiated the “priority catchment project” with ten case study catch-

ments. These are characterised by high rates of freshwater withdrawals, unmet and further growing demand for freshwater use and accompanying deterioration of ecosystem health. Through stakeholder engagement, targeted research efforts and collaborative projects, innovative solutions for improving the access to water and reducing unsustainable abstractions while ameliorating the aquatic ecosystem health shall be established (Environment Agency, 2021e).

Climate change is aggravating the protection of environmental flows and requires the regulator's particular attention (Environment Agency, 2018e; Watts et al., 2015). The latest climate projections for the UK (UKCP18, Lowe et al. (2018)) suggest hotter, drier summers and warmer, wetter winters (Murphy et al., 2018). Climate change effects in the UK are characterised by high spatial and temporal uncertainty due to the variable geography and inherently high interannual variability of the UK's climate (Hulme and Barrow, 1997; Wheeler and Mayes, 1997). This makes it harder to detect robust long-term climate change signals than in continental inland regions (Hannaford, 2015; Wilby, 2006). Hence, water managers and policy makers, particularly those developing larger (e.g. country) scale guidance, must account for a wide range of possible futures and considerable uncertainty across both temporal as well as spatial scales (Derepasko et al., 2021; Kennen et al., 2018). Hydrological modelling of catchment-scale hydrological response to climate change plays a decisive role in providing insights into future developments and support in robust decision making under uncertainty (IPCC, 2014a; Kundzewicz et al., 2018). Alternative methods, notably "storyline" approaches (Shepherd et al., 2018) employ scenario-neutral hydro-climatic assessments based on vulnerabilities and the qualitative understanding of driving factors (e.g. Bhave et al., 2018).

Unfortunately, there is a discrepancy between the requirements of decision makers for water management planning and the considerable variety of different projections produced through hydrological climate impact modelling (Weaver et al., 2013). For understanding hydro-climatic causes of hydrological changes and implications for water resources management including environmental flow protection, site-specific projections and robustly quantified assessments of uncertainty and variability of hydrological climate change impacts are necessary. But uncertainty is hard to quantify and the "cascade of uncertainty" describes the fact that its range grows along the modelling chain (Wilby and Dessai, 2010). Climate impact results should always be evaluated within the context of the uncertainty associated with their production (IPCC, 2013). It is crucial to identify and understand the nature of uncertainty sources and their propagation throughout the assessment process, its interaction with the risk level as well as its communication for the decision making process (Jones, 2001; Kundzewicz et al., 2018; Shepherd, 2014).

3.1.1 Sources of Uncertainty in Hydrological Climate Impact Modelling

The coupled hydrological climate impact modelling chain relies on the application of three kinds of models: General Circulation Models (GCMs), Regional Climate Models (RCMs) and Hydrological Models (HMs). The major sources of uncertainty for using climate model simulations for hydrological studies are detailed below (Figure 3.1).

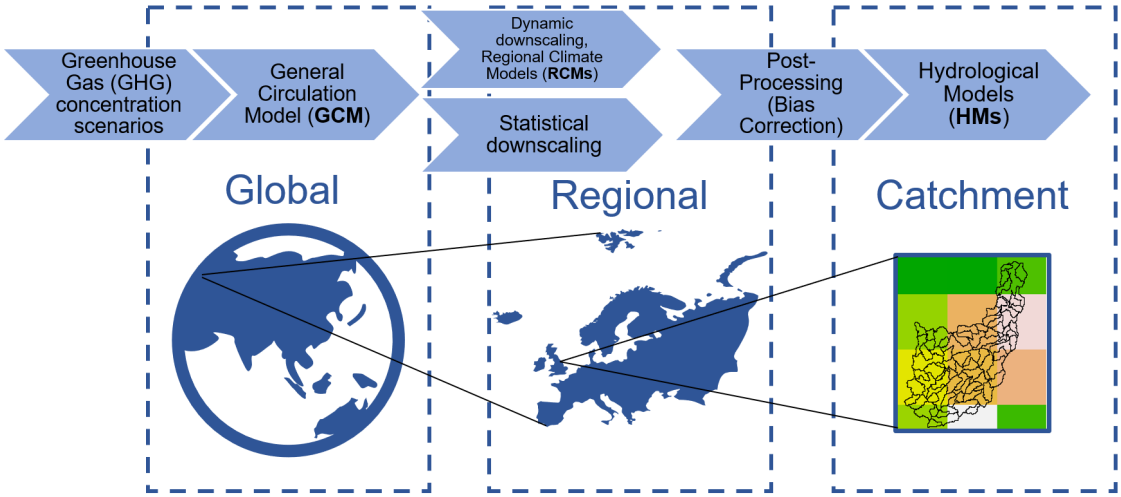


Figure 3.1: Schematic of a typical hydrological climate impact modelling chain, the scale and main sources of uncertainty associated with its individual steps (adapted from Teutschbein (2013) and Hakala et al. (2019)).

Numerous studies have shown that the largest share of uncertainty is generally due to the choice of GCM, followed by the uncertainty due to RCM (applied for downscaling GCM output) while the uncertainty due to HM is smallest (Huang et al., 2012; Kundzewicz et al., 2018; Vetter et al., 2015). GCMs are the main tool underpinning climate (impact) modelling and simulate how the global climate might change under different land use, air pollutant and Greenhouse Gas (GHG) concentrations. In addition to ocean and atmosphere processes, GCMs simulate future global carbon cycles, vegetation and atmospheric chemistry (IPCC, 2014b). GCM uncertainty stems from differences in mathematical model structures (structural uncertainty). Next to simplified and idealised representation of physical processes, a major contribution to structural uncertainty stems from parameterisation schemes used to describe processes that cannot be explicitly represented because they work at scales finer than what GCMs can computationally solve (e.g. clouds or turbulences) (Frigg et al., 2014; McFarlane, 2011; Parker, 2010). Another substantial source of uncertainty is parametric uncertainty that describes the uncertainty of parameter values in the model physics scheme (Murphy et al., 2004). Other sources of uncertainty are due to the simulation of natural variability and our incomplete understanding of feedback mechanisms such as those related to ocean circulation and water vapour (Torn and Harte, 2006). Variable feedback mechanisms as well as the representation (= parameterisation) of clouds are the major reason why GCMs respond differently to the same GHG emissions, this feature is called climate sensitivity and is commonly used for comparing GCMs (Boucher et al., 2013; Vial et al.,

2013; Zelinka et al., 2017). The Coupled Model Intercomparison Project (CMIP) was established by the world's major climate modelling groups with the aim to provide systematic comparisons of GCM outputs and coordinate research efforts to better understand past, present and future climate changes (https://www.wcrp-climate.org/wgcm-cmip). The most recent project phase is CMIP6 (Eyring et al., 2016).

The emissions scenarios used to force GCMs are another important source of uncertainty in climate modelling (Nakicenovic et al., 2000). In 2008, the Intergovernmental Panel on Climate Change (IPCC) requested for GHG concentration scenarios to account for adaptation measures Moss et al. (2008). Since their use in the IPCC (2014a) Fifth Assessment Report, RCPs (Vuuren et al., 2011) have become the commonly used set of scenarios in climate (impact) analyses. Corresponding to four different socio-economic trajectories they were named after the respective radiative forcing level reached by the year 2100 e.g. RCP8.5 refers to a global forcing of 8.5 Wm^{-2}. The most recent IPCC (2022) report relied on RCPs and a combination of RCPs and complementary Shared Socioeconomic Pathway (SSP) scenarios. The SSPs describe how factors such as population and economic growth or technological development affect greenhouse gas emissions represented through the RCPs (Riahi et al., 2017).

GCMs work on coarse spatial resolutions and can inform high-level understanding of potential risks to the water environment (e.g. Ajjur and Al-Ghamdi (2021), Padrón et al. (2020)). However, the global-scale scenario projections they provide are not directly usable in hydrological applications at the catchment or regional scale and need to be downscaled to regional climate scenarios. The two main methods to achieve this are statistical and dynamic downscaling (Wilby and Wigley, 1997). Statistical downscaling relies on defining the statistical relationships between large scale climate predictors and regional and local climate predictands; these statistical relationships are then applied to GCM projections of future climate to estimate the regional and local details of these projections (Benestad, 2004; Wang et al., 2004). However, most commonly RCMs are used to dynamically downscale GCMs. This is done by forcing an RCM with (atmospheric) boundary conditions of a GCM (Dickinson et al., 1989; Giorgi and Bates, 1989). RCM outputs then account for the effects of mountains, coastlines etc. in greater detail than the driving global projections from the GCMs do (Murphy et al., 2018; Rummukainen, 2016). RCMs were for example found to provide good simulations of extreme rainfall events at various return periods (Fowler et al., 2005) and were shown to simulate mean and extreme precipitation better than coarse resolution climate models (Prein et al., 2016). Recent advances in hydrological modelling have focused on using this finer resolution climate model weather data from RCMs to directly drive hydrological models in catchment scale impact assessments (Donnelly et al., 2017; Papadimitriou et al., 2016). Unfortunately, while RCMs bridge the scale gap between local scale applications and GCMs, they are still subject to substantial errors partly inherited from the driving GCMs (Hall, 2014). This means that, while RCMs add realistic smaller scale detail, they cannot substantially deviate from the boundary forcing defined by the GCM and for example inherit their (potentially erroneous) placement of storm tracks and their climate sensitivity

(Giorgi, 2019). Particularly for climate variables that are strongly tied to local processes the RCM uncertainty can be considerable (Déqué et al., 2007).

Fully assessing and characterising the climate model uncertainties in impact assessment studies requires well-designed multi-model approaches. The considerable parametric uncertainty of single GCMs can be sampled through perturbed parameter ensembles (PPEs) that are produced by simultaneously perturbing GCM parameters that represent key uncertainties (Murphy et al., 2007; Murphy et al., 2004). PPEs provide a large number of ensemble members (e.g. 53 in Murphy et al. (2004)) of one GCM that systematically explore uncertainties in processes and feedbacks and isolate different sources of uncertainty (e.g. varying climate sensitivity but not forcing) (Collins et al., 2010). The latest country-specific projections for the UK, the UK Climate Projections 2018 (UKCP18), include a PPE of the Met Office's GCM (Williams et al., 2018) that has been used to produce global projections as well as to force RCM-PPE variants to produce regional projections (Murphy et al., 2018). The use of Multi-Model Ensembles (MMEs) of varying combinations of GCMs, RCMs and RCPs is recommended to sample uncertainty in projected changes originating from GCM structure (Hagemann et al., 2013; Parker, 2013). It is however important to notice that the MME mean is not suited to describe "typical" hydrological changes as these are rarely normally distributed or even unimodal and the use of several model runs' mean can lead to a loss of signal (Arnell, 2011; Knutti et al., 2010). The median is less sensitive to outliers in a distribution of model responses within a particular MME experiment. So the best way of describing the uncertainty in (hydrological) response is to find a way to show the full range of modelled outcomes, for example through reporting ensemble mean, median and spread measures (Hakala et al., 2019). Furthermore, applying well-designed and balanced scenarios allows to systematically quantify the share of uncertainty introduced through individual modelling components - GCM, RCM, RCP and HM (Hattermann et al., 2018; Vetter et al., 2016).

Several GCM working groups have formed initiatives for systematic uncertainty assessments along the modelling chain. They provide impact modellers with regional projections produced from systematically varied GCM-RCMs across the different RCPs (e.g. CORDEX (Giorgi et al., 2009) or PRUDENCE (Christensen et al., 2007)). A side effect of the computational costs of providing these high-resolution simulations is that due to many missing combinations these large MMEs are often unbalanced. This means that standard Analysis of Variance (ANOVA) cannot be performed (Evin et al., 2021; Fernández et al., 2019). Recent efforts to circumvent this problem have focused on sub-sampling available MMEs (Christensen and Kjellström, 2020) or data augmentation techniques such as employed by Evin et al. (2019) separating forced climate response from internal variability.

Another important source of uncertainty in the modelling chain is post-processing of model output data. One kind of post-processing is bias correction which is needed to account for systematic differences between observed and RCM-simulated climate

(Christensen et al., 2008). Complex methods such as those relying on quantile-based transformations were found to outperform more simple bias correction methods based on adjusting mean and variance (Chen et al., 2013; Gudmundsson et al., 2012). This is particularly relevant, as climate change will have stronger effects on extremes than on mean values (Trenberth et al., 2003). The share of bias correction in overall uncertainty in hydrological climate impact analyses is usually small (Teutschbein and Seibert, 2012; Zhang et al., 2022). Its potential impact on the climate signal should however not be underestimated (Hempel et al., 2013). One of its major weaknesses is the assumption that the causes of biases during the observational period do not change in the future (stationarity of bias) (Chen et al., 2015; Ehret et al., 2012; Raisanen and Raty, 2013). The choice of appropriate bias correction method strongly depends on the study aim and cannot overcome limitations in the underlying GCMs (Chen et al., 2016; Maraun, 2016).

Next to climate model projections and their post-processing, the steps in the impact modelling chain performed with HMs (Figure 3.1) also require attention. A wide range of HMs varying in complexity of represented physics, input data and focus of application have been developed (Devia et al., 2015). The most complex HMs are fully distributed physically-based models, which explicitly consider the spatial distribution of physical catchment properties (Hrachowitz and Clark, 2017). HMs are set up for the area under investigation and simulated streamflow is calibrated and validated based on observed streamflow and climate. For quantifying climate impacts on streamflow and mapping future outcomes, they are then either run with perturbed observed flow series applying a change factor (Anandhi et al., 2011) or they are run with (bias corrected) simulated climate projections (e.g. Lobanova et al. (2018), Chien et al. (2013)). The main uncertainties associated with this step in the impact modelling chain are due to the quality of the observed input data including precipitation, temperature or land use (McMillan et al., 2018). Furthermore, depending on the catchment, the uncertainty of the measured output variable that the HM is calibrated for can be considerable (see next section). Typically this output variable is either a gauged flow series or a rating curve (Sikorska and Renard, 2017). Other sources of HM uncertainty are due to the way catchment hydrological processes are approximated and therefore structured within the HM, as well as the HM parameter settings (Renard et al., 2010). In some regions (Hagemann et al., 2013) and when complex and/or slow hydrological processes dominate river flows, the HM and its parameter settings can induce the largest share of uncertainty (Her et al., 2019).

3.1.2 Hydrological Modelling, Naturalisation and Baselines

When applying HMs in catchments highly influenced by anthropogenic activities, the uncertainty in the measured output variable used for calibration, requires particular attention (Beven and Binley, 1992; Bjerklie et al., 2003; Smith et al., 1996). While HMs can be calibrated for other variables including nutrient loads (e.g. Jiang et al. (2015), Yuan and Koropeckyj-Cox (2022)), most hydrological impact studies focus on simulat-

ing river flow. Depending on model setup and aim, an understanding of the natural flow isolated from anthropogenic water use effects is usually required to make adequate projections of the climate change impacts on the system. The degree of influence of water use must therefore be quantified and accounted for as a first step. If water use is well-known and documented, the isolation of effects can be achieved through the naturalisation of gauged flows (Terrier et al., 2020) and these naturalised flows can then be used for HM calibration. Other options include the transfer of measured river flows from similar catchments that are known to be natural or near-natural (Harrigan et al., 2018), a water balance study (Irwin et al., 1975; Wurbs, 2006) or rating curve analysis (Gustard et al., 1992; Petersen-Øverleir and Reitan, 2009). Moreover, some HMs allow water withdrawals and/or impoundments as input parameters (Bieger et al., 2017) including HMs with a global resolution (Hanasaki et al., 2018; Müller Schmied et al., 2021). The success of these methods is highly dependent on data availability and accessibility and progress is made in making information on sub-catchment to national-scale abstraction rates available (Rameshwaran et al., 2021).

The often limited data availability for flow naturalisation entails a major downstream challenge that can significantly affect the credibility of subsequent results, particularly the length of the reference period upon which climate change analyses are based (Terrier et al., 2020). When detailed information on water use is only available for a certain period, this reference period may be insufficient for reflecting natural climate and hydrological variability (Liersch et al., 2020). As climate is strongly dominated by natural variability, the uncertainty associated with it can be similar of even larger than that of climate change signals (Deser et al., 2012; Fatichi et al., 2014). Thirty years is commonly chosen as baseline length, though not always with clear reasoning (Werndl, 2016) and the "best" baseline strongly depends on study focus (Liersch et al., 2020). Liersch et al. (2020) analysed the sensitivity of discharge simulations to different baseline lengths and while, along with common practice, recommending a length of at least thirty years, they found less sensitivities to the choice of baseline length and timing in results derived from model ensembles as compared to those produced based on single model simulations. In highly impacted basins where limited information on freshwater withdrawals and other water management activities does not allow for a 30-year baseline that guarantees to cover natural variability, the use of climate model ensembles is critical for the credibility of results.

3.1.3 Aim of this Study

The Environment Agency (EA)'s priority catchment project provides the unique opportunity to develop robust hydrological projections for two priority catchments representing two catchment typologies identified in chapter 2. To provide greater confidence for planners and decision makers when designing management interventions, climate projections from the UKCP18's RCM-PPE of a single GCM (sampling parametric uncertainty) for a high emission scenario (RCP8.5) and from a MME of several GCM-RCM pairs (sampling structural uncertainty) available for three emission pathways (RCP2.6, 4.5 and 8.5) are assessed. This will be achieved with the following research questions:

- How are water balance components, flow duration statistics (used for environmental flow allocation) and monthly to annual streamflow projected to change under differing climate projections and emissions scenarios?
- How do streamflow projections under UKCP18 compare to streamflow projections under an MME reflecting a broader range of climate model and emissions uncertainty?
- How do these projected changes differ between a wet coastal and a dry lowland catchment?
- What are the implications for managing river flows and abstractions?

The projected changes to river flow outlined in this chapter provide the climate scenario input for the water resources modelling undertaken in the next chapter.

3.2 Methods

The selection of catchments for the climate impact analysis from the pool of priority catchments was guided by the classification developed in the previous chapter. By selecting the Idle from group 1, a flat, dry slow flowing, lowland river and the Western Rother from group 4, a steep and wet, coastal catchment, two common catchment types could be considered. The differing catchment characteristics were expected to manifest in different responses to climate change and reveal insights relevant to abstraction planning more broadly.

3.2.1 Western Rother

The Western Rother (hereafter referred to as Rother) is 346 km^2 in size and located in southern England in the Hampshire and West Sussex counties (Figure 3.2(a)). The catchment is steep, on average 72.8 m/km (Table 3.1). Elevations range from 2.5 m to 279 m (NRFA, 2019d). Large parts of it are underlain by a highly permeable Lower Greensand aquifer (Environment Agency, 2013a) and the higher lying northern parts of the catchment are underlain by impermeable Weald Clay (NRFA, 2022e). The baseflow index is 0.66[1], indicating the high influence of permeable bedrock (NRFA, 2019e). The Rother is predominantly rural with over 55% of its area being covered by grassland and woodland and 33% by agriculture. Only roughly 8% of the catchment is classified as urban. The most commonly grown crops between 2016 and 2018 were wheat, oilseed rape, maize and sugar beet (CEH, 2018). A highly erodible catchment (Boardman et al., 2020), the typical soil types include well drained sandy and coarse loamy soils as well as slowly permeable clayey soils (NSRI, 2015). The Rother receives 1007 mm of rainfall per year with highest rates of precipitation during the winter months and least during summer and autumn. The difference between the dry and wet months is considerable; between 1998 and 2017, the four driest months – March, May, June and July – received an average of less than 60 mm rainfall while the four wettest months – October, November, December and January - received more than 110 mm (NRFA, 2017b). Due to its coastal location, the inter-annual rainfall variability is also high, ranging from 785 mm to 1399 mm (1998 – 2017 period). While many springs provide a large baseflow component, the Rother is very responsive to rainfall (NRFA, 2019g). The mean natural flow exceeded 95% of time (Q_{95}) at the Rother's outflow in Hardham is 1.6 m^3s^{-1} (basis years: 1998 – 2017). Freshwater withdrawals are mainly required for public water supply (delivering water to 155,000 people) and for agriculture (CPES, 2018). Mean monthly consumptive freshwater withdrawals in the Rother amount to 18.4 m^3s^{-1} (standard deviation: 1.4 m^3s^{-1}) (Environment Agency, 2018a).

3.2.2 Idle

The Idle is located in Yorkshire and Nottinghamshire in the East Midlands (Figure 3.2(b)) and drains an area of approximately 529 km^2 (NRFA, 2019c). It is a predominantly

[1] bfih in Chapter 2

flat lowland catchment with average slopes of only 32.7 m/km (NRFA, 2019a). The catchment is underlain by mixed to highly permeable geologies including magnesium limestone, Sherwood sandstone, alluvium and Mercia Mudstone (Environment Agency, 2020c). The baseflow index is 0.79[1] (NRFA, 2019b). The main land use is arable farming covering 47% of the catchment area. The most commonly grown crops between 2016 and 2018 were wheat, oilseed rape and barley (CEH, 2018). Common soil types in the Idle catchment are well drained sandy and lime-rich loamy soils (NSRI, 2015). The standard average annual rainfall in the Idle catchment is around 689 mm (NRFA, 2017a). Most rain falls in autumn while least rain falls in late winter, the rainfall seasonality is less pronounced than in the Rother and summer rainfall is not distinctly lower than during the other seasons. The driest month March received on average 41 mm between 1998 and 2017 while the wettest month October received on average 71 mm while annual rainfall varied from 462 mm to 951 mm. The Idle is a low energy, slow flowing river system. The mean natural flow at Q_{95} in the catchment's outflow is around 2.5 $^3s^{-1}$ (basis years: 1998 – 2017). Like the Rother, the Idle is an important source of freshwater for irrigation and for public water supply for Severn Trent Water. Mean monthly freshwater withdrawals in the Idle are 46.6 m^3s^{-1} (standard deviation: 12.9 m^3s^{-1}) (Environment Agency, 2018d).

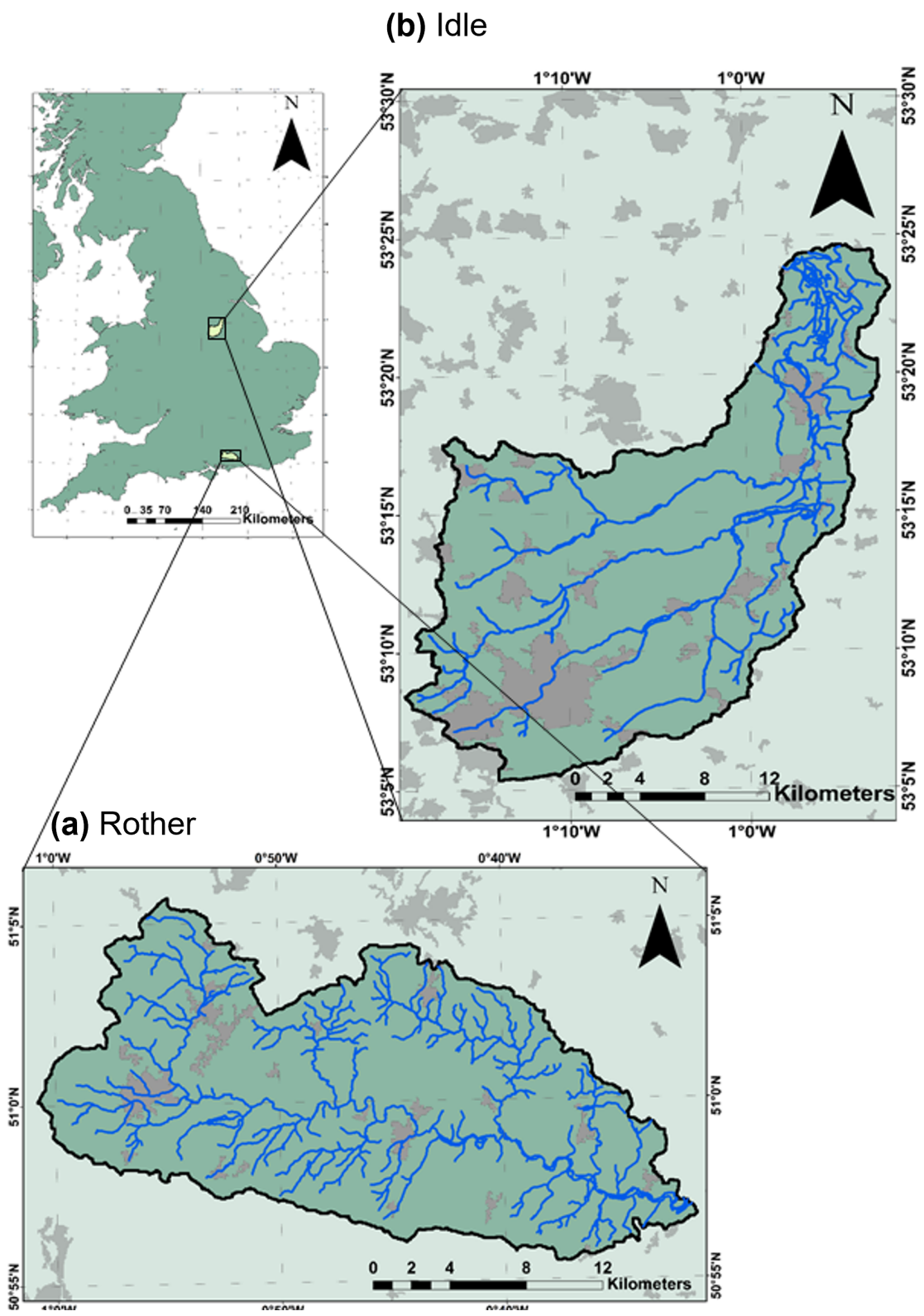


Figure 3.2: Location of the Rother and the Idle in England, (NERC (CEH) Contains Ordnance Survey data © Crown copyright and database right (2022))

Table 3.1: Catchment characteristics (derived from Boardman et al. (2020)[a], NRFA (2019f)[b], NRFA (2019c)[c], NRFA (2017b)[d], NRFA (2017a)[e], NRFA (2019d)[f], NRFA (2019a)[g], NRFA (2019e)[h], NRFA (2019b)[i], NSRI (2015)[j], Environment Agency (2018a)[k], Environment Agency (2018d)[l])

	Rother	**Idle**
Catchment Area (km^2)	346[b]	529[c]
Elevation (m)	2.5 – 279.0[f]	5.7 – 205.0[g]
Gradient (m/km)	steep: 72.8[f]	flat: 32.7[g]
BFI	0.63[h]	0.79[i]
Geology (permeability)	moderate[f]	permeable[g]
Soil types	well-drained sand, coarse loams, slow permeability clay [j]	well-drained sand and lime-rich loams [j]
Land use	woodland / grassland (57%), arable (33%), urban (8%) [f]	woodland / grassland (34%), arable (47%), urban (16%) [g]
SAAR (mm) (standard deviation), (1998-2017)	1007 (169)[d]	685 (117)[e]
Hydrological sensitivity	responsive[b]	low-energy, slow flowing[c]
Q_{95} (m^3s^{-1}) (naturalised)	1.61[k]	2.45[l]
Q_{50} (m^3s^{-1}) (naturalised)	3.39[k]	3.40[l]
Consumptive abstraction at Q_{95} (m^3s^{-1}) (mean %)	0.67 (42%)$_k$	1.56 (64%)[l]
Consumptive abstraction at Q_{50} (m^3s^{-1}) (mean %)	0.61 (19%)[k]	1.53 (46%)[l]
Consumptive abstraction at Q_5 (m^3s^{-1}) (mean %)	0.54 (3%)[k]	2.12 (31%)[l]
mean monthly withdrawal (%)	18[k]	42[k]

3.2.3 Catchment Hydrological Characteristics

While the Idle is larger than the Rother, at 3.40 m^3s^{-1} and respectively 3.39 m^3s^{-1}, the natural flow exceeded 50 percent of the time (Q_{50}) is very similar between the two catchments. With only around two thirds of the rainfall of the Rother, the Idle is considerable

drier. Its soils are wet only around 27% as compared to 34% of the time[2] in the Rother. The high(er) base flow component, flat(ter) terrain, soil types and high(er) permeability moreover indicate high(er) infiltration rates. This reflects in only 18.9% of rainfall contributing to runoff generation[3] as compared to the more responsive Rother where it is 27.4%. The high responsiveness to rainfall combined with considerable differences in rainfall between the dry months (March to July) and wet months, (October to January) translate into high flows in winter and low flows in summer in the Rother. Natural flows at the end of the recharge period in January when rain is falling on saturated soils are on average 284.8 m^3s^{-1} (baseline: 2001-2017). In both catchments the low flow period lasts from July to September. At 68.8 m^3s^{-1}, natural flows in the Rother are lowest at the end of that period in September when groundwater tables are low and there has been little rain since March. The more stable (lower) precipitation rates in the Idle reflect in more stable river flows throughout the year. While at 154 m^3s^{-1} considerably lower than in the Rother, highest flows are also observed in January. Lowest flows are recorded at the beginning of the low flow period in July at on average 85.7 m^3s^{-1}. In the Idle, the recharge period starts earlier, lasts longer and is less concentrated on autumn and winter like in the Rother.

These observations suggest sensitivity to amount and timing of precipitation sustaining summer streamflow and groundwater recharge patterns in both catchments. The Rother's hydrology indicates sensitivity to a shift in the onset of the wet season potentially extending the low flow period to autumn and delaying and slowing groundwater recharge. In the Idle the sensitivity to decreasing summer rainfall is exacerbated by its high infiltration rates. Due to its long(er) recharge period, the Idle is additionally sensitive to autumn rainfall reductions and increasing temperatures altering groundwater – surface water exchange processes. These might affect streamflow in autumn, winter and spring. These sensitivities are amplified by the high rates of freshwater abstraction, particularly in the Idle.

3.2.4 The Hydrological Model SWAT+

To assess potential impacts of climate change on river flows, the HM SWAT+ was chosen. SWAT+ is a completely restructured version of the Soil and Water Assessment Tool (SWAT), one of the most widely used hydrologic models. SWAT is an open access continuous-time, semi-distributed, process-based (deterministic) ecohydrological river basin model. It was developed in the early 1990s with the aim to evaluate the effects of different water management options on water resources (Krysanova and White, 2015). Many climate change impact studies have applied it (see comprehensive reviews of Gassman et al. (2007) and Krysanova and White (2015)). It has recently undergone a complete revision resulting in an improved spatial representation of interactions and processes within a watershed (Bieger et al., 2017). Within the new SWAT+, the Hydrological Response Units (HRUs) are now separate objects. HRUs are areas within

[2]prop in Chapter 2
[3]shost in Chapter 2

a subbasin with a unique combination of land use, soil type and slope. Unlike in previous versions, runoff calculations in SWAT+ factor in HRUs' actual area and their hydrologic interactions can be defined to represent the physical characteristics of the watershed more realistically. Runoff generation is computed for each of the HRUs, aggregated at subbasin level and added to the stream corresponding to each subbasin (Bieger et al., 2019; Bieger et al., 2017). This study used SWAT+ revision 60.5.2 for Linux and to date represents the first SWAT application of UKCP18.

3.2.4.1 Input Data

The land management routines and datasets used for setting up the SWAT+ models for the Rother and Idle catchments are provided in Table 3.2.

Table 3.2: SWAT+ Input Data used for the model setup of Rother (R) and Idle (I) and land management routines used in model calibration.

Data		Resolution	Source
Topography		5 m	Ordnance Survey (2019)
River network		1 : 50,000	Moore et al. (1994)
Land use type		25 m	CEH (2017)
Soil & Soil Properties		∼1.3 m	Cranfield University (2014), NSRI (2015), BGS (2011)
Climate	precipitation & minimum and maximum air temperature	1 km	Met Office (2018a), Hollis et al. (2019)
	humidity	6 stations (R), 7 stations (I)	Met Office (2019), Richardson and Wright (1984), CFSR
	solar radiation	3 stations (R), SWAT+ Weather Generator based on 5 CFSR stations (I)	
	wind	4 stations (R), 4 stations (I)	

Table 3.2 Continued: SWAT+ Input Data used for the model setup of Rother (R) and Idle (I) and land management routines used in model calibration

Land Management

Type of HRU	Crop Rotation	Routine (when)	Source
agricultural	winter wheat⇒grass⇒ rape seed (R)	fertilizer: cow manure, inorganic nitrogen, phosphorous	CEH (2018), Defra (2019)
	winter wheat⇒ winter barley⇒ rape seed⇒ grass (I)	conservation tillage (before winter wheat) max. one ploughing per year	Townsend et al. (2016)
grassland	-	grazing: cattle at medium intensity (spring, summer)	
	-	hay cut (autumn)	

Based on the Digital Terrain Model (DTM), 53 subbasins were delineated for the Rother and 81 for the Idle catchment. Instead of automatic positioning based on the DTM, the burn-in option was applied to position the river network in the catchments based on the 1:50,000 Watercourses dataset by Moore et al. (1994). The structural SWAT+ model setup, the subbasins delineated from the DTM, and the land cover and soil types used for determining HRUs for both catchments are shown in Figure 3. To limit computation time, HRUs with less than 3 ha were merged with neighbouring HRUs, resulting in 1875 and 1909 HRUs for the Rother and Idle, respectively.

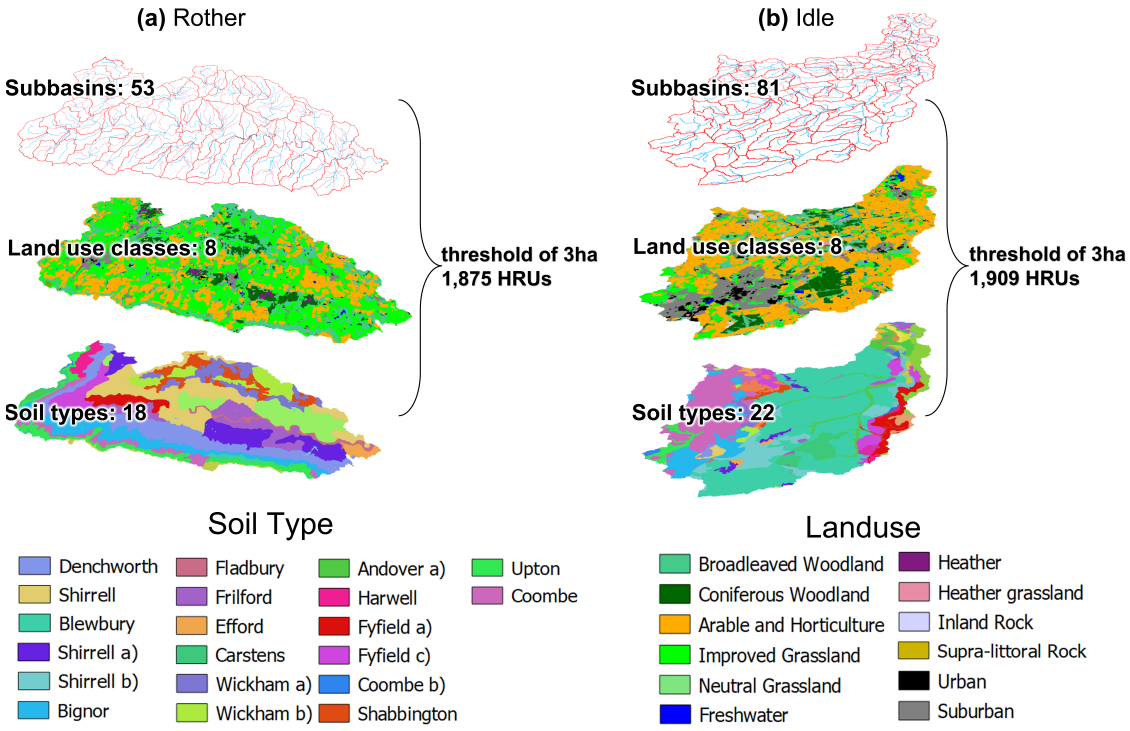


Figure 3.3: SWAT+ Model Structure for Rother (a) and Idle (b), number of subbasins, land use classes, soil types and resulting Hydrological Response Units (HRUs) (Soils Data © Cranfield University (NSRI) and for the Controller of HMSO [2022], Land Cover Map © CEH (2017), Contains Ordnance Survey data © Crown copyright and database right (2022)).

For temperature and precipitation, the 1-km HadUK gridded observations datasets provided by the Met Office and described by Hollis et al. (2019). The MIDAS station data was used for wind, solar radiation and relative humidity (Met Office, 2019). Due to the limited MIDAS station coverage, solar radiation in the Idle was simulated with the SWAT Weather Generator using long-term statistics from the five closest stations in the global Climate Forecast System Reanalysis (CFSR) dataset (https://globalweather.tamu.edu/#pubs).

3.2.4.2 Flow Naturalisation

As both catchments are highly influenced by water abstractions (Table 3.1), model set-up and testing required naturalising the observed, gauged daily streamflow data at the main watershed outlets (available from the NRFA). Several steps were undertaken to receive credible naturalised flows and the process relied on the Environment Agency Catchment Abstraction Management System (CAMS) (Environment Agency, 2001, 2021c). This spreadsheet tool includes all abstraction information and calculates natural flow duration curves based on gaugings and daily and monthly licenses and reported recent actual groundwater and surface water abstraction rates. Depending on the catchment it is linked with other hydrological software such as LowFlows 2 (https://www.hydrosolutions.co.uk/software/lowflows2/). It provides the most detailed

information on licensed versus actually abstracted volumes and their locations. For groundwater it additionally provides estimated effects on adjacent surface water. It is used for license and abstraction management as well as environmental flow planning in the EA (R. Soley 2019 personal communication, 5 July).

It is possible to directly compute abstraction in SWAT+, however this would require information on location, rates of withdrawals and discharges which is not publicly available. Furthermore, next to the large withdrawals for public water supply, CAMS documents over 200 small to medium licensed surface and groundwater abstractions at a minimum of 20 m^3day^1 in both catchments (Environment Agency, 2018a,d). These would have to be adequately represented in both catchment models. To receive naturalised monthly flows for this study, the flow duration influences were instead extracted from CAMS and used to interpolate across the NRFA daily gauged flows. This means that every point on the flow duration curve is assumed to be abstracted by a certain rate that remains stable across the naturalisation period, i.e. consumptive abstractions at Q_{50} in the Rother are considered to always be 19%. As CAMS information is limited to the most recent years, the baseline period of this study is 2001 to 2017.

There is no CAMS assessment point close to the location of the gauge in the Idle. Naturalisation for this flow series was done with a combination of CAMS data and outputs from the Sherwood Sandstone groundwater Model (Farren et al., 2012; Shepley and Soley, 2009) to account for the complex groundwater situation. Calibration and validation of SWAT+ was undertaken on a monthly basis and daily naturalised flows were only considered in the evaluation of model performance in simulating high and low flows with bias corrected climate data.

3.2.4.3 Sensitivity Analysis and Calibration

A Fourier amplitude sensitivity test (Fourier Amplitude Sensitivity Testing (FAST)) (Cukier, 1975) was run to determine key parameters influencing hydrological processes within the model. FAST is a global sensitivity analysis where all SWAT+ parameters are changed at the same time and the sensitivity of a model output for the entire possible range of model inputs is considered (Gupta and Razavi, 2017; Pianosi et al., 2016). This study assessed 9188 different combinations of 34 parameters (given in Table B.2). Those model parameters with an effect on the performance criteria (described below) were used for calibration.

The models were calibrated using data from 2001 - 2008 and validated for the period 2009 - 2017. These periods contain both wet (2008, 2012) and dry years (2003, 2010) and years with average rainfall (2001, 2005, 2006, 2009, 2010, 2013). The validation period is however on average drier than the calibration period (Met Office, 2023). The first year of simulation was 1998 to allow for a three-year spin-up period. The sensitive parameters were calibrated in a further 10,000 model simulations, each with a different parameter value combination sampled through Latin Hypercube (McKay et al., 1979). The best parameter combinations were determined using the performance cri-

teria. These parameter combinations were then tested for their performance during the validation period. Hydrological model parameters and their calibration represent a major source of uncertainty in hydrological climate impact analyses (Beven and Smith, 2015). To reflect this uncertainty and include the effect of different parameter settings in the climate impact analysis, the 50 parameter sets that performed best in the validation period were used in the subsequent climate impact analysis (e.g. Beven and Binley, 1992, 2014; Teutschbein and Seibert, 2012; Yang et al., 2014).

3.2.4.4 Performance Criteria

To assess hydrological model performance during sensitivity analysis, calibration and validation, five numerical efficiency criteria were analysed. The most widely used efficiency criterion is the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). However, the NSE is biased against high flows (Mizukami et al., 2018; Zhang et al., 2011) and model selection therefore used the inverse NSE (NSE_{inv}; Le Moine (2008)) which shows no sensitivity to high flows and allows to focus on the lowest 20% of flows (Pushpalatha, 2013). The Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) was chosen because it is better than the NSE for evaluating performance in flow variability. The other criteria included in the analysis were the modified Coefficient of Determination (R^2) bR^2 (Krause et al., 2005), calculated by multiplying R^2 by the coefficient of the regression line b, thepercent bias (pbias) and the Volumetric Efficiency (VE) that measures the ratio of water delivered at the right time (Criss and Winston, 2008). 50 parameter combinations were selected based on good or very good performance across all five efficiency criteria, although a few runs were chosen that maximised individual performance criteria while performing at acceptable ranges across the remaining criteria. The effects of this isolated optimisation were then briefly assessed by analysing if any of these parameter sets were part of these 20% driest and 20% wettest simulation runs. Furthermore, the variability introduced by different SWAT+ parameters was approximated by analysing the standard deviation within the different climate ensembles.

3.2.5 Climate Change Assessment

3.2.5.1 Climate Scenarios

To produce estimates of future river flow for the two catchments in England using SWAT+, this study applied the UKCP18 Regional (12 km) Projections (Murphy et al., 2018). This is one of several, complementary sets of projections (including a set of global climate simulations and a set of probabilistic projections) based on the updated and improved UKCP18 model. Each has their own benefits and ideally should be used together to gain maximum insight to a particular problem, although practically this is not always possible.

Few studies have evaluated UKCP18 for hydrological climate impact assessments. Using the change factor method, Kay et al. (2019) compared streamflow projections under the probabilistic projections from UKCP09 with those from UKCP18 and found central estimates to be similar but UKCP18 probabilistic uncertainty ranges to be larger. Kay (2021) applied the UKCP18 Regional Projections in a national-scale climate impact analysis using a grid-based hydrological model and found a large model spread in projections, particularly in winter – the clearest signal was projected for summer with median streamflow decreases of -45%.

The Met Office (2018b) guidance suggests that the UKCP18 Regional Projections are appropriate for catchment-scale hydrological modelling applications owing to their enhanced spatial detail, the fact they are spatially and temporally coherent and improve consideration of extremes and provide direct access to 'raw' climate model data. Using another UKCP18 product such as the probabilistic projections would increase the emissions uncertainty considered and would be appropriate for contextualising the Regional Projections but does not provide time series with which to directly drive hydrological models in a comparative manner. The statistical post-processing the probabilistic projections require implies a limited spatial, physical and temporal coherence and they are not recommended for impact assessments that want to reflect a wide range of climate change indicators and changes in climatic phenomena such as the North Atlantic Oscillation (Murphy et al., 2018).

The Regional Projections' time series of changes in climate variables at 12 km (0.11°) resolution were derived from 12 RCM variants. They were produced through dynamic downscaling using a PPE of RCM variants (PPE-RCMs) of 12 global versions of HadGEM-GC3.05. The perturbations of the global models are hence mirrored in the RCMs. To date this PPE lends itself for considerations of risks under a high emissions pathway only as it is solely available for RCP 8.5 (Murphy et al., 2018). One PPE member uses the standard RCP8.5 whereas the other members were produced using plausible pathways consistent with how emissions are converted in carbon cycle feedbacks under RCP8.5 (Murphy et al., 2018)[4]. As previously stated, the largest share of uncertainty in hydrological climate impact modelling is due to GCM uncertainty (Hattermann et al., 2018; Her

[4]The final CO2 pathways for the remaining PPE members were selected based on several steps of performance filtering, the last step maximising between-member independence in variation in CO2 and aerosol forcing as well as climate feedback strength (page 53 in Murphy et al. (2018))

et al., 2019; Vetter et al., 2016), these RCM projections should therefore be combined with projections from MMEs (Murphy et al., 2018). This allows to study impacts in a more comprehensive manner (Yamazaki et al., 2021). Murphy et al. (2018) concede the limitations associated with a single model and emissions scenario (sampling a narrower range of potential future outcomes) and suggest using the Coordinated Downscaling Experiment–European Domain (euro-CORDEX) multi-model RCM simulations (Jacob et al., 2014) to explore other potential futures.

The analysis was hence extended with the euro-CORDEX (eCX) projections. This facilitated to delineate where the UKCP18 projections sit within the broader context of climate change hydrological modelling uncertainty. It revealed how projections of future river flows may be influenced by emissions and GCM (structural) uncertainty and increased robustness of results for catchment managers. The eCX initiative (Jacob et al., 2014) offers a substantial number of simulations using different configurations including two more RCPs (2.6 and 4.5) and inputs from nine CMIP5 GCMs in combination with thirteen RCMs (Taylor et al., 2012). They were produced using a common model domain for Europe at a resolution of 0.11° and have been extensively scrutinised in hydrological impact assessments (Pastén-Zapata et al., 2020; Vu et al., 2019). 18 GCM-RCM combinations (Table 3.3) from the eCX project were chosen; six combinations for the historical period and each of the three RCPs 2.6, 4.5 and 8.5 (Moss et al., 2010).

Table 3.3: General Circulation Model (GCM) and Regional Climate Model (RCM) combinations and their Representative Concentration Pathways (RCPs) used in this study

RCP	Institute	Driving GCM	RCM	Name in this study
8.5	Met Office Hadley Centre (MOHC)	HadGEM3-GC3.05	12 PPE, HadREM3-GA7-05	UKCP18
8.5	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CNRM-CM5	ALADIN63	CNRM-ALADIN
8.5	Norwegian Climate Centre (NCC)	NorESM1-M	HIRHAM5	NCC-HIRHAM
8.5	Institut Pierre Simon Laplace (IPSL)	IPSL-CM5A-MR	WRF381P	IPSL-WRF
8.5	Institut Pierre Simon Laplace (IPSL)	IPSL-CM5A-MR	REMO2015	IPSL-REMO
8.5	Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-LR	ALADIN63	MPI-ALADIN

8.5	Met Office Hadley Centre (MOHC)	HadGEM2-ES	HadREM3-GA7-05	HAD-HAD
4.5	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CNRM-CM5	RACMO22E	CNRM-RACMO
4.5	Irish Centre for High-End Computing (ICHEC)	EC-EARTH	RCA4	EC-RCA
4.5	Institut Pierre Simon Laplace (IPSL)	IPSL-CM5A-MR	RCA4	IPSL-RCA
4.5	Norwegian Climate Centre (NCC)	NorESM1-M	REMO2015	NCC-REMO
4.5	Institut Pierre Simon Laplace (IPSL)	IPSL-CM5A-MR	WRF381P	IPSL-WRF
4.5	Met Office Hadley Centre (MOHC)	HadGEM2-ES	RACMO22E	HAD-RACMO
2.6	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CNRM-CM5	RACMO22E	CNRM-RACMO
2.6	Irish Centre for High-End Computing (ICHEC)	EC-EARTH	RCA4	EC-RCA
2.6	Irish Centre for High-End Computing (ICHEC)	EC-EARTH	HIRHAM5	EC-HIRHAM
2.6	Max Planck Institute for Meteorology (MPI-M)	MPI-ESM-LR	RCA4	MPI-RCA
2.6	Norwegian Climate Centre (NCC)	NorESM1-M	REMO2015	NCC-REMO
2.6	Met Office Hadley Centre (MOHC)	HadGEM2-ES	HadREM3-GA7-05	HAD-HAD

To best complement the UKCP18 and explore streamflow implications under a wide climate model and emissions uncertainty, the aim was to include a high number of GCMs across all available RCP. Unfortunately, as detailed in the introduction, eCX does not allow the construction of a perfectly balanced ensemble for the required domain, resolution and climate variables. Systematically evaluating the sources of uncertainty introduced by GCM, RCM and RCP was therefore not possible. The ensembles across the three RCPs are made up of 6 pairs of different GCM-RCM. IPSL-CM5A-MR is dominant as it

drives two of the RCMs under RCP 8.5 and two under RCP 4.5, while EC-EARTH drives two of the RCMs for RCP 2.6. The highest RCP allows direct comparison between the UKCP18 and eCX projections driven with five different GCMs. The unperturbed standard configuration RCM used in the UKCP18 (ensemble member 1, Table B.1) was also used in eCX where it is called HadREM3-GA7-05. Driven by HadGEM2-ES it is included for RCP8.5 and for RCP2.6. This GCM is the predecessor of the HadGEM3-GC3.05 – the GCM used to drive the UKCP18 PPE. To gain an insight into the variability introduced by the different climate projections and SWAT+ parameters, the standard deviation within (intra-ensemble) and between (inter-ensemble) GCM-RCM members for each ensemble across the year was quantified.

The UKCP18 Regional Projections (hereafter referred to as UKCP18) and the eCX initiative provide a range of climate variable simulations; six were used in this study: minimum and maximum temperature, wind speed, humidity, precipitation and shortwave radiation. While originally produced on the eCX latitude – longitude grid, the UCKP18 are published re-projected on the GB national grid – aligning with the other input data such as land use and soil datasets. For use in this study the 18 eCX projections were hence re-projected to align with the GB national grid. The 30 GCM-RCM combinations' daily time series for these six variables were applied to force the HM for 1998 to 2080.

3.2.5.2 Bias Correction

The 12 UKCP18 and the 18 eCX projections for temperature and precipitation show systematic differences when compared to observations and post-processing is usually required prior to using RCMs to simulate future streamflow (Fung, 2018). A range of methods have been described for bias correcting regional climate model outputs, with performance varying depending on the modelling chain and the studied area (Maraun, 2016). In this study, temperature and precipitation were bias corrected independently with linear scaling (LS). LS is one of the simplest bias correction techniques in which solely the mean value of the RCM time series is adjusted (Lenderink et al., 2007). In the guidance for bias correcting UKCP18, Fung (2018) emphasises that this approach represents the minimum correction needed to attain meaningful results. Unlike some more complex methods, LS is inherently trend preserving and has previously been shown to be adequate for hydrological analyses on the monthly scale (Chen et al., 2016; Gutjahr and Heinemann, 2013; Shrestha et al., 2017a). Two further bias correction methods relying on quantile mapping were applied but neither was found to beat LS with regards to performance in the historical period and trend preservation (section B.3.2). This agrees with the findings by Chen et al. (2016) who showed that the corrections to additional details of hydrological statistics often get buried within the ranges of natural variability. This study therefore focuses on LS, all analyses and results were also produced for the two quantile mapping methods and are included in section B.3.

The bias corrected temperature RCM projections were obtained by adding a constant offset to the entire time series. This offset is the average difference between observa-

tions and simulations for the historical period (25 years in this case: 1980-2005). This preserved the absolute change as well as the variability of the simulated temperature in the projections. Minimum and maximum daily temperature were bias corrected separately. The trend preservation for precipitation was achieved with a multiplicative factor received by dividing the total observed precipitation by the total simulated precipitation in the historical period. The transfer functions were derived for the historical period 1980 – 2005 and applied to 1998 – 2080, after the UKCP18 RCMs and, where needed, the eCX projections were linearly interpolated to the standard Gregorian calendar (365 days plus leap days) to match the temporal resolution of the observations and of SWAT+. The 1 km daily HadUK gridded climate was used as the observations dataset. The historical period from 1980 to 2005 was chosen because the UKCP18 projections start in December 1980 (the eCX simulations start in 1951). The eCX and UKCP18 projections both begin in 2006. To analyse the performance of LS in reducing the biases of the climate datasets, naturalised observed streamflow was compared to SWAT+ simulated streamflow driven with observations (simobs), driven with uncorrected climate simulations and with LS-corrected climate simulations.

3.2.5.3 Hydrological Indicators

The 50 calibrated and validated SWAT+ models were run for both study catchments from 1998 to 2080, including a 3-year warmup period (1998 to 2001). They were forced with the 12 different UKCP18 RCMs and with the 18 eCX ensemble members' climate projections. They hence contain 50 simulations for each of the 30 ensemble members totalling 300 simulation runs per each of the three eCX ensembles (= 900 eCX simulations) and 600 simulations for UKCP18. Both corrected and bias-corrected climate projections were used. Projected changes were first assessed for temperature and precipitation and the overall catchment water balance to better understand underlying climate and catchment processes. Projected changes to standard hydrological metrics used in water management were then evaluated: mean annual and mean monthly flow (absolute and percentage change) and Flow Duration Curve (FDC) statistics (Q_5, Q_{30}, Q_{50}, Q_{70}, Q_{95}). The latter signify a range of flow conditions; from high flows that are exceeded five percent of the time (Q_5), to the low flow volume that is exceeded 95% of the time (Q_{95}). Metrics were evaluated for 3 different time periods (near (2021-2040), intermediate (2041-2060) and far future (2061-2080)) relative to the 2001-2017 reference period. All results were calculated based on hydrological years, the year 2021 hence beginning 1st of October 2020, ending 30th of September 2021.

3.3 Results

The HM SWAT+ was successfully calibrated and validated for both catchments. The bias correction improved the performance of streamflow simulations under modelled climate for all ensembles. For both catchments, the calibrated models were applied to produce streamflow projections under the bias corrected UKCP18 and eCX until 2080.

3.3.1 SWAT+ Model Performance

3.3.1.1 Sensitivity Analysis

Of the 34 parameters considered in the sensitivity analysis (Table B.2), eleven were found to be sensitive and have a measurable effect on efficiency parameters in the Rother and twelve in the Idle. Ground- and soil water exchange processes play an important role in these catchments, both have highly responsive aquifers, the Rother has moderately permeable soils and the Idle is dominated by highly permeable soils. These characteristics reflected well in the models' sensitive parameters. Return flow from aquifer storage (flo_min) and the parameter adjusting soil moisture for percolation to occur (perco) were influential in both catchment models. These parameters represent opposing water movement through the ground, the former controls the minimum aquifer storage required for return flow while the latter controls the relationship between soil moisture content and percolation to aquifers (USDA-ARS & Texas A&M AgriLife Research, 2020). In the Rother the depth of the soil layer (z) was sensitive in all efficiency parameters while in the more groundwater dominated Idle the baseflow recession constant (alpha) played an important role. Soil layer depth is related to the simulation of soil water content, soil water availability and water holding capacity (Zare et al., 2022), while alpha describes the intensity with which the (shallow) aquifer responds to changes in recharge (Rycroft and Smedema, 1983), it is strongly related to physical watershed characteristics such as hydraulic conductivity (Brutsaert and Nieber, 1977). Both models showed sensitivity to changes in parameters controlling the surface response, specifically the curve number for determining runoff at average soil moisture (cn2) and the plant uptake compensation factor (epco). Sensitive subsurface response parameters were those controlling biomass density (bd) and available soil water capacity (awc). These sensitive parameters were considered for model calibration and validation (Table B.2 in appendix section B.2).

3.3.1.2 Calibration & Validation

Following sensitivity analysis, the 50 best parameter combinations were determined through calibration and validation and used to simulate streamflow for both catchments and both periods. Modelled flows were compared with the naturalised observed streamflow (Figure 3.4) and the performance assessed across monthly values of the five efficiency criteria (Table 3.4). All Rother models systematically overestimated flows (wet bias) during the calibration period reflected in positive pbias in all simulations. However, this bias was smaller and more balanced during validation. The Rother simulations

Table 3.4: SWAT+ performance during calibration and validation

	Calibration 2001 - 2008	**Validation** 2009 - 2017
Rother		
pbias (%)	5.1 - 14.9	-4.4 - 5.9
VE (%)	0.8 - 0.85	0.75 - 0.8
bR^2	0.77 - 0.83	0.78 - 0.83
KGE	0.65 - 0.8	0.54 - 0.75
NSE/NSE_{inv}	0.7 - 0.81 | 0.81 - 0.95	0.6 - 0.74 | 0.61 - 0.87
Idle		
pbias (%)	-2.8 - 9.3	-8.9 - 1.9
VE (%)	0.86 - 0.91	0.83 - 0.88
bR^2	0.79 - 0.87	0.71 - 0.81
KGE	0.71 - 0.93	0.73 - 0.88
NSE/NSE_{inv}	0.71 - 0.88 | 0.69 - 0.77	0.66 - 0.79 | 0.66 - 0.8

furthermore showed a dry bias in October and a wet bias for the whole of winter (Figure 3.5a). During the calibration the winter floods of 2002 and during the validation those of 2014 were overestimated. However, Rother models performed very well at simulating low flow months with all models' NSE_{inv} at over 0.81 for the calibration and over 0.61 for the validation period. While the NSE_{inv} was good in all Idle models with over 0.65 in both periods, in both calibration and validation period the lowest monthly flows were often simulated too late (2003, 2005, 2006, 2011, 2015), too low (2003, 2011, 2015, 2016) or not low enough (2005, 2006) by all or a large share of model runs. This also reflected in October and September flows that were generally simulated as too low and in the wet bias in June and July (Figure 3.5b). However, the timing of streamflow volume was generally simulated better in the Idle models than in the Rother models with all runs for both periods succeeding in simulating over 80% of flow volume at the right time (VE). Generally, most models for the two catchments were classed as having 'good' or 'very good' performance according to the efficiency criteria with values greater than 0.65 for bR^2 and NSE_{inv}, greater than 0.75 for VE and KGE and a pbias of less than 15% (these thresholds were taken from Kouchi et al. (2017), Moriasi et al. (2007), and Rocha et al. (2020)).

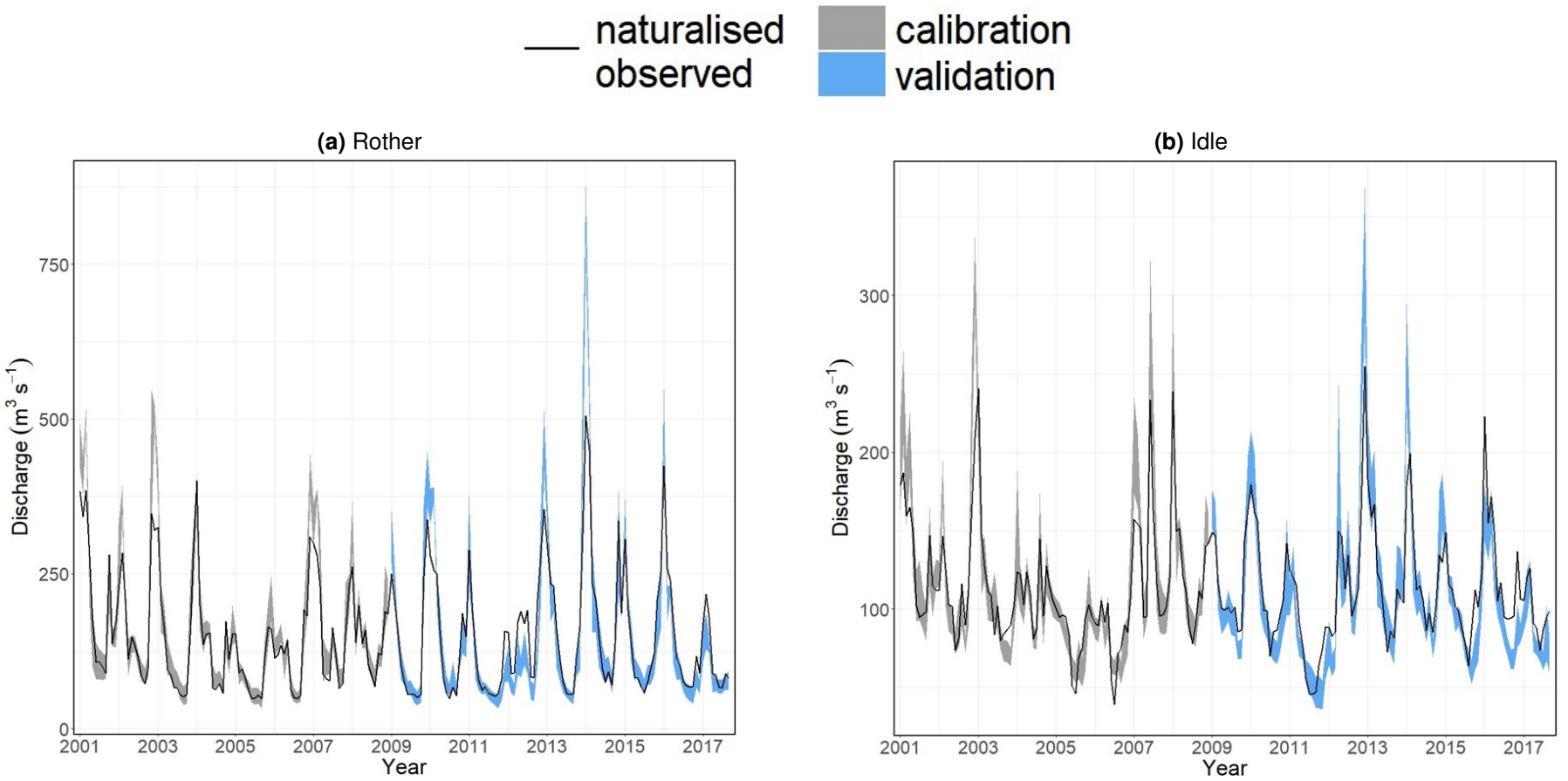


Figure 3.4: Comparison of the observed and simulated monthly discharge of Rother (a) and Idle (b) for 2001-2017. SWAT+ simulations were driven by observed climatology and are shown as a range considering the 50 best parameter combinations

3.3.2 Performance of bias corrected regional projections

Bias correction using LS improved the streamflow simulations using both sets of climate projections and therefore enhanced the credibility of subsequent climate impact analyses. Improvements were however variable between catchments, climate projections, and performance criteria. Figure 3.5 and Figure 3.6 show a comparison of SWAT+ run with observed climate (simobs) with the bias corrected simulation runs under UKCP18 and across the three eCX ensembles.

In both catchments bias correction strongly reduced the wet bias in both monthly as well as daily streamflow simulations (Figure 3.6) and the mean and median of the pooled ensembles are close to simulations run with observed climate (Figure 3.5). After correction, the simulations aligned more closely in the performance criteria, most notably in the eCX for the Idle that show a high range in the raw simulations. The model spread was larger in the Idle than in the Rother. Daily and monthly mean flows were most strongly reduced for the eCX ensembles, most notably for low and medium emissions in the Idle, where streamflow simulations driven with bias corrected climate were lower than under observed climate (simobs, Figure 3.6g and Figure 3.6h). In the Rother, simulated discharge under bias corrected climate simulations matched observations more closely for eCX than for UKCP18 (Figure 3.5a). In the Idle models, the reverse applied with simulated mean annual streamflow closer to observations for the UKCP18 than for the eCX, which presented as too dry across the whole year. For the different performance criteria, the general pattern of improvement appear consistent between projections and catchments, with some exceptions (Figure 3.6). In particular, the NSE_{inv} and bR^2 values did not improve for any ensemble in the two catchments and results for pbias lfv were consistent between catchments – while a large share of raw and corrected low flow simulations performed well in the Rother models, bias correction could not eliminate the systematic dry bias in low flow processes in the Idle displayed in the models run with observed climate (simobs). The performance of high flow simulations was however improved through bias correction in both catchments.

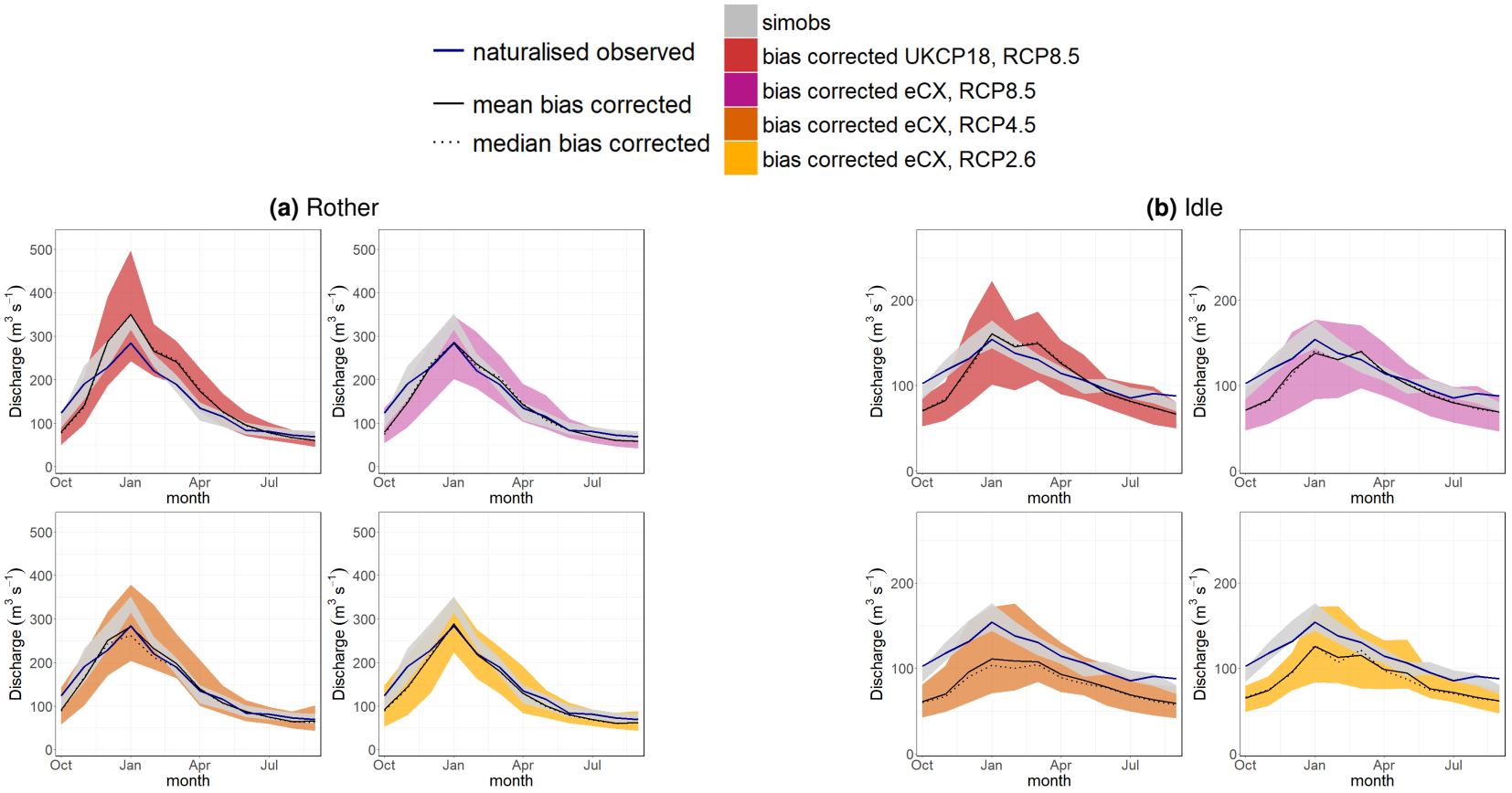
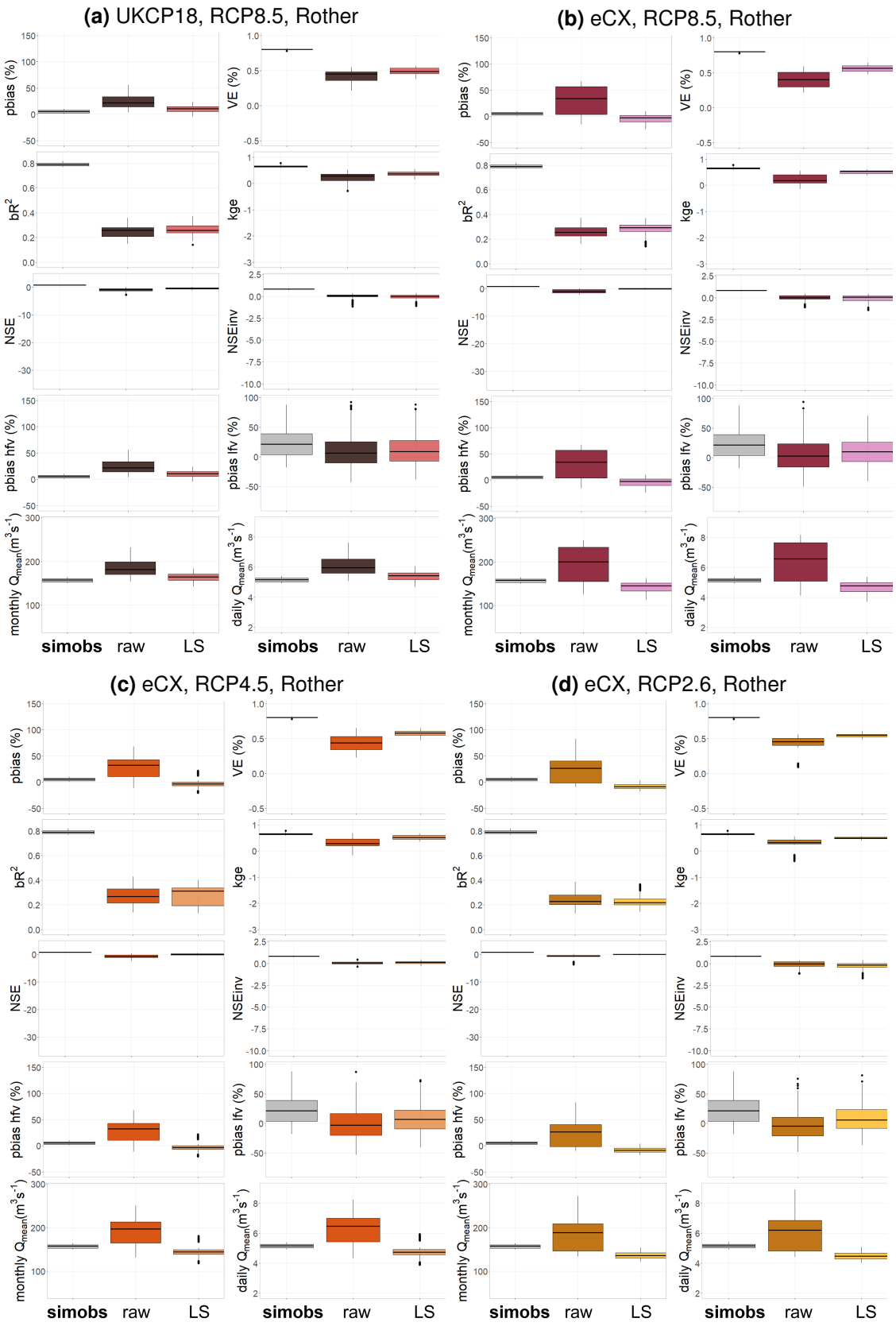


Figure 3.5: Comparison of simulated mean monthly discharge driven by observations (simobs) and by UKCP18 and euro-CORDEX (eCX) climate projections bias corrected with Linear Scaling (LS) with naturalised flow observations over the reference period (2001 – 2017) for the Rother (a) and Idle (b).


(a) UKCP18, RCP8.5, Rother
(b) eCX, RCP8.5, Rother
(c) eCX, RCP4.5, Rother
(d) eCX, RCP2.6, Rother
pbias (%)
VE (%)
bR2
kge
NSE
NSEinv
pbias hfv (%)
pbias lfv (%)
monthly Qmean(m3s-1)
daily Qmean(m3s-1)
simobs
raw
LS

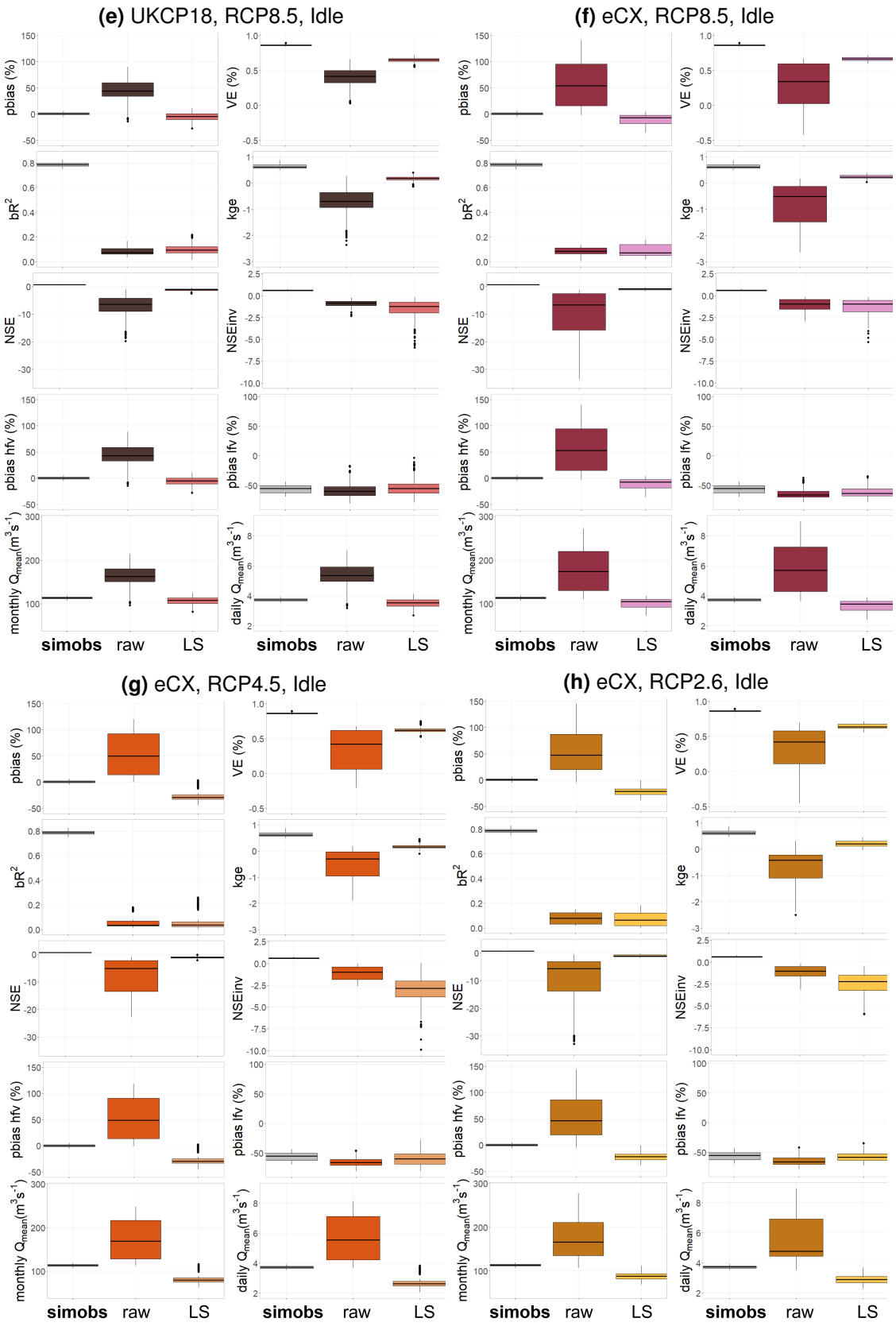


Figure 3.6: Model performance during the calibration and validation period (2001-2017). Models run with observed climate (simobs), uncorrected "raw" simulated UKCP18 and euro-CORDEX (eCX) climate and with Linear Scaling (LS) - bias corrected climate simulations. Monthly performance according to percent bias (pbias), Volumetric Efficiency (VE), modified Coefficient of Determination (bR^2), Kling-Gupta Efficiency (KGE), Nash-Sutcliffe Efficiency (NSE), inverse NSE (NSE_{inv}) and in mean monthly flows, daily performance according to pbias in high flow volume (hfv, Q_{30} to Q_5) and low flow volume (lfv, Q_{70} to Q_{95}) and in mean daily flows,for the Rother (a-d) and Idle (e-h).

3.3.3 Projected Changes to the Hydrological Cycle

To gain an understanding of relevant processes underlying streamflow response to climate change and differences between projections in the catchments, the projected changes to the hydrological cycles of the two catchments and across the four ensembles were assessed. Figure 3.7 shows the climate data used to force SWAT+ summarising the changes in the long-term monthly dynamics of temperature and precipitation between the far future (2061-2080) and the reference period (2001-2017). It is underpinned by six climate projections per eCX ensemble and by 12 UKCP18 projections.

The patterns of change in temperature and precipitation are similar in the two basins. The UKCP18 suggest seasonal changes with increasing rainfall in winter and decreasing rainfall with at the same time increasing temperatures in summer. The eCX present as wetter and imply less distinct changes. Temperature is projected to increase in both catchments throughout the year, most pronounced in summer, only the low emissions project some decreases in winter and spring. The main difference between UKCP18 and eCX lies in stronger summer and autumn increases; the former project beyond three degrees for all summer and autumn months in both catchments. The differences in forcing across the ensembles reflects more clearly in temperature than in precipitation with magnitudes of temperature change increasing from RCP2.6 to RCP8.5. Under the high emissions ensembles, particularly under UKCP18, changes in temperature play a larger role in future hydrology than under the low and medium emissions.

The UKCP18 project precipitation to increase from December to April and to decrease from May to October in both catchments, most pronounced in the Rother (Figure 3.7a). The high emissions eCX project increases in October and from December to March and decreases from May to September, yet at smaller magnitudes. Across all emissions scenarios, eCX project increases for October compared to decreases found for UKCP18. Under low and medium emissions, a more variable pattern is seen. Precipitation is projected to increase from October to December under both scenarios in both catchments, least clear in November. The ensemble median of RCP4.5 project decreases from June to September in the Rother and for March, May and June in the Idle. Under RCP2.6 decreases are projected for January, February and July in the Rother and for July and August in the Idle. Under lower forcing, the climate signal is stronger masked by model internal variability. In the Rother, a catchment with high inter-annual variability in observed precipitation, the model spread for projected precipitation changes is large, particularly under RCP2.6 in spring and autumn. Table 3.5 shows an overview of changes in the components of the hydrological cycle by the far future (2061-2080) relative to the reference period, specifically in PCP, AET and PET, Surface Runoff (SR) and the Budyko aridity index (potential evaporation divided by precipitation) across the four ensembles. It includes the mean magnitude of change as well as the percentage of the runs (300 runs per eCX /RCP and 600 for UKCP18 RCP 8.5, bias corrected with LS) that agree on the direction of change indicated by that mean.

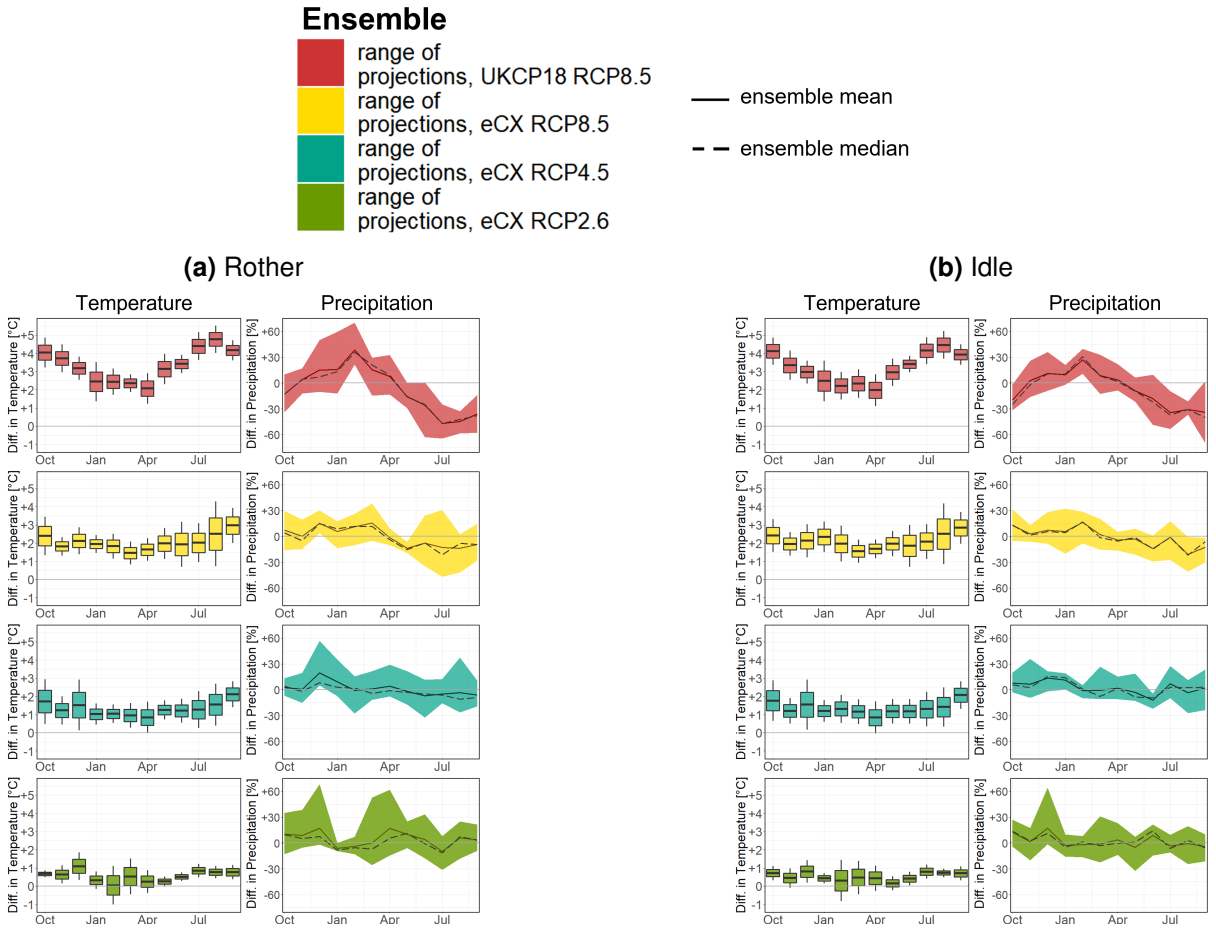


Figure 3.7: Projected percentage changes in long-term mean monthly temperature and precipitation between the reference and far-future period (2061 - 2080), projected by the UKCP18 and euro-CORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b), (n=6 per eCX ensemble, n=12 for UKCP18).

Table 3.5: Changes in the Budyko aridity index (Potential Evapotranspiration (PET)/acfPCP), Precipitation (PCP), surface runoff and Actual Evapotranspiration (AET) in Rother and Idle for the far future period (2061-2080). Agreement across all ensembles, the direction of change is considered to be 'likely' when at least 66% of all simulations agree in the direction (IPCC, 2014b) (n=300 per eCX ensemble, n=600 for UKCP18).

			Rother			Idle		
			magnitude of change (%)	**direction of change**	**agreement (%)**	**magnitude of change (%)**	**direction of change**	**agreement (%)**
Aridity Index	UKCP18	RCP8.5	+33.5	++++	100.0	+37.6	++++	100.0
	eCX	RCP8.5	+8.8	+	83.3	+12.2	++	83.3
		RCP4.5	+3.3	minor	66.7	+2.7	minor	66.7
		RCP2.6	-2.3	minor	66.7	-0.3	minor	50.0
PCP	UKCP18	RCP8.5	-2.1	minor	58.3	-6.8	–	91.7
	eCX	RCP8.5	+2.1	minor	66.7	-1.5	minor	66.7
		RCP4.5	+1.8	minor	83.3	+1.8	minor	66.7
		RCP2.6	+4.5	minor	100.0	+1.5	minor	83.3
runoff	UKCP18	RCP8.5	+10.7	+	84.8	-24.8	– – –	95.0
	eCX	RCP8.5	+20.4	++	86.3	-6.0	–	66.7
		RCP4.5	+13.0	++	91.0	+16.1	++	67.7
		RCP2.6	+12.3	++	83.3	+8.2	+	53.7
AET	UKCP18	RCP8.5	-10.5	–	99.5	-4.4	minor	85.5
	eCX	RCP8.5	-6.3	–	99.7	-0.3	minor	60.7
		RCP4.5	-4.2	minor	95.3	-0.2	minor	50.0
		RCP2.6	+0.6	minor	66.7	+0.1	minor	50.3
PET	UKCP18	RCP8.5	+30.2	++++	100.0	+27.7	+++	100.0
	eCX	RCP8.5	10.7	+	83.3	+10.2	+	100.0
		RCP4.5	+5.2	+	100.0	+4.4	minor	100.0
		RCP2.6	+2.0	minor	83.3	+1.8	minor	100.0

Legend,(%):

– – – –	<-30	++++	>+30
– – –	-21 to -30	+++	+21 to +30
– –	-11 to -20	++	+11 to +20
–	-5 to -10	+	+5 to +10
		minor	-5 to +5

Both catchment models display high responsiveness to precipitation and AET which lead to changes in the water balance. In the Rother, which is part of the wet and steep group of mostly coastal catchments, all ensembles project only minor differences in

overall precipitation, negative under UKCP18 and positive under the three eCX ensembles. Nevertheless, mean surface runoff is projected to increase across all scenarios, on average $>$10%, despite some differences across the other water balance components – in particularly evapotranspiration. As indicated through the stronger increases in temperature outlined above, temperature-driven evaporative processes play an important role in the models driven with UKCP18. These project strong increases in aridity in the Rother, driven largely by growing PET, subject to increasing temperatures. While less pronounced, these processes are also observed in eCX driven with RCP8.5, while RCP2.6 and RCP4.5 project the ratio of PET and PCP as well as AET to remain practically stable.

The projected changes to the water balance of the Idle which is part of the group containing dry, flat lowland catchments, suggest that runoff decreases under both UKCP18 and eCX for RCP8.5. Under UKCP18, small decreases in precipitation translate into substantial runoff decreases accompanied by strongly increasing aridity. Under the low and medium emissions on the other hand, the signal of change is reversed and runoff is projected to increase under only minor increases in overall precipitation. Runoff increases are higher under RCP4.5 than under RCP2.6. AET is practically stable under both emissions scenarios and in both there is little agreement on the direction of change in AET across ensemble members.

These findings suggest that other characteristics not reflected in the overall water balance play a role in determining hydrologic climate response. Despite similar timings of climatic changes, such as decreasing precipitation from May to October under UKCP18, the two catchments' physical characteristics and hydrological sensitivities imply distinctively different hydrological responses to climate change.

3.3.4 Projected Changes to Streamflow

The projected changes to streamflow vary between the two catchments, RCPs and time periods (monthly, seasonal changes and considered time frames) in addition to the climate ensembles. The strongest changes and the highest range of estimates are projected under UKCP18.

In the Rother the streamflow largely responds with decreases under decreasing precipitation and vice versa. Streamflow in the Idle also decreases under decreasing precipitation but is not as reactive to increasing precipitation. Annual streamflow is projected to increase under all ensembles in the Rother. In the lowland Idle, annual streamflow is projected to decrease under high emissions and to increase under low and medium emissions ensembles. Projections under both the UKCP18 and the high emissions eCX outline the same direction of change - increases in streamflow seasonality in the Rother and streamflow decreases across most of the year in the Idle. However, magnitudes of monthly and seasonal changes projected under eCX RCP8.5 are predominantly smaller than under UKCP18. Under low and medium emissions eCX there are a few outliers, but projected changes are largely small in magnitude and present as wetter than pro-

jections under RCP8.5. The use of different GCM-RCM combinations across the three eCX ensembles reflects in a high variability of projected changes. The overall model spread is however largely smaller than under the UKCP18. The projected changes for individual ensemble members are reported in section B.2, the original member names for UKCP18 (Table B.1) and eCX (Table 3.3) were used. If not specified, the ensemble medians ($\tilde{x}$) for the far future when changes are most clear are reported.

3.3.4.1 Annual Streamflow

Rother

The four ensembles indicate some variability in the direction of change for annual streamflow in the Rother but by the far future (2061-2080), aligning with the findings on increasing runoff, all ensemble means and medians agree on increasing annual streamflow. The medians of the three eCX are similar, highest under eCX RCP8.5.

In the near and intermediate futures, the median projections under UKCP18 are minor. By the far future the majority, 9 of the 12 ensemble members, project streamflow increases, both mean and median are however small (μ = 4.2%, $\tilde{x}$ = 4.6%). (Figure 3.8a). The ensemble spread is high, by the far future it ranges from -13.1% (ensemble member 13) to 14.9% (ensemble member 4) (Table B.3).

Under the high emissions eCX, half of the ensemble members project decreases in the near future, the lowest at -11.8%. The ensemble median is however consistently positive and larger than under UKCP18. It ranges from 2.2% in the near future to 8.9% by the far future. Under RCP4.5, in the near and intermediate future mean annual streamflow is projected to slightly decrease with ensemble medians of -2.8% and -2.0%. Projections for the far future however align with the other eCX ensembles, projecting increases with a median of 7.4%. The estimates under the lowest emission pathway project increases across all future time slices. The ensemble mean and median are similar at around 8%.

Idle

As indicated in the water balance, despite only small (UKCP18) and minor (eCX RCP8.5) decreases in overall precipitation, mean annual streamflow for the Idle is projected to decrease under both high emissions ensembles. Conversely, despite only minor increases in precipitation, annual streamflow under low and medium emissions is projected to increase (Figure 3.8b). The UKCP18 ensemble median decreases from -8.0% to -16.2% between near and far future. The spread within the ensemble of between -0.65% (mean projections of ensemble member 4) and -29.9% (members 9 and 13) with projections as low as -42% by the far future is considerable (Table B.3). While smaller than under UKCP18, the decreases projected under the high emissions eCX also becomes more pronounced in the far future when the ensemble median is -10.0%. The distribution of the projected changes is skewed with a few ensemble members projecting increases across all time periods, the wettest run with IPSL-WRF (Table B.5). The spread of projections under RCP4.5 and RCP2.6 is also high. The medians of both ensembles

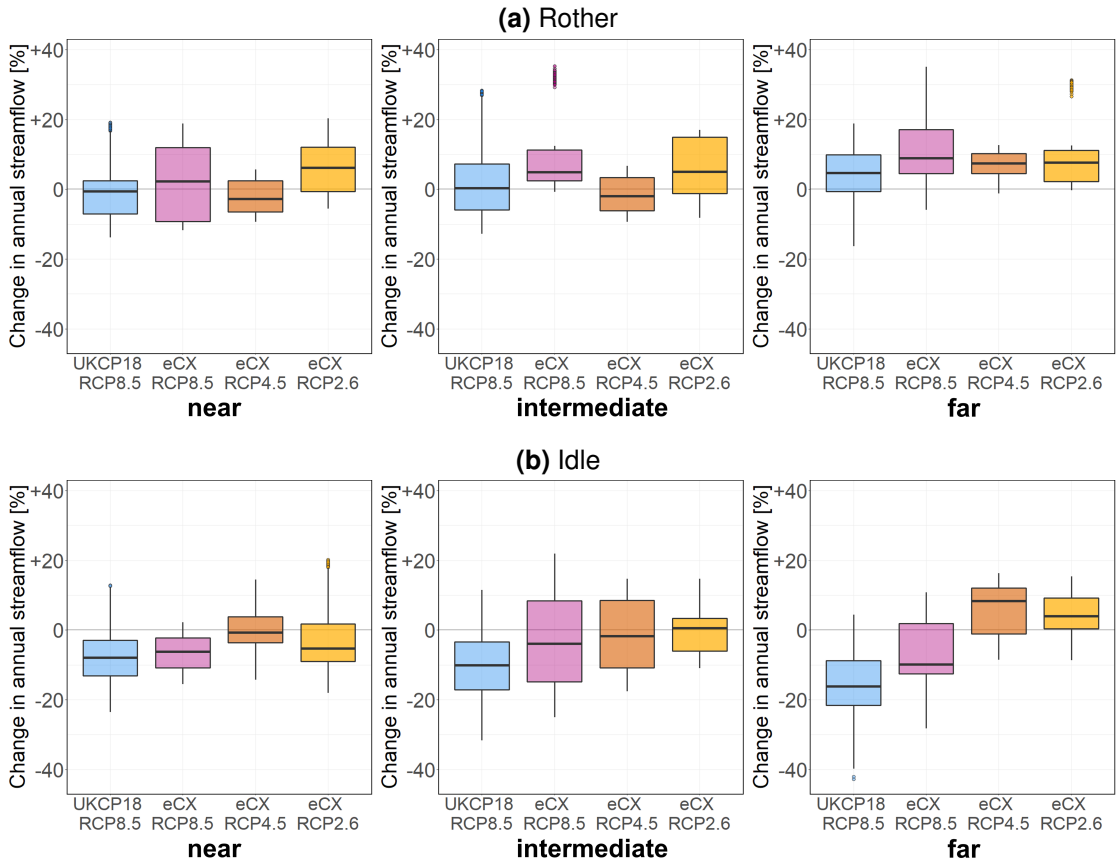


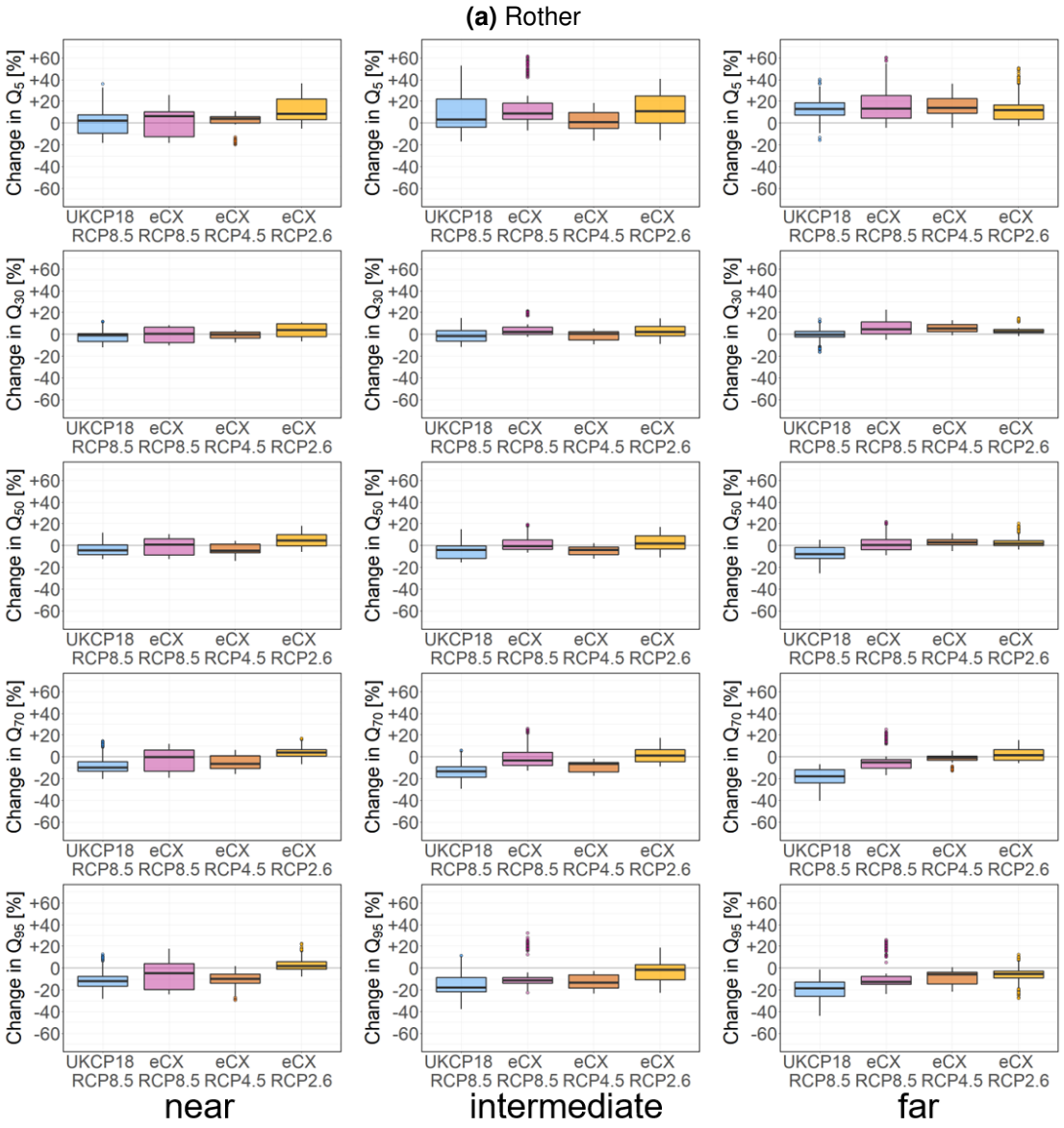
Figure 3.8: Percentage change in mean annual streamflow in the near, intermediate and far future compared to the reference period simulated with SWAT+ model, driven by the UKCP18 Regional Climate Models (RCMs) and euroCORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b), (n=300 per eCX ensemble, n=600 for UKCP18)

see largely stable flows in the earlier periods. However, the majority of simulations oppose the direction of change outlined under high emissions and agree on increasing annual streamflow by the far future. The median between near and far future varies between -1.8% and 8.3% under RCP4.5 and by between -5.3% and 4.0% under RCP2.6. The wettest runs were again produced by IPSL-WRF for RCP4.5 and by HAD-HAD for RCP2.6.

3.3.4.2 Flow Duration Curve Statistics

Using the models to simulate five FDC statistics, from low flows (Q_{95}) to high flows (Q_5), the simulations across the four ensembles show a considerable spread, particularly in the Idle under the two high emissions ensembles. Projected changes to the flow percentiles become more evident in the future (Figure 3.9). The low and medium emissions eCX projections outline the wettest future pathways. The mean annual streamflow increases observed in the coastal Rother for all ensembles and those in the Idle under low and medium emissions are driven by increasing high flows. In the lowland Idle, the

mean annual streamflow decreases projected under the two high emissions ensembles are driven by decreases across all flow quantiles yet affect low flows most severely.



(b) Idle

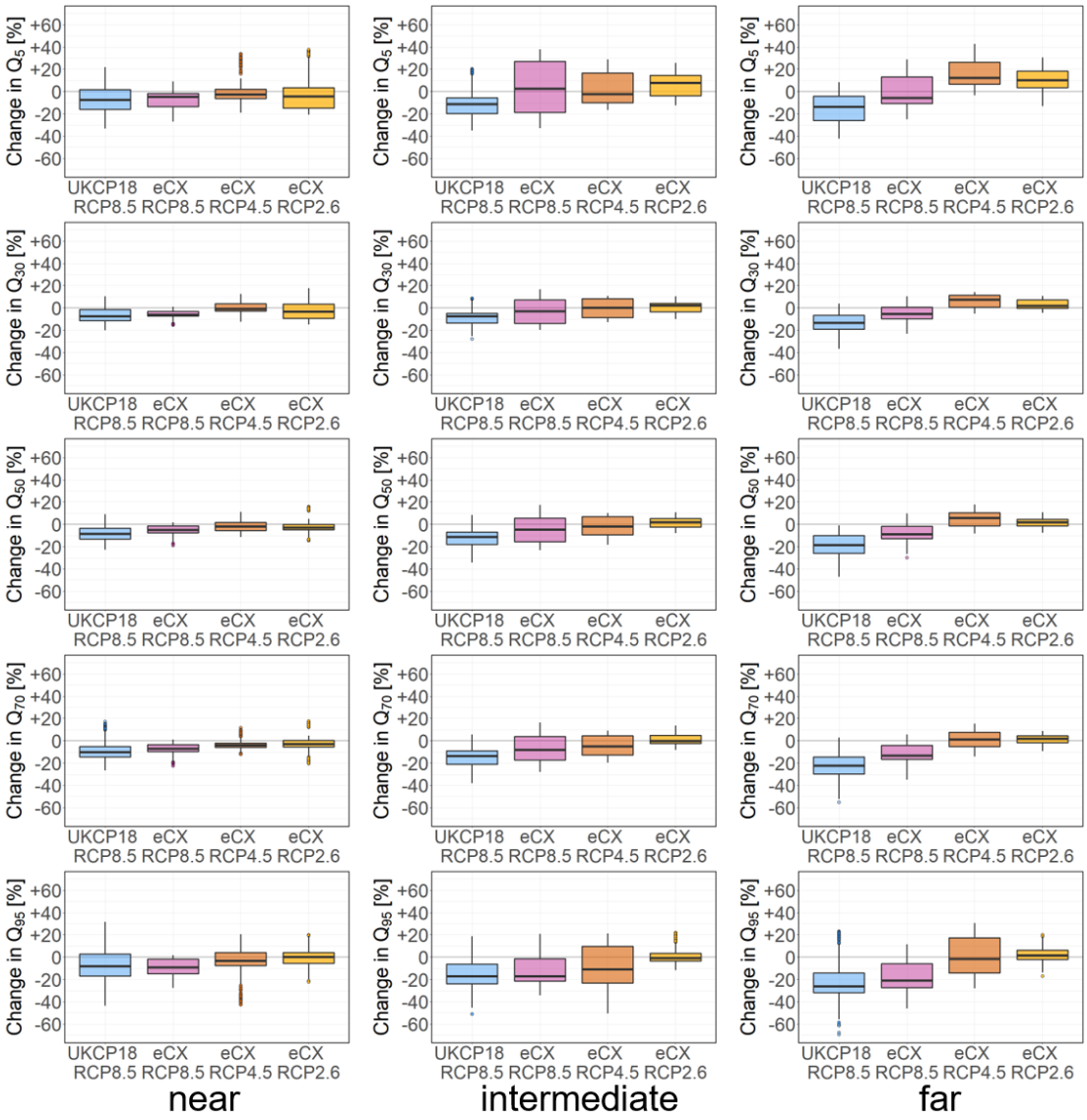


Figure 3.9: Comparison of percentage changes in flow duration statistics (Q_5, Q_{30}, Q_{50}, Q_{70}, Q_{95}) in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b), (n=300 per eCX ensemble, n=600 for UKCP18).

Rother

In the Rother, at around 13%, the medians of all four ensembles see similar increases for high flows (Q_5) (Figure 3.9a). Conversely, low flows (Q_{95}) are projected to decrease. Aligning with the considerable decreases in summer precipitation and increases in summer temperature, under high emissions projected decreases are largest for Q_{95} at -18.8% under UKCP18 and -12.8% under eCX . Climate change results in larger flow reductions across more of the flow distribution curve under UKCP18 than under eCX. Under UKCP18 flows at Q_{50} and below are projected to decrease and higher flows above Q_{50} are projected to increase. Under high emissions eCX, flows at Q_{70} and below are projected to decrease and flows above are projected to increase. This falls in line with larger annual streamflow increases projected under eCX RCP8.5. Under the RCP2.6 and RCP4.5 emissions scenarios, only flows at Q_{95} are projected to decrease. Mean and median projections for Q_{70} are largely stable while projections for flows at Q50 and beyond are projected to increase at similar rates than under high emissions.

Idle

Unlike in the Rother, winter rainfall increases do not translate into increasing high flows (Q_5) under the two high emissions ensembles in the Idle. Instead, decreases are projected across the whole flow duration curve (Figure 3.9b). For Q_5, they reach -13.9% under UKCP18 and -6.0% under eCX RCP8.5. Under eCX RCP8.5 a large share of projections is however positive for Q_5. While the range of projected changes is large, projected decreases are most pronounced for low flows (Q95) ($\tilde{x}$ = -26.4% under UKCP18, $\tilde{x}$ = -21.2% under eCX). The earlier start and longer lasting increases in winter precipitation translate into increasing high flows (Q_5) under low and median emissions ranging around 11%. Median projections under RCP2.6 are largely stable for all other flow duration curve statistics and time periods. The median of the eCX under RCP4.5 projects small increases of 7.2% and 5.4% for flows at Q_{30} and at Q_{50} while flows below Q_{50} are also projected to largely stay the same. This indicates that, similar to the Rother, annual streamflow increases under these scenarios are driven by high flow increases. Higher annual streamflow increases under RCP4.5 are driven by increases affecting more of the FDC.

3.3.4.3 Projected Changes to Monthly and Seasonal Streamflow

The mean absolute and percentage seasonal and monthly flow changes and the range across the projections for the near, intermediate and far futures for both catchments show several important characteristics. There are clear differences in response to climate change between the two catchments reflecting changes in seasonality, evolution over time and the range of impacts. Figure 3.10 shows the percentage and absolute changes across the year. Due to the large difference in absolute streamflow and for better visibility, the absolute change depicted in blue on the secondary y-axis is scaled differently.

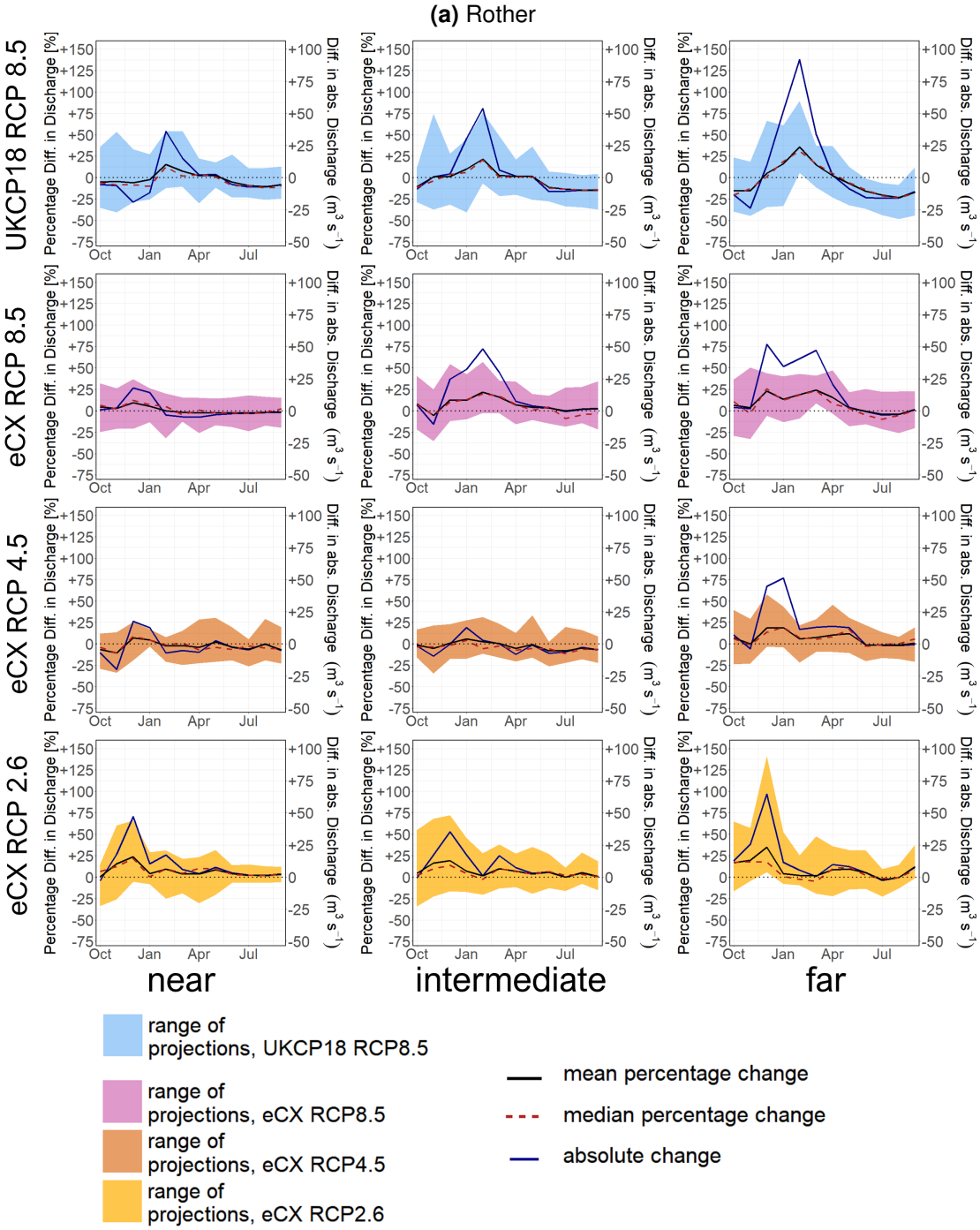
In both catchments the UKCP18 projections agree on decreasing streamflow in summer. The month with the highest streamflow increase is February. In both catchments magnitudes of change become more pronounced over time in summer (during low flows) under high emissions and in winter (during high flows) under low and medium emissions. Projections under ensemble member 13 are consistently driest for both catchments while members 6, 15 and 4 are wettest, the latter projecting the wettest outcomes by the far future (Table B.3).

Besides these general similarities, projected seasonal and monthly changes differ greatly between the two catchments. As indicated by the changes projected for the flow duration curve, in the Rother, streamflow seasonality is projected to become more pronounced with some strong increases in winter (high) flows and decreases in summer (low) flows. Idle streamflow on the other hand is projected to decrease across the whole year with February as the sole exception and some strong decreases during the months with decreasing precipitation, from May to October. Despite being driven by only one GCM, the model range under the UKCP18 is larger than under eCX, in the Rother in winter and in the Idle in all seasons.

Extending the results with projections from the eCX initiative outlined some wetter and less extreme future pathways. Projections under the high emissions eCX agree on the direction of change with those projected under UKCP18 for both catchments. However, while also becoming more pronounced from near to far future, magnitudes of change are smaller than under UKCP18. They see less pronounced increases in February and instead project more even increases for all of winter in the Rother. Streamflow decreases projected for most of the year the Idle and for summer in the Rother aew less extreme under eCX RCP8.5. Projected changes under low and medium emissions are variable over time in both catchments. Increases are projected for autumn and winter in both catchments with few clear summer decreases. The direction of change projected for autumn is thus the opposite than that under high emissions. The range of projected changes is narrow in the Idle while it is larger in the Rother, particularly under RCP2.6 where the HAD-HAD scenarios represent a wet outlier in winter. The same GCM-RCM combinations are at the wet end of projections for both catchments and across the three eCX ensembles: HAD-HAD for RCP2.6 and IPSL-WRF for both RCP4.5 and RCP8.5. Different eCX ensemble members are at the dry end of projections. Since changes to summer and winter flows have largely already been reported through the changes projected to low (summer) and high (winter) flows, the following section extends on streamflow changes projected for autumn and spring.

Rother

In the Rother, under UKCP18, the clear increase in projected rainfall seasonality translates into a clear increase in hydrological seasonality. It is characterised by decreasing flows in summer (June to August) and autumn (September to November) and increasing flows in winter (December to January) (Figure 3.10a, top row). By the far future, all simulations under UKCP18 agree on decreasing streamflow in all summer months.


(a) Rother
UKCP18 RCP 8.5
eCX RCP 8.5
eCX RCP 4.5
eCX RCP 2.6
Percentage Diff. in Discharge [%]
Diff. in abs. Discharge (m³ s⁻¹)
Oct
Jan
Apr
Jul
near
intermediate
far
range of projections, UKCP18 RCP8.5
range of projections, eCX RCP8.5
range of projections, eCX RCP4.5
range of projections, eCX RCP2.6
mean percentage change
median percentage change
absolute change

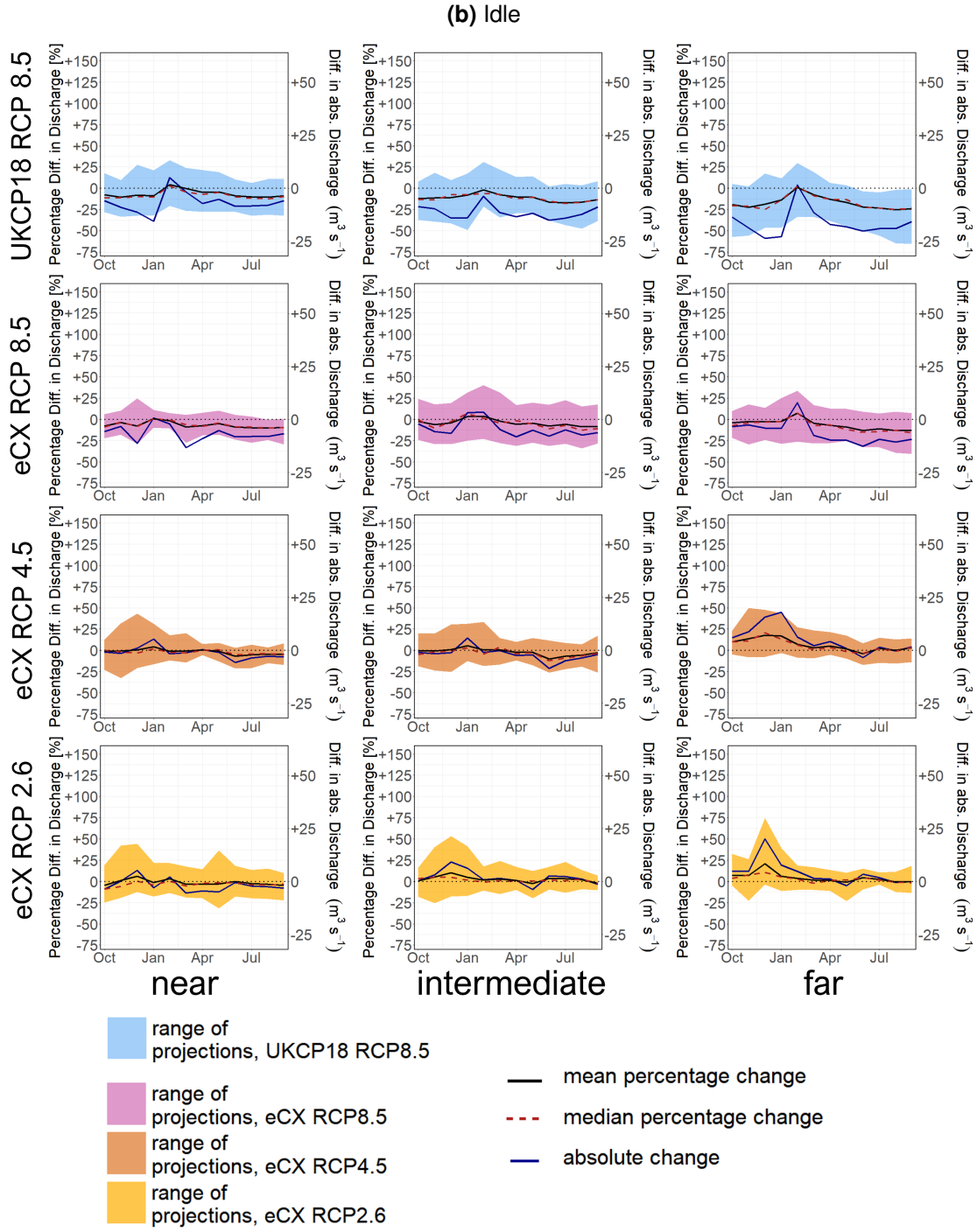
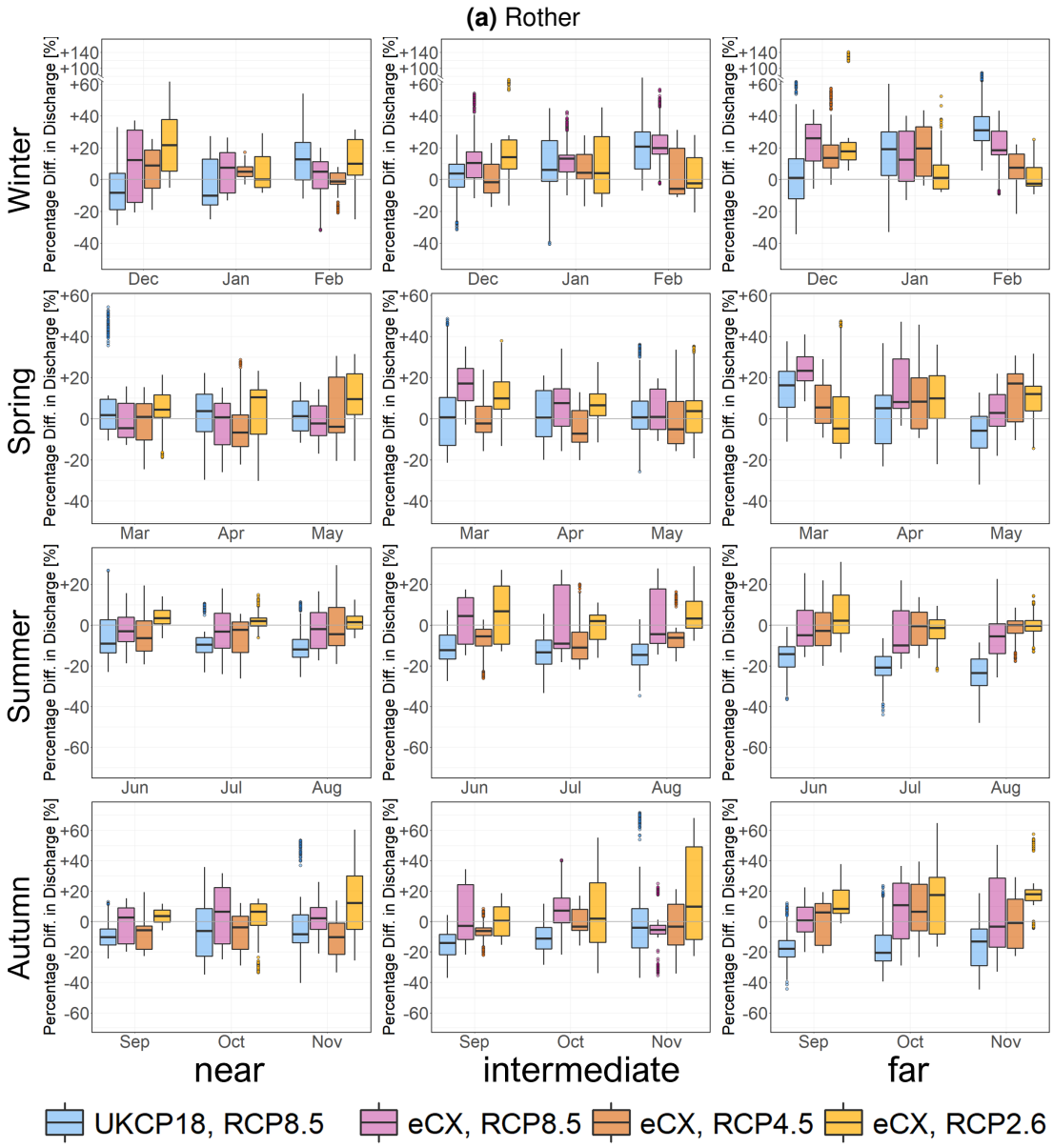


Figure 3.10: Comparison of the percentage changes (on the left y-axis) and absolute long-term mean annual dynamics (on the right y-axis) of discharge in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+ model, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b), (n=300 per eCX ensemble, n=600 for UKCP18).

The greatest reductions are projected under ensemble member 13 (Table B.3). The strong reductions projected for August ($\tilde{x}$ = -23.7%), suggest a shift of minimum flows from September to August. The reductions in precipitation between May and October with simultaneous increases in aridity additionally translate into considerable streamflow decreases in autumn. The large majority of simulations agree on decreasing streamflow across all autumn months with ensemble medians at -18.0% for September, -20.5% for October and -13.1% for November. The variability across ensemble members is highest in November in the intermediate future when the projections vary between -37.1% decreases (member 15) and 74.3% increase (member 6). The range of projected changes is also high for winter, higher than under all eCX combined. This aligns with the high range of winter simulations during the observations period, particularly during the peak flow month January.

Table 3.6 and Figure 3.11 provide a comparison of monthly changes, the former showing mean projections per ensemble. Figure 3.11 is ordered by seasons that vary in scaling for improved visibility. The upper end of the winter scale is compressed to show the outlier in winter streamflow in the Rother under RCP2.6. Early spring streamflow is projected to increase along with late winter flow while May streamflow is projected to slightly increase at first but projected to decrease by on average -6.7% along with summer flows by the far future.


(a) Rother
Winter
Spring
Summer
Autumn
Percentage Diff. in Discharge [%]
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
near
intermediate
far
UKCP18, RCP8.5
eCX, RCP8.5
eCX, RCP4.5
eCX, RCP2.6

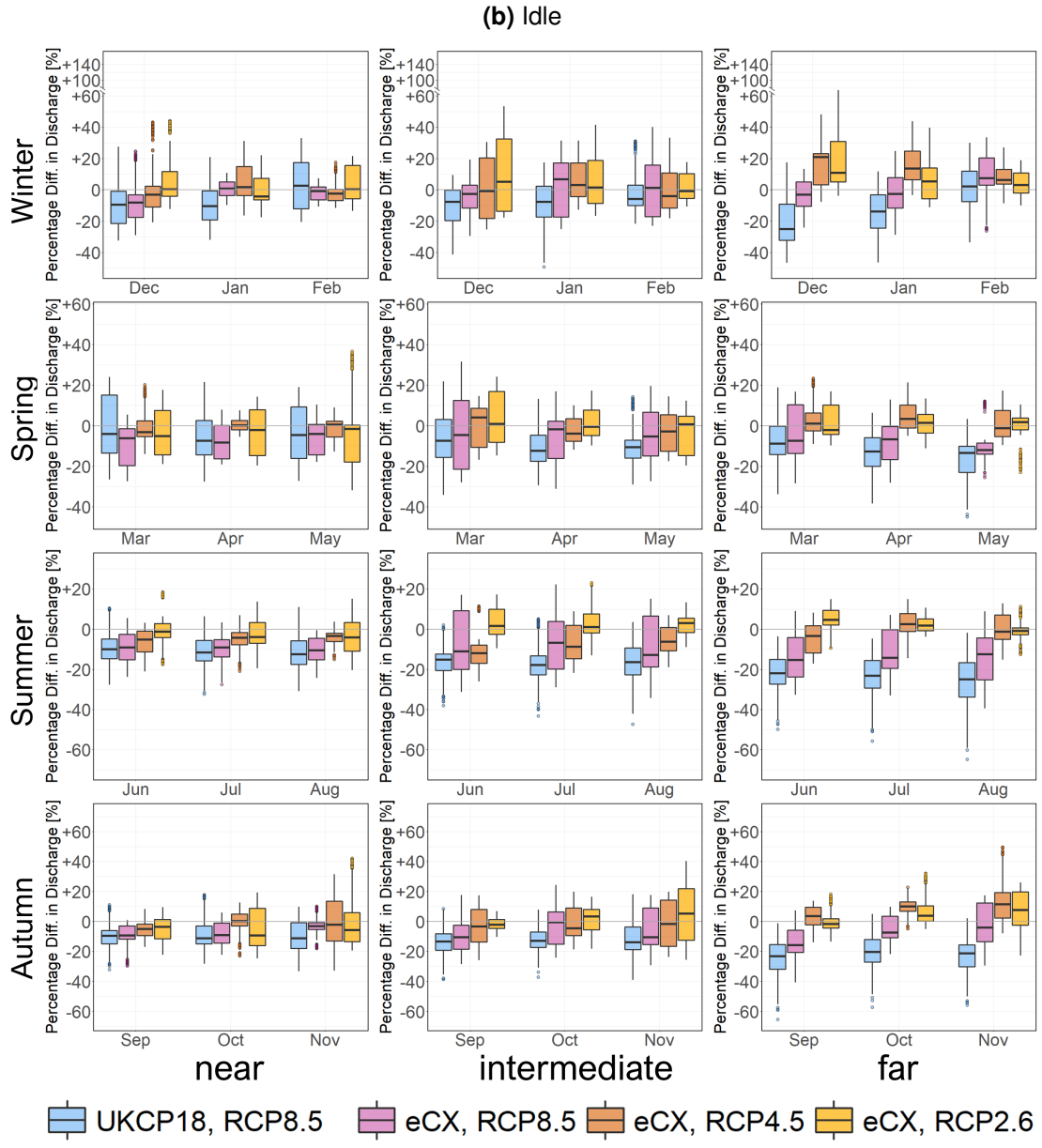


Figure 3.11: Monthly percentage change across the four seasons and three future time slices, simulated with the SWAT+ model, driven by UKCP18 and euro-CORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b), (n=300 per eCX ensemble, n=600 for UKCP18).

Table 3.6: Observed monthly flow in the reference period (2001-2017) and projected mean monthly percentage change in natural streamflow across the euro-CORDEX (eCX) and UKCP18 in the near (2021-2040), intermediate (2041-2060) and far future (2061-2080) compared to the reference period, (n=300 per eCX ensemble, n=600 for UKCP18).

Rother	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	284.8	-2.3	10.1	16.1	5.4	12.4	13.5	4.7	5.7	19.0	3.9	6.8	4.0
Feb	220.6	15.2	21.4	36.0	-0.0	21.6	18.7	-2.4	2.7	5.8	9.2	1.6	2.1
Mar	188.6	7.6	2.7	14.7	-1.9	15.8	24.0	-1.7	0.6	7.4	3.5	9.9	1.7
Apr	135.2	2.1	1.4	2.0	-2.5	6.8	15.6	-4.1	-5.4	10.3	3.5	6.9	8.7
May	115.3	2.1	1.4	-6.7	-2.0	4.1	3.3	2.1	-0.8	12.2	8.5	3.6	9.2
Jun	83.9	-5.4	-11.2	-15.9	-2.4	3.1	-0.5	-3.6	-8.1	-0.9	4.1	5.8	5.1
Jul	81.3	-9.3	-13.3	-20.5	-2.6	-0.2	-4.0	-6.2	-8.2	-1.4	2.1	-0.1	-3.4
Aug	73.0	-10.7	-14.6	-23.4	-1.9	2.1	-4.0	-0.2	-4.8	-1.7	1.8	5.4	-0.4
Sep	68.8	-8.6	-15.1	-17.3	-1.4	3.0	1.7	-6.8	-6.6	0.9	3.5	0.6	12.1
Oct	123.8	-5.0	-10.7	-15.6	4.5	8.2	6.7	-6.4	-1.1	7.0	0.3	4.5	16.6
Nov	190.7	-4.2	1.0	-15.4	2.9	-5.2	3.5	-10.5	-5.0	0.1	15.6	16.5	19.8
Dec	228.5	-6.2	1.5	5.1	9.6	12.7	23.0	7.3	0.9	18.5	23.9	19.4	35.0
annual	149.1	-0.3	1.9	4.4	1.7	9.4	11.7	0.1	-0.9	8.9	7.7	7.8	9.5
Idle	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	154.2	-8.7	-7.9	-13.9	0.5	3.3	-2.5	4.4	5.7	17.0	-1.4	4.7	6.1
Feb	138.3	4.2	-2.0	1.1	-1.7	3.6	7.3	-1.2	0.7	7.2	3.2	1.7	3.7
Mar	130.6	-0.2	-7.5	-7.5	-9.0	-2.1	-4.5	-0.7	0.4	3.0	-3.5	2.7	1.6
Apr	114.5	-4.9	-10.3	-12.9	-7.5	-5.9	-7.3	0.6	-2.2	5.0	-3.5	1.0	1.0
May	106.3	-4.3	-10.6	-16.6	-5.1	-4.5	-9.1	-1.1	-2.3	1.7	-3.1	-2.7	-1.0
Jun	94.9	-9.0	-16.4	-22.0	-9.1	-7.9	-13.2	-7.0	-10.1	-4.0	-0.2	3.6	4.4
Jul	85.7	-10.1	-17.0	-23.2	-9.9	-5.8	-11.3	-5.3	-6.7	2.3	-2.6	3.1	2.3
Aug	90.9	-10.4	-16.4	-25.5	-10.5	-8.9	-13.1	-4.4	-5.4	-0.0	-3.3	2.0	-0.7
Sep	87.7	-8.8	-13.3	-23.9	-9.7	-8.7	-13.0	-4.9	-2.7	3.1	-4.7	-1.9	0.1
Oct	102.6	-7.7	-12.2	-19.2	-7.9	-2.4	-4.3	-1.0	-0.8	10.0	-4.8	0.9	7.1
Nov	117.6	-10.3	-11.4	-22.3	-3.6	-6.4	-2.4	-0.7	-0.8	13.5	1.1	5.2	7.0
Dec	131.4	-8.0	-10.8	-18.9	-8.0	-4.3	-2.8	0.7	1.0	17.8	6.0	10.3	21.1
annual	112.8	-6.7	-11.5	-16.1	-7.4	-3.9	-6.2	-2.2	-3.1	6.2	-1.8	2.1	4.3

Aligning with the findings for the FDC, the high emissions eCX projections (Figure 3.10a, second row) agree with the findings under UKCP18 also projecting increases in seasonality, yet at smaller magnitudes. A major difference lies in small increases instead of decreases projected for the autumn months. This aligns with earlier projected rainfall increases in October under this ensemble. Ensemble mean and median projections

for streamflow in autumn are however small, highest in October by the far future ($\tilde{x}$ = 10.6%). The range of projected changes is also highest in November, most pronounced by the far future when increases projected under IPSL-WRF are as high as 50.3% and decreases under IPSL-REMO as low as -33.0% (mean projections in Table B.4). Another notable difference lies in more even winter increases and wetter projections for spring. From the intermediate future (2041-2060) onwards, spring streamflow is projected to increase stronger than under UKCP18. The ensemble median is highest in March at 17.1% and 23.2% across intermediate and far future.

By the far future, projections under eCX for RCPs 2.6 and 4.5 are largely stable for summer and project increases across the other seasons. While mixed, the direction of change for autumn is hence the opposite than under UKCP18. Under RCP2.6 increases instead of decreases are projected for all autumn months. Under RCP4.5 increases are projected for September and October while November flows are projected to largely stay the same. HAD-HAD for RCP2.6 is an outlier as it projects streamflow to increase by 130% in December (Table B.4) which would imply a shift of peak absolute discharge from January to December. Removing this ensemble member the median increase is 16.6% for December, including it implies a median increase of 17.8%. As throughout all projections, the direction of change projected for spring is not very clear and the ensemble median shows some alternation in the direction of change across the considered future periods. April projections are similar by the far future across all four ensembles, March streamflow is negative under RCP2.6 ($\tilde{x}$ = -5.7%) and positive under RCP4.5 ($\tilde{x}$ = 5.5%) and May projections range from -10.5% to 30.7% (RCP4.5) and -14.5% to 31.5% (RCP2.6). Aligning with eCX for RCP8.5, IPSL-WRF outlines the wettest projections.

Idle

Under UKCP18, streamflow decreases are projected across the whole year with February as the sole exception in the Idle (Figure 3.10b top row, Figure 3.11b, Table 3.6, Table B.3). This reflects a higher responsiveness to decreasing precipitation than in the Rother. Strongest decreases in streamflow are found for summer, most pronounced in the month with lowest flows, July. By the far future all members agree on decreasing streamflow from June to September of on average beyond -20% (Table 3.6, Figure 3.11b last column). Autumn flows are also projected to decrease considerably with ensemble members agreeing at on average beyond -7% decrease from September to October for all time periods. Peak absolute discharge is projected to shift from January to February - evident in the pronounced difference between the two months' absolute streamflow projections (Figure 3.10b – blue line). Despite projected increases in precipitation between December and April, February is the only month when median streamflow is projected to slightly increase under this ensemble. Spring streamflow is projected to decrease less strongly than summer and autumn. However, particularly for May some ensemble members project pronounced decreases. The driest members 9 and 13 project mean decreases of beyond -30% from May to October.

While agreeing on the direction of change indicated by UKCP18, under the high emissions eCX, streamflow projections are less extreme and wetter throughout the year. Next to the magnitude the spread of projections is smaller for all months across the 300 eCX simulations than under the 600 UKCP18 simulations. The smaller decreases projected for summer are most notable for (the early low flow period in) June ($\tilde{x}$ = -15.3%). Decreases projected for autumn are also smaller with a high number of simulations projecting increases for November ($\tilde{x}$ = -3.3%). A shift in peak streamflow from January to February is not implied. Projections under the two high emissions ensembles align most closely in spring, in May the median of both range around -12.0%. Like in the Rother, wettest projections stem from IPSL-WRF, under this ensemble there are no increases projected for spring in any of the time periods. The driest member of this ensemble is IPSL-REMO followed by HAD-HAD which is the previous version of the GCM (HadGEM2) that is driving the UKCP18.

In the Idle, the differences across the RCPs are more pronounced than in the Rother. Aligning with the findings on the FDCs, the low and medium emissions ensembles present as (even) wetter than the eCX forced with high emissions, particularly under RCP4.5. This reflects in largely minor changes projected for summer. Compared to the two ensembles driven with RCP8.5, these wetter projections under RCP4.5 and 2.6 furthermore imply the opposite direction of change for autumn. While the variability of projected changes across time frames and within ensembles is high, largest autumn increases are projected under RCP4.5 for October ($\tilde{x}$ = 9.9%) and November ($\tilde{x}$ = 11.4%). Spring streamflow projections are also variable with mostly minor changes. As in the Rother, HAD-HAD under RCP2.6 represents an outlier for December projections – without this ensemble member, median projected streamflow is projected to increase by 8.6%, when considering it by 10.8%.

3.3.5 Variability introduced by SWAT+ parameters and GCM-RCM members

In the results on projected changes to streamflow, HM uncertainty was not separated from GCM−RCM uncertainty. Therefore, the variability introduced by the 50 SWAT+ parameter sets (intra-ensemble variability) and the variability introduced by different GCM−RCM ensemble members (inter-ensemble variability) shall briefly be analysed. The former (intra-ensemble variability) was approximated by calculating the mean standard deviation (σ) across the 50 SWAT+ runs for each member of the four ensembles. The latter (inter-ensemble variability) was assessed by calculating across the 600 (UKCP18) and respectively 300 (eCX) members within each ensemble. The latter was calculated while holding one SWAT+ parameter set stable. The inter-ensemble variability is substantially higher than the intra-ensemble variability. The latter is higher within UKCP18 than within the eCX ensembles.

In the Rother projections, different SWAT+ parameter sets introduce the highest variability in autumn and the least in winter and early spring across all four ensembles (Figure B.1 in Chapter A.4.2). Variability within the UKCP18 is higher than within the eCX

ensembles for almost all months, highest in December (σ =3.7). Variability is lowest under RCP4.5 in March (σ =0.89). The variability introduced by ensemble members is highest in winter and lowest in summer. It is highest overall within the RCP2.6 ensemble in December (σ =44.5) and it is lowest under the same ensemble in August (σ =6.6).

In the Idle the variability across SWAT+ parameters is higher than in the Rother. Different SWAT+ settings also introduce most variability in autumn but instead of early spring late spring and winter are least variable. Variability is highest within the UKCP18 ensemble throughout the year with a maximum in September (σ = 6.8). It is lowest under RCP2.6 in April (σ = 1.2). In the Idle intra-ensemble variability is also highest in winter and lowest in summer. The variability introduced by different ensemble members is, similar to the Rother, highest within the RCP2.6 in December (σ = 26.3) and lowest within the same ensemble in July (σ = 3.1).

Analysing the ranges of the most sensitive SWAT+ parameters across the 20% driest and wettest future projections (n=10), few relationships can be observed (Table 3.7 and Figure B.2). Wet projections in the Rother were connected to high values in available soil water capacity (awc) and three of the wettest runs were received under high settings in the base flow recession constant (alpha). Driest projections were largely received with low values in awc and eight out of the ten moreover had low values in the curve number for projecting runoff at average soil moisture (cn2). Five of the driest runs additionally had noticeably low values in alpha. In the Idle, the 20% wettest runs have mostly low values of the plant uptake compensation factor (epco) and rather higher values in awc than the dry runs. Three of the driest runs were received with low settings of the lateral flow coefficient (latq_co). When analysing the different parameter sets for their performance in the observations period a notable finding was that the four sets determined through (separately) maximising NSE_{inv}, VE, KGE, bR^2 were all among the 20% driest runs in the Idle. In the Rother only the parameter set maximising VE was among the 20% driest runs.

Table 3.7: Sensitive SWAT+ parameters, their change type and parameter range across 20% wettest and 20% driest projections across the four ensembles.

		Rother				**Idle**			
parameter	**change type***	20% driest projections		20% wettest projections		20% driest projections		20% wettest projections	
		min	max	min	max	min	max	min	max
cn2	abschg	**-13.40**	8.85	-9.01	8.95	-14.78	6.49	-11.70	6.73
epco	abschg	-0.91	0.20	-0.98	-0.10	-0.84	**0.50**	**-0.94**	**-0.06**
esco	abschg	-1.00	0.98	-0.92	0.93	-0.77	0.99	-0.76	0.93
perco	absval	0.24	0.66	0.35	0.54	0.11	0.29	0.12	0.30
z	pctchg	-10.0	67.0	22.4	68.8	-20.3	58.1	13.6	59.0
awc	absval	**0.02**	**0.08**	**0.11**	**0.14**	**0.02**	**0.07**	**0.06**	**0.11**
alpha	abschg	**-0.01**	0.90	0.08	**0.98**	0.19	0.99	0.13	0.94
flo_min	abschg	724.1	4109.9	300.8	4911.4	323.93	4845.5	302.6	4514.2
bd	absval	0.90	1.04	0.93	1.18	0.93	1.58	0.97	1.56
snofall_tmp	abschg	-6.98	9.19	-9.77	9.06				
k	pctchg	-40.68	58.55	18.89	56.09				
revap_min	relchg					-0.40	0.38	-0.60	0.53
revap_co	absval					0.03	0.20	0.05	0.18
latq_co	abschg					**-0.99**	0.64	-0.62	0.97

* abschg = absolute change, pctchg = percentage change, absval = change by absolute value, relchg = relative change

3.4 Discussion

This study has assessed climate change impacts on natural streamflow in two English priority catchments which are used for developing and testing innovative solutions to achieve greater access to water and address unsustainable abstraction. By using two sets of climate projections, the eCX sampling parametric uncertainty, the UKCP18 (Regional Projections) sampling GCM structural uncertainty, a range of potential consequences of climate change across three emissions pathways were outlined. In the Rother, annual streamflow is projected to increase under all assessed ensembles. High flows are projected to increase while low flows are projected to decrease. Under both ensembles forced with RCP8.5, UKCP18 and eCX, increased seasonality is an important element of streamflow response - summer streamflow is projected to decrease while winter streamflow is projected to increase. The magnitude of change is considerable smaller under the eCX RCP8.5 ensemble however, particularly summer decreases are less pronounced. The projected monthly to seasonal changes under the eCX forced with RCPs2.6 and 4.5 present as wetter with earlier streamflow increases in winter, less decreases in summer and increases in all autumn months. The direction of change for autumn hence opposing that under UKCP18. In the Idle, annual streamflow is projected to decrease under UKCP18 and eCX for RCP8.5 and to increase under eCX for RCPs 2.6 and 4.5. Decreases projected under high emissions affect the whole flow duration curve and are projected for the whole year with the exception of February. Annual streamflow increases projected under low and medium emissions are driven by high flow increases with largely stable low and median flows. Streamflow in winter (when high flows occur) is projected to increase earlier and longer in the year under the low and medium emissions eCX. There are less decreases projected for summer and autumn streamflow is projected to increase instead of decrease.

These results provide insight for water managers when enhancing abstraction management and environmental protection in the priority catchments represented by the Idle and Rother, as well as in similar catchments more widely.

3.4.1 Climatic Drivers of Change

By using two sets of climate projections across three different emissions scenarios, climatic drivers of streamflow change could be determined. UCKP18 Regional Projections describe the effects of a high end warming scenario useful for cautious decision making (Yamazaki et al. (2021) referring to the global PPE variants driving the Regional Projections). Additionally considering an MME of eCX projections allowed to delineate a range of wetter and less extreme futures to be considered in water management.

The patterns of change in temperature and precipitation were found to be similar in the two basins; rainfall is projected to shift from summer to winter under high emissions. The low and medium emissions project a more variable pattern with increases in spring and small decreases in summer. All ensembles project temperature increases throughout the year, most pronounced in summer and under UKCP18. Compared to the CMIP5

GCMs, some of which drive the eCX projections applied in this study, UKCP18 Regional Projections represent a narrow yet high level of warming (Yamazaki et al., 2021) . The assessment of the hydrological cycle and water balance components shows that aridity and potential evaporation are projected to increase much stronger under UKCP18 than under eCX. Despite only minor changes in rainfall and actual evapotranspiration, runoff is projected to increase considerably, at comparable rates across the four assessed ensembles in the Rother. In the Idle, strong decreases are projected for surface runoff under both high emissions scenarios, strongest under UKCP18 driven by decreases in precipitation accompanied by increases in aridity. Under low and medium emissions the projected changes are similar for the two catchments.

When assessing how the two types of climate uncertainty translate into streamflow projections, this study found a markedly stronger hydrological response and a wider range of projected changes in models driven with UKCP18 than in those driven with eCX projections. Rajczak and Schär (2017) and Murphy et al. (2018) found that in both, the UKCP18 Regional Projections and eCX projections, the increase in winter precipitation is driven by an increase in rainfall intensity of between 10-40% and little change in number of wet days. Winter precipitation for the two assessed catchments is projected to increase stronger under UKCP18 however and elicits a very different winter streamflow response between the two (see section 4.2.). The differences between the two ensembles are most evident when projections show reductions in flow. UKCP18-driven models project stronger drying than eCX-driven models for all months other than January and February in the Rother but across the whole year in the Idle. Particularly projections for the summer months are considerably drier under UKCP18 than under eCX.

Under low and medium emissions, summer streamflow in the Rother is projected to largely stay the same. The increases projected for annual streamflow under low and medium emissions are driven by longer but less extreme increases in winter as well as some increases in autumn and spring streamflow. Idle streamflow is projected to decrease during large parts of the year under both high emissions scenarios yet also considerably more pronounced under UKCP18. Projections under low and medium emissions yield largely stable summer and spring streamflow and increases for winter and autumn streamflow. While changing precipitation patterns are the main driver of these changes in streamflow, changes in water balance components have highlighted the high(er) importance of temperature-driven evaporative processes under UKCP18.

The UKCP18 Regional Projections are also drier compared to other UKCP18 products, between 5 and 10% than both strand 1 (probabilistic projections) and strand 2 (a set of 13 CMIP5 models plus a PPE of 15 global simulations, 12 of which drive the Regional Projections). The clearer summer drying under the Regional Projections as compared to eCX is partly explained through some of the global PPEs driving the UKCP18 Regional Projections simulating larger increases in summer North Atlantic Oscillation than any of the (13) CMIP5 members do (Murphy et al., 2018). Moreover, biases have been found in the representation of some physical processes in the driving HadGEM3 and slightly

excessive drying has been suggested as cause for HadGEM3 simulating too intensive heat waves (Vautard et al., 2019). Moreover, HadGEM-GC3.05 has a particularly high climate sensitivity, higher than that of any models featured in CMIP5 (that drive the eCX and a number of strand 1 and 2 simulations) (Andrews et al., 2019; Collins et al., 2013). The Regional Projections are so dry because they are driven by only this GCM. Additionally, the processes used in the parameter choice for perturbation and for selecting the UKCP18 strand 2 model members from a larger subset have favoured those ensemble members with high climate sensitivity. This means that although representing plausible parameter specifications some HadGEM3-PPEs with lower climate sensitivity have been discarded (Yamazaki et al., 2021). The comparison to high emissions eCX suggests that the UKCP18 might therefore potentially be too dry, overestimating reductions in low flow.

Moreover, in the final 12-member set, only member 1 uses standard RCP8.5. The other members describe a range of emissions that, while consistent with RCP8.5, do not perfectly outline the same emissions uncertainty. The aim of such exploratory scenarios is to assess a wide range of potential futures (Vuuren et al., 2012) and this study could thus provide decision makers with an extended range of potential outcomes. However, there is growing criticism of the RCP8.5 "business as usual", non-mitigation scenario and its extreme, inconsistent and implausible assumptions (Hausfather and Peters, 2020; Pielke and Ritchie, 2021). The main argument concerns the assumed development of coal consumption (e.g. Ritchie and Dowlatabadi, 2017). This line of argument suggests that while the implications of different types of GCM uncertainty described for streamflow response are useful, projections received under RCP8.5 might not be realistic. Consequently, adapting to climate change might be easier than indicated by projections received under RCP8.5 (Hausfather and Peters, 2020).

Recent studies found that the climate sensitivity of the HadGEM3 GCM-family is at the upper end of CMIP6 like HadGEM2 was at the upper end of previous CMIP5. At the same time, the climate sensitivity of CMIP6 models has been found to generally be higher than CMIP5 models (Forster et al., 2020; Meehl et al., 2020). This suggests that, while (due to high climate sensitivity, amplified through the biased PPE selection) UKCP18-driven projections are certainly at the extreme (dry) end of CMIP6, they might be closer to projections under other (drier) CMIP6 GCMs (as compared to the CMIP5-driven eCX). Future impact studies using dynamically downscaled CMIP6 projections might evaluate this (Xu et al., 2021). It should be noted that CMIP6 are driven with SSP-based scenarios (O'Neill et al., 2016). The SSPs are intended as an extension to projections received under RCPs but are not directly comparable for the same emissions uncertainty (O'Neill et al., 2017). This means that similar radiative forcing is received under different GHG compositions (Kriegler et al., 2017; Riahi et al., 2017).

Moreover, Boé et al. (2020) have shown that the current eCX ensemble does not capture the warmest and driest summertime projections present in CMIP5. They might therefore underestimate streamflow decreases during summer as well as autumn. Demory et al.

(2020) found that eCX overestimate winter precipitation over the British Isles. Accordingly, Pastén-Zapata et al. (2020) found that eCX overestimate winter discharge in all British catchments they assessed (by between 3-63%). Aitken et al. (2022) assessed the ability of eCX to reproduce NRFA observed flow records and found that particularly IPSL-WRF, which outlined the wettest future pathways for the RCPs 4.5 and 8.5 eCX ensembles in this study, performed poorly across large parts of the UK. These wet biases in eCX explain the wet end of projected changes under eCX. The wet end under RCP 2.6 is represented by the previous version of the GCM driving the UKCP18 HADHAD (HadGEM2). Together, these considerations highlight the value of using eCX and UKCP18 Regional Projections in combination. UKCP18 has enhanced the eCX and vice versa, allowing to assess a range of outcomes between dry and wet future pathways.

3.4.2 Underlying Catchment Characteristics

The effects of different physical catchment features were not systematically analysed and separated from climatic effects. This can be done by running models with other catchments' climate input data (see for example Charlton and Arnell (2014)). Such an approach is challenging and would have required a reanalysis of all climate input data. The number of climate stations (53 in the Rother, 81 in the Idle) doesn't match and the respective climate time series are spatially distributed. Furthermore, many of the SWAT+ parameters that were found to be sensitive, such as awc, can be affected by land use. Land use is a major determinant for soil moisture, infiltration and aquifer recharge (Garg et al. (2019) and therein). For both catchment models, land cover data from 2017 and on agricultural HRUs a crop rotation based on 2018 CEH data was implemented that was held stable throughout the simulation period. The interaction between streamflow and potential land use change and adaptation was therefore not considered.

Instead, here, two catchments were examined that were each representative of two distinct catchment classes as delineated in chapter 2. By comparing the projected changes in climate variables, the overall water balance and monthly to annual streamflow, conclusions on the role of physical characteristics in shaping streamflow response to changing climate could be drawn. From the physical catchment characteristics of the two groups, catchment relief and groundwater recharge appear as most important for modulating streamflow response. Due to the good and very good performance of all SWAT+ models, it can be assumed that most important groundwater exchange processes, including recharge, are well represented in the two catchment models. Especially across similar patterns of change in climate, these can hence realistically explain some of the differences observed between the two catchments.

The role of groundwater reflected in projected changes to the hydrological cycle; when precipitation shifts to winter overall runoff might increase despite only minor changes in total precipitation as it occurs when soils and aquifers are saturated. Under low and medium emissions, the climatic pattern of change in temperature and precipitation as well as overall runoff response are very similar between the two catchments. The role

of groundwater, in particular the speed of aquifer recharge might partly be responsible for differences in the timing of winter (high) flows between Rother and Idle under these emissions scenarios. While more sensitive in the Idle, some of the wettest projections in the Rother were for example made under high settings of alpha indicative of rapid groundwater response and less percolation to the deep aquifer. Shallow groundwater has previously been shown to be more vulnerable to depletion than deep groundwater (Hare et al., 2021), wetter Rother projections occur at the expense of (deep) aquifer recharge. The recharge period in the more permeable Idle is longer and summer is more important for recharge. Since in both catchments summer precipitation is largely stable under these scenarios, soil moisture and groundwater tables likely rise and reach their maximum quicker under autumn and winter precipitation (increases) in the Idle. Winter rainfall on saturated soils therefore implies earlier increases in winter streamflow in this catchment. It was previously shown that the timing of maximum soil moisture is more important than that of extreme precipitation for determining flood timing in English catchments with large subsurface water storage (Bayliss and Jones, 1993; Blöschl et al., 2017).

Minor decreases in precipitation under eCX for RCP8.5 (from May to September) and small decreases under the UKCP18 (from May to October) outline high risks of decreasing streamflow for summer (low flows) in the Rother and across the whole flow duration curve and almost the whole year in the Idle. The high permeability, infiltration rates and base flows of catchments such as the Idle represent important drivers of predominantly decreasing streamflow. The high(er) infiltration rates of precipitation and importance of summer precipitation for groundwater recharge imply that decreases in precipitation lead to more severe decreases across a longer time in this catchment. This is also reflected in autumn streamflow projections; they are projected to decrease under both high emissions ensembles subject to decreasing precipitation in summer and projected to increase under low and medium emissions subject to stable summer precipitation. Streamflow in the Rother on the other hand is responsive to both increases as well as decreases in precipitation with the direction of change projected for streamflow largely aligning with that of precipitation. These results fall in line with the national-scale analysis of Great Britain by Rudd et al. (2017) that showed that groundwater dependent regions experience long(er) and more severe droughts under drier climate. For both (types of) catchments, the high importance of fewer months for aquifer recharge suggests a higher sensitivity to droughts in these months (Hughes et al., 2021). The differences in relief reflect most strongly in the projected changes to high flows. Increasing high flows drive annual streamflow increases, under all scenarios in the Rother and under low and medium emissions in the Idle. They are due to a change in rainfall timing, occurring when soils are saturated, but they are also triggered by increasing rainfall intensities in autumn and winter (Murphy et al., 2018). These translate into more increases in high flows in steep, moderately permeable, coastal catchments like the Rother. Minor changes in precipitation rates under all scenarios imply beyond 10% runoff increases in this catchment. The differences found for the catchments are indicative of trends

characterised by Prudhomme et al. (2013) who classified British catchments according to their flood sensitivity to climatic change and found a considerable influence of physical catchment properties but few geographical patterns. The predominantly negative streamflow response of the Idle is likely amplified by its flat relief allowing more time for rainfall to infiltrate its permeable soils.

3.4.3 Management Implications

The evidence presented in this study highlighted the advantages of augmenting the UKCP18 Regional Projections with eCX as recommended by the Met Office (Murphy et al., 2018). It provides greater certainty to water managers as the dynamics of changing flows under a range of climate change uncertainty could be detailed. Furthermore, a high range of potential changes in flow was outlined for the high emissions pathway. This allows managers to assess the limits of management options across a range of risks under the same emissions pathway.

Reductions in low flows could have serious consequences for the aquatic ecosystem, adversely affecting dilution of nutrient and pollutant loads (Charlton et al., 2018; Pathak et al., 2021), increasing the probability of harmful water temperatures (Mosley, 2015) and altering physical characteristics of habitats (Laizé et al., 2014; Rolls et al., 2018). Moreover, domestic and agricultural water supply might not be guaranteed. Emergency water restrictions such as through emergency drought orders (Defra, 2016b) can have serious societal, economic and environmental consequences (Environment Agency, 2014b). In all catchments yet particularly in those with high rates of water withdrawals such as Idle and Rother, risk averse and robust management therefore requires relieving pressures from low flows by reducing rates of water abstractions.

The results presented in this study emphasise this importance. In the Rother, decreases in low flows at Q_{95} are projected under all assessed ensembles. Since pronounced decreases on the monthly scale were only found under UKCP18, this indicates the need for flexible and reactive water management. Thus, abstractions can be reduced during days of extreme low flows which might occurr throughout the year. Measures to achieve this include real-time monitoring supporting water co-management (Ellison et al., 2019) and more flexible abstraction licenses (Wilby et al., 2011). To develop appropriate alleviation measures, key sensitivities of the river's ecology should be established such as to increased streambed drying (Font et al., 2021; Verdonschot et al., 2015). Highly risk-averse adaptation would entail adapting to decreasing streamflow from May to November as projected under UKCP18. This would necessitate considerable change to current demand structures and likely include increased water reuse (Allam et al., 2016).

The increases projected for winter high flows in the Rother under all climate ensembles assessed in this study suggest that despite no scope for new licenses, securing future water availability and supply to abstractors can be supported through withdrawals of "bonus water" during (winter) floods (Defra, 2016). This would require the introduction of suitable and flexible storage infrastructure (Perry and Praskievicz, 2017) subject to

feasibility studies and potentially significant financial investments and resistance of local stakeholder groups (Hakimian, 2022; International Water Management Institute, 2009; Wolsink, 2010). The main options are above ground storage through large reservoirs (Di Baldassarre et al., 2018), distributed (agricultural) water storage for example through retention ponds (Berry et al., 2017; Weatherhead et al., 2014) and below ground storage in unconfined or confined aquifers (Gale et al., 2002). In combination these measures would provide more resilience to react to changing water availability and alleviate the lack of water for abstractors while reducing abstraction stress on aquatic ecosystems, particularly during low flow periods.

The projections on increasing winter high flows furthermore suggest an increase in the frequency and magnitude of floods, a widely observed (Blöschl et al., 2017; Hannaford et al., 2021; Marsh et al., 2013; Schaller et al., 2016) and researched (Fowler and Wilby, 2010; Kay and Jones, 2012; Sayers et al., 2020) risk of climate change in England. Among other aspects, strategic flood risk management involves avoiding inappropriate developments and maintaining flood defense assets (weirs, pumping stations, river channel walls etc.) (Environment Agency, 2022d). The projected increases for high flows in the coastal catchment coupled with increasing runoff intensities might furthermore exacerbate erosion, sedimentation and pollution from increased transport of organic and inorganic matter into the river (Eekhout et al., 2018; Nilsson and Renöfält, 2008). Mitigation that protects the freshwater ecosystems of the Rother and catchments with similar relief, soil type and intensive farming from increasing sedimentation need to be expanded (Boardman et al., 2020). Typically applied measures are retention structures (Quinn et al., 2007) and buffer strips (Muscutt et al., 1993). The large scope for land use adaptation when revising catchment management to account for climate change has been recognised by the priority catchment project (Carbó et al., n.d.; Craigen et al., 2021).

Under the low and medium emissions, the increases projected for autumn and spring with largely no change projected for summer indicate easier adaptation for water management under these scenarios. However, high flows are also projected to increase and low flows are projected to decrease. Due to its importance for low-flow protection, the risk averse adaptation to high emissions scenarios with the aim to supply continued access to water is therefore likely a robust decision under these lower emissions pathways as well. The formation of ecological bottlenecks (Maron et al., 2015) due to exacerbated tapping into water needed for the environment is more easily prevented. Abstraction (licenses) could be shifted from summer to all other seasons.

Comparing the findings for the two catchments indicates that protecting environmental flows and fulfilling anthropogenic water demand under climate change likely poses a larger challenge in the lowland Idle than in the coastal Rother. For adaptation to low and medium emissions, solutions as outlined for the coastal catchment might be advisable for both. However, shifting water use from summer to the other seasons is not a robust option under high emissions for the lowland catchment. Due to the greater

chance of supply limitations and considerably high abstraction rates (64% at Q_{95}), a clear focus should instead lie on precautionary adapting to lower flows across most of the year. Real-time monitoring (Ellison et al., 2019), investment in storage infrastructure (Perry and Praskievicz, 2017) and more flexible abstraction licensing (Wilby et al., 2011) outlined for the coastal catchment are also appropriate. Projections under high emissions indicate a higher urgency to reduce abstraction rates and increase water returns (non-consumptive water use) for achieving environmental objectives. Additionally, there is a great risk of groundwater resources not adequately replenishing (Hughes et al., 2021; Marsh et al., 2007). This reflects in decreasing streamflow projections under high emissions for both December and particularly January despite increasing rainfall. Groundwater recharge is moreover threatened by the dry period starting earlier with rainfall decreases projected from May onwards and streamflow decreasing from April onwards under both high emissions ensembles. Adaptive groundwater management necessitates intervention based on locally derived projections because recovery times of groundwater droughts are highly dependent on local precipitation patterns and aquifer sensitivity (Hellwig et al., 2021). The risk of climate induced decreases in streamflow aggravating environmental protection and demand fulfilment has been recognised by the Idle's priority catchment project. Its guidance outlines a range of measures to achieve risk averse management including water demand reductions for example through adapting to less water sensitive crop types and examining potential use of winter runoff for aquifer recharge and storage for agriculture (CaBA, 2021).

3.4.4 Naturalisation and its Implications

As outlined in the introduction, in highly influenced catchments the uncertainty of the variable the HM is calibrated on, in this case streamflow, requires particular consideration. There are several methods available for removing the effects of anthropogenic activities from gauged streamflow. For assessing the two case study catchments the effects of large amounts of water withdrawals had to be accounted for. Detailed information on licensed volumes and locations of abstractions is not publicly available for input to SWAT+. Unfortunately, a recent dataset of national scale discharge and abstraction measurements developed by Rameshwaran et al. (2021) does not provide the required resolution and detail for these highly influenced basins. Gauged flows were therefore naturalised outside of the HM, using the information available in the catchments' CAMS ledgers (Environment Agency, 2018a,d). This represents the current best-practice approach that is also applied for environmental flow regulation by the EA (R. Soley 2019 personal communication, 5 July). CAMS is a spreadsheet tool that relies on detailed inputs including gauged flows, location and rate of abstraction, return flow/discharge and groundwater response. It represents a simple model often extended by more complex groundwater modules (LowFlows 2 https://www.hydrosolutions.co.uk/software/lowflows2/), it produces typical patterns of recent abstractions and is subject to uncertainties arising from input data and model structure (Environment Agency, 2021c).

The use of daily flow naturalisation and calibration data with high confidence was not possible due to the high number of abstractors and difficulty in separating natural from artificial effects such as groundwater withdrawals. There is nevertheless reason to have confidence in the monthly naturalisation applied in this study as the monthly net upstream artificial influence is well represented in CAMS. Without a comparison of the outputs from SWAT+ calibrated on flows naturalised in another way, the uncertainty associated with naturalisation is however hard to quantify.

The major limitation arising from naturalisation is the considerable short baseline on which subsequent analyses were based. In general, a minimum of 30 years is recommended for regional impact studies (Liersch et al., 2020). However, the current baseline for naturaliasion used by decision makers (commonly 1990-2007 (Environment Agency, 2009)) in water management and environmental flow planning in England meant that a 17-year naturalisation and hence climate impact baseline had to be used, as this is what is available from the CAMS. Despite the importance of climate impact assessments in highly influenced catchments (Bisselink et al., 2018) there is little research linking the effects of naturalisation with the uncertainties associated with climate impacts derived from short baselines. In this study, the basic statistical properties of the Rother's climate and natural streamflow variability were likely not adequately covered by the baseline period as its hydro-climate is characterised by considerable inter-annual rainfall variability (NRFA, 2017b). Projected streamflow responses, particularly under low and medium emissions, are difficult to separate from high natural "internal" climate variability (Deser et al., 2012; Frankcombe et al., 2015) and the variable direction of change seen in spring and autumn projections might be one example where the high internal variability of the GCMs is concealing climate forcing. The outlier for December streamflow projections received under HAD-HAD RCP2.6 is partly due to this GCM-RCM combination simulating particularly low December streamflow in the reference period. A longer baseline might have facilitated the inclusion of wetter December simulations/observations prior to 2001. The magnitude of projected changes might have been smaller for this month under this ensemble member in the future. Nevertheless, while a longer baseline might have provided a more accurate picture of natural variability, the high uncertainty inherent in abstraction effects (of a longer period not comprehensively recorded by CAMS) outweigh this consideration (Liersch et al., 2020). The focus of this study lay on determining projected climate impacts based on the current situation and this baseline is therefore justifiable. The use of both an MME and a PPE allowed a number of baseline simulations with varying internal variability and a wide range of potential future outcomes to support decision making could be described. Future research on hydrological climate impacts should either aim for a good explicit representation of water use activities through the HM or, if this is not feasible, assess approaches to naturalisation that produce longer time series of realistically naturalised streamflow.

This is an instance highlighting the importance of tuning the modelling approach to the questions that are to be answered. Careful consideration and weighting are needed to adapt the required detail to the modelling scope. In studies with another spatial scale or

in other catchments, it might be easier to model water use due to less influence of small abstractions and/or fewer larger water users. These are easier to explicitly represent in existing HM modules. Furthermore, for other catchments the data coverage of (public) water use information might be available at the required resolution. For studies of the UK, the dataset by Rameshwaran et al. (2021) might be suitable

3.4.5 Climate Model Uncertainty - Parameters and Model Structure

Due to its significance for understanding the implications of different climate projections for streamflow, water availability and adaptation management, a major focus of this study was exploring uncertainty. An important finding is that the parametric uncertainty sampled in the UKCP18 Regional Projections translates into an equally large and often larger model spread as well as into higher variability in streamflow projections than the GCM structural uncertainty sampled through the eCX MME. The eCX projections stem from five different GCMs with single (stable) parameter settings across six different GCM-RCM pairs across three emissions scenarios.

The UKCP18's model ensemble members 9 and 13 are at the dry end across all projections, while wettest projections were received under IPSL-WRF for RCPs 4.5 and 8.5 and under HAD-HAD for RCP2.6. Due to eCX not allowing for a balanced study design, a systematic uncertainty analysis, e.g. with ANOVA, was not possible (as detailed in the introduction). Instead, the results on projected changes to streamflow were extended with a brief analysis of variability introduced by different ensemble members as described through the standard deviation. It has shown that variability within the UKCP18 is high but not generally higher than within the eCX ensembles. This highlights the need for an improved separation of uncertainty contribution. Knowing main drivers of different aspects of change and improving adaptation measures accordingly would allow to enhance their robustness (Babaeian et al., 2021; Dessai and Hulme, 2007). Hurk et al. (2014) for example quantified the contributions of emissions scenarios, model response and natural variability in the range of temperature and precipitation response of CMIP5 over Western Europe.

A key conclusion of this study is that GCM specifications strongly influence hydrological projections. It would therefore be useful to assess UKCP18-introduced sensitivity and to establish a more detailed picture of how different parameter settings translate into streamflow responses. Unfortunately, background information on GCM parameter settings within the UKCP18 PPE is not available (Pacchetti et al., 2021).

GCM structure, parameterisation and feedback simulation are generally seen as the largest source of uncertainty in hydrological climate impact modelling (Hattermann et al., 2018; Vetter et al., 2016). The use of several GCMs reflected most strongly in the high variability in the near future under low and medium emissions, indicative of the uncertainty introduced by GCM internal variability (Giorgi, 2002; Hingray and Saïd, 2014; Lafaysse et al., 2014). However, RCMs can also contribute considerably to uncertainty, as reflected in the large difference in projections received from IPSL driving the two

RCMs, REMO and WRF, under RCP8.5 for both catchments. A balanced design such as with a smaller subset (Christensen and Kjellström, 2020; Kiesel et al., 2020) or produced through post-processing (Evin et al., 2019) might shed light on dominant modes of climate change in the future. However, these approaches cannot account for general limitations of MMEs. These include the limited number of models, their potentially extreme behaviour, unclear distribution in the parameter space and the exchange of code between models (lack of independence) (Knutti et al., 2010, 2013).

Watterson et al. (2014) have shown that some GCMs perform considerably better in their home domain. In their study CNRM-CM5 performed best across all tested domains, followed by MPI-ESM and HadGEM2. Recent advances have focused on weighting different MME members based on their performance, usually in large scale atmospheric circulation, during the observations period (Christensen et al., 2010; Gillett, 2015). Another approach lies in evaluating performance to create a subset (Fernandez-Granja et al., 2021; Palmer et al., 2022). Particularly due to its importance for winter rainfall, for Northern Europe the climate model performance in representing North Atlantic Oscillation variability is an important criterion (Hurrell and Deser, 2010; Scaife et al., 2014). Selecting model members based on their performance in simulating this large-scale variability has been proven to improve flood (Moulds et al., 2022) and low and high flow projections (Donegan et al., 2021). Chen et al. (2017) and Wang et al. (2019) have however shown that if bias correction is applied, the hydrological projections received with MMEs under streamflow-based weights do not significantly differ from non-weighted MME projections. This study has not evaluated individual GCM-RCM performance in the observations period. With regards to reproducing naturalised observed streamflow, it however showed that simulations under the ensemble mean and median of the bias corrected UKCP18 do not outperform those under mean and median of three eCX ensembles. In the Rother, the eCX perform better while in the Idle the UKCP18 are closer to observations. Given the UKCP18's and eCX's known biases, a more balanced study design with the best performing GCM-RCM pairs (Palmer et al., 2022) or post-processing to distinguish internal variability (Deser et al., 2012) appear as most useful extensions of this study.

The application of climate scenarios across three different GHG concentration pathways has facilitated to analyse the streamflow effects under different socio-economic pathways. In the Idle the differences in outcomes across the three RCPs are more pronounced than in the Rother where annual streamflow was projected to increase similarly under all four scenarios. An important finding is that in both catchments, the high emissions scenarios are consistent and agree on the direction of change in monthly to annual streamflow with higher magnitudes of change projected under UKCP18. In the Idle the projections under high emissions translate into a strong drying under both ensembles, while low and medium emissions are markedly wetter and imply more increases instead of decreases in monthly streamflow.

The main conclusion to be drawn is that the excessive climate sensitivity caused in part by the biases found in HadGEM3 (Vautard et al., 2019) and the methodology for selecting the PPE (Rostron et al., 2020; Yamazaki et al., 2021) translates into a strong and largely dry hydrological response. The extension with eCX has allowed to capture some of the wetter end of the climate change uncertainty range. By using the UKCP18 supplemented with by eCX, water managers are provided with detailed flow dynamics under a wide envelope of uncertainty.

3.4.6 SWAT+ Model Uncertainty

SWAT+ models were successfully calibrated and validated for both catchments. The choice of a baseline of 17 years from 2001 to 2017 was guided by limited availability of abstraction information. The focus of this study lay on producing robust projections of river flow that can inform water management (e.g. for assessing water availability for different uses as explored in the next chapter). By determining an optimised set of 50 parameter combinations one aspect of HM-related uncertainty, the parameter uncertainty was accounted for in future streamflow projections. All 50 models performed good or very good in simulating naturalised observed streamflow according to five efficiency criteria. It was therefore assumed that major processes controlling streamflow in the catchments were simulated accurately, allowing robust estimates of natural streamflow.

The bias correction with LS strongly improved streamflow simulations under modelled climate. The wet bias was reduced and simulations' performance improved and aligned in all efficiency criteria other than NSE_{inv}. Flows for the Idle were generally simulated as too low when run with bias corrected climate projections. Low flow simulation is a common challenge of hydrological modelling with many studies reporting difficulties (e.g. Lee and Bae, 2016; Tian et al., 2014). In a national-scale analysis of Great Britain with the G2G model Rudd et al. (2017) found that low flow performance strongly depends on the considered catchment. Since a large share of simulations under observed climate performed good or very good, low flow processes are likely simulated well. It is however unclear how the dry bias during the observation period under simulated climate compounds the drying effect described in the future. Unfortunately, the strong effects of abstraction imply that a calibration with daily observed flows is unlikely to provide more insights.

Examining the 20% driest and wettest parameter combinations allowed some insights to HM parameters' role in climatic response. It was shown that by separately maximising individual efficiency criteria while accepting less than optimal performance across other criteria, some drier catchment responses were obtained. Particularly in the Idle, four of the five runs maximising efficiency descriptors were part of the ten (20%) driest future simulations. While the variability, and by proxy the uncertainty, introduced through HM parameters is considerably smaller than the uncertainty introduced by different GCM-RCM, this finding emphasises the importance of accounting for different expressions of hydrological processes for future projections. Due to the limited number of simulation

runs an analysis of the significance of different parameter expression was not undertaken. Nevertheless, some broad patterns were identified. One finding is that many of the influential parameters relate to land use.

Wet projections in the Rother were shown to be connected to high values of available water content (awc), this parameter is correlated to evapotranspiration but also affects percolation to shallow and deep aquifer (Garcia and Tague, 2015, Selle et al., 2008). Green water has been shown to be less sensitive to climate change than blue water (Jeyrani et al., 2021; Shrestha et al., 2017b). High values of awc suggest green water to play a more important role in wetter projections as, in combination with the soil layer depth z, awc determines green water storage (Zhu et al., 2018), the part of precipitation that is stored in the root zone and does not contribute to surface or groundwater runoff (Falkenmark, 1995). Due to their strong influence on infiltration patterns both green water and available soil water content are highly related to land use (Falkenmark and Rockström, 2010). Moreover, eight of the driest projections were observed with very low settings of cn2, the curve number for predicting runoff at average soil moisture. This is another indicator of the importance of land cover for determining streamflow response in these catchment models – lower cn2 means higher (quicker) runoff and less infiltration and (potentially) more groundwater depletion (Kiprotich et al., 2021). The findings for the Idle also suggest a connection between high values of awc and wetter projections. Furthermore, some of the wettest Idle projections showed low values in epco, the plant uptake compensation factor. Together with esco, this parameter determines water allocation between percolation and ET (Wu and Johnston, 2007). It specifies which soil layers contribute to plant water demand with lower values indicative of upper soil layers meeting water demand (USDA-ARS & Texas A&M AgriLife Research, 2020). Together, the sensitivity of these parameters indicates that land use is also important in the Idle.

It was shown that different SWAT+ parameter settings have the highest influence on streamflow volume during autumn (Rother) and late spring (Idle) while these settings introduced least variability in winter. The highest intra-ensemble variability was found in the UKCP18-driven projections. This is due to drier streamflow projections under this ensemble. Infiltration, evapotranspiration and other hydrological processes play a major role in determining flows during times of little to no rainfall (Hagemann et al., 2013; Maurer et al., 2010). While another reason could be the lower performance of SWAT+ for low flows compared to high and mean flows, these findings are consistent with those of other studies showing that uncertainty introduced by HMs is highest during low flows (Lee and Bae, 2016; Vetter et al., 2016). In the catchments, aquifer levels are at their lowest point towards the end of summer (Rother) and respectively spring (Idle) before the recharge period when different settings of parameters such as alpha, flo_min and awc exert the highest influence on streamflow outcomes.

Only one aspect of HM uncertainty, the parameter uncertainty, was sampled and while SWAT+ performed well in simulating observed streamflow, the implications of different HM structures and of input data uncertainty were not considered. Maurer et al.

(2010) and Velázquez et al. (2013) found that HM structural uncertainty most strongly affects low flow climatic response and has fewer implications for high flows. Studying three HMs in Eastern China, Tian et al. (2014) found that parameter uncertainty outweighed model structural uncertainty's effect on streamflow projections. The contributions of the different sources of HM uncertainty are very dependent on study focus – the HM should be fit for purpose and the modelling process and the broad order of uncertainty contributions should be evaluated Abbaspour et al. (2018) and Addor and Melsen (2019). For calibrating and validating SWAT+ this study used climatic data from two main sources – the HadUK gridded climate dataset (Hollis et al., 2019) for temperature and precipitation as well as the MIDAS dataset for solar radiation, relative humidity and wind (Met Office, 2019). Due to a lack of data points, short-wave solar radiation in the Idle was extracted from the CFSR dataset for the SWAT Weather Generator (https://globalweather.tamu.edu/#pubs). CFSR relies on long term weather statistics and has been proven a good alternative as model input in data sparse regions (Cuceloglu and Ozturk, 2019; Gu et al., 2020). The quality of such reanalysis solar radiation as input for hydrological modelling studies has been shown to significantly affect runoff and ET simulation (Badgley et al., 2015; Hinkelman et al., 2015). Considering that precipitation is the dominant climate input variable introducing the highest share of uncertainty (Bárdossy et al., 2022), this study nevertheless deemed the uncertainties introduced through solar radiation from the Weather Generator as acceptable and smaller than those introduced by records from a distant station.

HM input interacts with HM structural uncertainty and the effects of high (rainfall) uncertainty strongly affects low flow simulations (Zhou et al., 2021). Pokorny et al. (2020) assessed how the effects of biases in gridded climate input data depend on the aggregation in the HM. They found a non-linear relationship between level of aggregation and input uncertainty with some spatial aggregation improving the performance and too much aggregation reducing performance. This indicates the advantage of (semi-) distributed HMs such as SWAT+ over lumped HMs when applying gridded input, such as the HadUK precipitation and temperature datasets.

3.4.7 Next Steps and Research Needs

The results on projected changes to monthly streamflow obtained for four climate ensembles in this chapter serves as input for the next chapter illustrates different environmental flow scenarios' implications for water availability. With regards to other potential extensions of this study, the considerable effect of land use (change) on streamflow (Gerten et al., 2008; Rost et al., 2008), reflecting in several of the sensitive HM parameters requires more detailed analysis. Land use change has previously been assessed with SWAT – separately and in combination with climate change (Tamm et al., 2018; Trolle et al., 2019; Zhang et al., 2020) and its ability to implement diverse land management practices is a major strength of the new SWAT+. An opportunity for extending this study for supporting decision making in the priority catchments and elsewhere therefore lies in the implementation of an improved land use scheme. Land use scenarios

could be evaluated with regards to implications for climate change adaptation, their effect on soil moisture (Pirret, Fung, Mitchell, and McInnes, 2020; Samaniego et al., 2018) crop yields (Qi et al., 2018), environmental flows (Pastor et al., 2019) and reduction of sediment (Bussi et al., 2016) and nutrient loads (Hutchins et al., 2018).

Appropriate water management, particularly in very permeable catchments furthermore requires a comprehensive understanding of groundwater-surface water interaction and the effects of climate change and abstraction on these processes (Griffiths et al., 2006). While SWAT+ simulates aquifer recharge and simple groundwater-surface water exchanges, it has not been calibrated with groundwater information of the study catchments and does not explicitly consider distributed groundwater processes (Kim et al., 2008). SWAT+ offers the possibility to enhance groundwater interactions through extension with the groundwater model MODFLOW (Bayliss et al., 2020) and there are efforts in advancing models of specific aquifers such as the Sherwood Sandstone Aquifer that contributes to Idle streamflow (Zhang and Hiscock, 2010). Considering the strong impacts of climate change found in this study of one moderately permeable and one very permeable catchment, a major recommendation is to improve the understanding of the groundwater processes controlling low flow hydrology and their sensitivity to climate change (Berg and Allen, 2007; Graaf et al., 2014). This study found a clear seasonal shift in recharge in both catchments. In a study in Germany, Hellwig et al. (2021) found that hydrogeological conditions determine groundwater drought recovery time and that baseflow drought severity is more dominated by dry spell length than by a shift in seasonal recharge. The aquifer response and sensitivity to increased and prolonged summer drying and increasing winter rainfall as well as interaction with surface and groundwater withdrawals therefore represent major research needs to support robust water management and resilience of groundwater to climate change (Taylor et al., 2013). Next to the effects of increasing winter precipitation, due to their importance for water management and environmental protection, a particular focus should also be on the effects of more pronounced and prolonged dry spells, and the sensitivities to winter droughts (Hannaford et al., 2014; Stoelzle et al., 2014). To improve low flow simulations a focus should lie on representing groundwater exchange processes and it might also be useful to perform daily calibration and bias correction appropriate for extreme events (such as dry spells). While this would be particularly useful in the Idle where low flow volume was not adequately simulated, detailed information on actual daily abstractions is hard to come by. Low flows are not only affected by parameter uncertainty but HM model structure plays a considerable role (e.g. Maurer et al. (2010)). This study applied the new SWAT+ but future assessments might consider using a HM MME to closer establish the implications of HM structure and parameter space. For example the Enhanced Future Flows and Groundwater applied four HMs to produce climate projections under UKCP18 for 200 UKBN catchments (Hannaford et al., 2022).

This study found a stronger hydrological response and a larger spread in streamflow simulations under the HadGEM3-driven UKCP18 Regional Projections than under an unbalanced subset across three RCPs of the eCX MME. This indicates the need to

closer establish the relationship between climate model settings as sampled through the different UKCP18 model members, future projections and streamflow response. Another important aspect is that the wide range of uncertainties within the coupled hydrological climate impact modelling chain at the regional scale can make supporting scenario-led climate adaptation very complicated (Wilby and Dessai, 2010). Against this background, other approaches to support decision making are emerging, such as the storyline approach (Shepherd et al., 2018). The storyline approach relies on developing a qualitative understanding of the range of future pathways, their interaction with particular vulnerabilities, compound risks and regional sensitivities. Stakeholders and climate scientists could cooperatively develop plausible scenarios of adaptation and event-based climate risks to evaluate outcomes and manage risks (Sillmann et al., 2021).

The UK-specific SSPs developed by Pedde et al. (2021) lend themselves for further scenario-led impact analyses. Also the UKCORDEX project, which ended in October 2022, aimed to close the gap between the UKCP18 and eCX projections by providing regional scenarios of both for use in impact studies similar to this one (UKCORDEX, 2022).

3.5 Conclusion

This study analysed streamflow projections for two English catchments with different geographies. It was shown that, while outlining consistent directions of change in streamflow, the two chosen sets of projections for high emissions pathways, one a product from UKCP18 (a PPE of the Hadley Centre's GCM), the other a set of six RCM-GCM combinations from the eCX initiative, differ strongly in their implications for hydrology. Both products contain biases. The UKCP18 projections have a particularly high climatic sensitivity and some of the eCX have been shown to strongly overestimate observed precipitation. The UKCP18 imply a markedly stronger, overall distinctly drier hydrological response and a larger spread of streamflow projections. The low and medium emissions scenarios, chosen from a subset of eCX projections, outline some wetter futures in both catchments. The two products thus complement each other well and this study covers a considerable range of uncertainty. It particularly emphasised the implications of different GCM parameter settings as significant sources of variation. Changes to streamflow projected under UKCP18 provide the basis for cautious and risk-averse decision making and limitations of adaptation measures to high-end outcomes can be established.

The catchments physical characteristics are important for modulating hydrological response to changing climate. Streamflow changes in the Rother largely align with projected changes in precipitation while the streamflow in the Idle is less responsive to increasing precipitation and infiltration processes play a larger role.

The findings suggest that, should decision makers want to adapt to the risks under high end projections, they need to implement measures that mitigate the effects of decreasing summer streamflow and pronounced decreases in low flows for a large range of catchment types. Furthermore, due to potentially strong increases in winter streamflow, flood risk adaptation will be required in coastal catchments such as the Rother. In lowland catchments such as the Idle adapting to decreasing streamflow across the whole flow duration curve is appropriate. Measures aiming to alleviate the effects of decreasing low flows are robust under all assessed ensembles in the Rother as, subject to storage infrastructure, is shifting abstractions from summer to winter. In the Idle the direction of change projected under different ensembles differs more strongly. Shifting abstractions to winter is only appropriate under low and medium emissions. The considerable range of uncertainty outlined in this study, emphasises that cautious adaptation with the aim to alleviate pressures on freshwater ecosystems should focus on reducing abstractions.

The next chapter evaluates new environmental flow allocation scenarios in terms of water availability for demand fulfillment and the environment. The projected monthly changes in streamflow under the four assessed ensembles serve as climate change scenarios.

Chapter 4. Environmental flow protection in the face of climate change and increasing water demand, lessons from England

Abstract

The problems faced by environmental flow protection are often “wicked” as they cannot be clearly defined, are subject to a range of uncertainties and do not provide clear-cut solutions. For overcoming wicked problems, the multi-disciplinary operating space of water management i.e. its political, governance and social dimension has to be taken into account. This multi-disciplinary study combined qualitative data gathered through stakeholder consultation and a simple water balance model. Using England as a case study, five scenarios for environmental flow allocation were evaluated and the deficiencies of current water management and governance in addressing existing and emerging pressures were established. Finally, five strategies for closing adaptation gaps and improving water management in a way that maximises outcomes for the environment and human water use under climate change were articulated and discussed.

It was shown that allocation scenarios that integrate climate change, accounting for its effects on flow regimes, might perform better at fulfilling demand and balancing water use with environmental needs. Particularly if water use is shifted between seasons (e.g. from summer to winter in catchments important for water abstractions) the potential for fulfilling and improving environmental flow protection may be realised. However, particularly in summer across a range of different catchment types and especially in those with high existing pressures, considerable changes in current water use are needed to attain any environmental flow protection under climate change.

Stakeholder consultation identified the need for an enhanced evidence base for innovative and confident decision making across spatial scales. This can be achieved by improved monitoring and collection of water flow and quality data, regional modelling, data sharing and improved data access. Furthermore, the high scope for demand reductions to alleviate pressure on water resources was emphasised. Leakage reduction was strongly endorsed by stakeholders as was metering and wider consultation on the location of new housing developments. Strengthening integration of catchment management by increasing the Environment Agency’s financial support and its coordination of processes with other regulators are also needed. A clearer policy focus and new policy for land integration as well as a shift towards allowing uncertain outcomes in environmental improvements are required. Moreover, the importance of clarifying different actors’ responsibilities and roles, power sharing and a higher focus on cooperation among the many successful schemes already established in England was highlighted. A fifth proposal considers the large scope for realising a multitude of synergies by embedding and restoring natural processes and ecosystems and learning from historic land uses incorporating natural land-water exchange processes.

4.1 Introduction

Civilisations evolved alongside and in close interaction with freshwater and their resilience is tightly linked. The pathways and limits of human development should therefore be governed by the requirements for water resilience (Boltz et al., 2019). To protect freshwater ecosystems from (further) deterioration from human activities including pollution, abstraction and impoundment, the protection of environmental flows is recognised as the best approach (10th International River Symposium, 2007; Arthington et al., 2018b).

Under climate change and increasing water demand the protection of environmental flows becomes more difficult and expensive (Vanham et al., 2022). One reason lies in water management having to address problems that are wicked or messy in nature (Rittel and Webber, 1973) because (1) they are perceived differently by different actors and have multiple definitions; (2) they do not allow for clear criteria for their solution; (3) the solution for one interested party is a problem for others; (4) they are subject to a range of uncertainties caused by limited data, information and knowledge and (5) there are no obvious stopping rules that define when enough has been accomplished (Cosens et al., 2014; Freeman, 2000; Pahl-Wostl, 2007). These characteristics of water management have been linked to lock-in dynamics in water governance (Lobina, 2019). Lock-ins emerge when it becomes extraordinarily expensive or impossible to leave the current development pathway due to a strong “tendency for past decisions and events to self-reinforce, thereby diminishing and possibly excluding the prospects for alternatives to emerge" (Fleurbaey et al., 2014, p. 312). The major adaptation gap to climate change identified by the IPCC (2022) is particularly problematic for protecting appropriate environmental flows and achieving water resilience. It highlighted that observed adaptation is fragmented and too small in scale, sector-specific, focussed on planning rather than implementation and on near-term risks and existing impacts instead of near to long term vulnerabilities (IPCC, 2022).

Three interlinked concepts are central for addressing wicked problems, overcoming lock-in dynamics and closing water management’s adaptation gap to climate change: Integrated Catchment Management (ICM) Adaptive Management and the Ecosystem-Based Approach (EBA) (DeFries and Nagendra, 2017; Overton et al., 2014; Rouillard and Spray, 2016). ICM refers to sustainable resource management that takes a holistic view of the social and natural processes in a catchment and integrates land and water management (Fenemor et al., 2011; Molnar et al., 2002). It relies on the implementation of participatory and adaptive management approaches (Rouillard and Spray, 2016). The fundamental insight guiding adaptive management is that major future drivers, system behaviours and responses in natural resource management are highly uncertain (Pahl-Wostl, 2007). It describes a way of dynamic management based on simultaneous learning and decision-making. Through feedback mechanisms these learning cycles continuously improve the understanding and management of the resource system (Williams, 2011). A similar concept as ICM, EBA aims for sustainable resource use

and equity that relies on management of social-ecological systems in an integrated way (Cook and Spray, 2012; Shepherd, 2004). It recognises the interdependence of human and natural systems and that social, economic or ecological aims can only be achieved through conservation of ecosystem processes and functions (Overton et al., 2014).

The mechanisms embedded through the three concepts are central for strengthening environmental flow protection. In particular, learning cycles that proactively and collaboratively gather information (Mysiak et al., 2010), embrace diverse interests and local knowledge (Woodhill and Röling, 1998) and generate a shared understanding (Pahl-Wostl, 2007) while enhancing the flow of information (Stankey, 2005) can reduce uncertainty, overcome inertia and multi-stakeholder opposition (Medema et al., 2008; Pahl-Wostl, 2007). Transfer of management rights and power sharing is thereby integral for participation (Folke et al., 2005). Solving wicked problems furthermore requires strong inter-disciplinarity and collaboration across scales, aligning of planning processes and multi-actor cooperation (Freeman, 2000; Rouillard and Spray, 2016).

Chapter 2 illustrated the high variability of natural flow regimes and the complexity of defining characteristics for their protection. The third chapter presented the high range of uncertainties associated with hydrological impacts of climate change. Systematic environmental flow implementation to overcome these challenges requires understanding the interactions between social/political and environmental systems (Pahl-Wostl et al., 2013). Key deficiencies of water governance and management in protecting environmental flows must be determined and overcome by applying the mechanisms provided by ICM, EBA and adaptive management. Thus, water management and governance are rendered fit for the purpose of supporting thriving freshwater ecosystems, human demand and economies. The effects of (further) degrading water resilience, while poorly understood, could otherwise be considerable, large scale and irreversible (Falkenmark et al., 2019). This chapter explores this space by uncovering the social and political dimensions of freshwater protection.

4.1.1 Water Management and Governance in England

In England, the largest demand for water stems from public water supply (Environment Agency, 2018e). There are eleven privatised water and sewerage and six private water supply companies in England and Wales, funded by charges to customers (Ofwat, 2022m; Water Act, 2014). The most important water governance and regulatory bodies in England are the Department for Environment, Food and Rural Affairs (Defra), the Office of Water Services (Ofwat) and the EA. Defra is a ministerial department tasked with restoring and enhancing the environment (Defra, 2022a). Founded in 1989 when the water sector was privatised, Ofwat is a non-ministerial department of Defra funded by license fees recovered from water companies (Ofwat, 2022a). Currently in its seventh five yearly Asset Management Plan (AMP) period (2020-2025), Ofwat is tasked with setting price limits by reviewing the water companies' investment plans and estimates (Ofwat, 2022j,k). The EA is a designated non-departmental public body that

manages the water environment and has a statutory duty to secure the proper use of water resources in England. It plays a key role in providing data and evidence and in enforcing legislation (Environment Agency, 2018e, 2022f).

Water planning and management were underpinned by EU Directives and, in collaboration with Defra, the European Environment Agency coordinated compliance with the EU Directive 2000/60/EC (2000) (the WFD) and the Directive 2007/60/EC (2007) (the Floods Directive). Both were transposed into domestic law via the The Water Environment (Water Framework Directive) (England and Wales) Regulations (2017) and the The Flood Risk Regulations (2009). After Brexit, EU laws were transferred into UK law through the Environment Bill and subsequently the Environment Act (2021) which also established the Office of Environmental Protection at the end of 2021. This new independent public body has scrutiny and advice functions but also enforcement duties that pertain to water use (Environment Act, 2021). The main mechanism to establish the government's local ambitions for water are the River Basin Management Plans (RBMPs) produced by the EA and required by the WFD (Defra, 2021a). The policy framework for managing water resources in England is set out by the 25-year Environment Plan (Defra, 2018). The EA's National Framework for Water Resources (NFW) (Environment Agency, 2020d) is the main strategic document for delivering on its ambitions and shall be carried out through regional plans developed by five regional water resources groups made up of the water companies and other water users (Environment Agency, 2016a, 2021b). Statutory environmental obligations and requirements for investing in sustainability improvements for the water industry are set out in the Water Industry National Environment Programme (WINEP) for the subsequent AMP. As the most important environmental investment program in England, WINEP comprises monitoring, interventions, environmental assessments and asset improvements of £5.2 (2020-2025) (Environment Agency, 2022e).

4.1.2 Challenges for Environmental Flow Protection

Projections of population growth describe a future where, if unaddressed, England will not have enough water to meet demand by 2040 (Committee of Public Accounts, 2020). Depending on climate change and demand development, by the 2050s demand is projected to exceed supply by 1.1bn to 3.1bn litres per day (NAO, 2020). Particularly in London and the South East pressure on water resources is high, the head of the EA, James Bevan, described the phenomenon of water supply falling below demand as the "Jaws of death" (Environment Agency, 2019b). Next to increasing water demand, population growth is accompanied by urban sprawl, a rise in impervious surfaces and water pollution (Chithra et al., 2015; Cosgrove and Loucks, 2015; Tortajada, 2020). Against this background, the status of freshwaters is particularly jarring as abstraction in 8% to 18% of surface water bodies and 28% of groundwater bodies is unsustainable (Defra, 2021b) with only 16% of rivers in England attaining good status in 2019 (JNCC, 2021). Within the UK, the status of water bodies is worst in England with 55% of Scottish rivers meeting high or good status (JNCC, 2021). Overall, the status of UK surface water

bodies has not improved since 2009; 36% or 3,317 of UK surface water bodies were classified as being high or good status in 2020 (JNCC, 2022). It is therefore unlikely that the WFD requirement for all rivers to reach good status by 2027 can be achieved. A recent report by the Royal Society for the Protection of Birds (RSPB) (RSPB, 2021) calls for immediate action to reverse and prevent significant ecological damage due to declining water quality. While highly spatially variable, climate change is projected to exacerbate these pressures with significant streamflow decreases projected for summer, most pronounced in the South East (Kay, 2021; Rudd et al., 2019).

There have been a number of policies that, in a range of ways, aim to improve the outcomes for the environment and counter unsustainable abstractions while securing supply for growing populations. WINEP seeks to ensure sustainable abstraction by water companies while the EA is reviewing time-limited licences, adjusting permanent licences, revoking unused licences, removing under-used licences and taking previously exempt abstraction into regulation (Defra, 2017, 2021b). To strengthen the catchment based focus, the EA designated ten priority catchments where a range of stakeholders were tasked with developing and testing innovative approaches that allow greater access to water and tackle unsustainable abstraction (Environment Agency, 2021e). The NFW presented five scenarios for changing the way environmental flows (as expressed through the EFI) could be allocated. Using national scale modelling, it estimated water availability and demand across sectors and for environmental needs across the five regional groups. The NFW found that, to achieve water sustainability goals, all scenarios indicate a need to strongly reduce abstractions (Environment Agency, 2020d).

The high complexity of the institutional and governance framework of water management in England might exacerbate the uptake of mechanisms from ICM, EBA and adaptive management such as the integration of top-down national environmental regulatory goals with local, bottom-up collective action (Robins et al., 2017; Rouillard and Spray, 2016). Organisations follow their own strategies and while there are some collaborative processes across the water sector, the many alternative uses, competing needs and different perspectives on water allocation suggest a lack of strategic oversight of processes and their interaction (Robins et al., 2017). To address the criticism from non-governmental stakeholders on the lack of appropriate funding and multi-sectoral integration within the WFD implementation process, the Catchment Based Approach (CaBA) was set up (Defra, 2013). Through engaging actors from across society it aims to support bottom-up approaches and encourage wider adoption and delivery of ICM (Rouillard and Spray, 2016). While not specifically promoting adaptive management and EBA, CaBA's cyclic workflow is strongly adaptive (CaBA, 2022a) and informed by the natural capital approach (Bateman and Mace, 2020) which builds on EBA and only differs in the way target metrics are defined and measured (Judd and Lonsdale, 2021).

4.1.3 Aim of this Study

Against the background of existing and emerging challenges, using the example of England and drawing from stakeholder consultation and a simple modelling framework, this chapter scrutinises different environmental flow allocation scenarios and outlines the deficiencies of current water management and governance in addressing existing and emerging pressures. Making reference to the strategies of ICM, adaptive management and EBA, opportunities for closing adaptation gaps and improving water management in a way that maximises outcomes for the environment and for human water use under climate change are outlined and discussed.

4.2 Methods

To contextualise and provide practical examples of the multi-faceted nature of environmental flow protection against the background of climate change and population growth, a case study approach was chosen (Crowe et al., 2011). Applying a participatory multi-disciplinary process, modelled environmental flows under climate change were assessed alongside stakeholder perceptions of water management and governance within England. This approach aims to overcome the limitations of potentially partial mono-disciplinary methodologies inappropriate for addressing complex, wicked problems (Cosens et al., 2020; Termeer and Dewulf, 2018).

The first strand of data was produced using a simple time series water balance model for five case study catchments to evaluate the EFI suggestions made in the NFW (Environment Agency, 2020d). This allowed an evaluation of the required reductions and allowable increases in abstractions and return flows across different scenarios of environmental protection and climate change. Secondly, qualitative data gathered via semi-structured in-depth interviews with representatives of organisations relevant to the water management within the case study catchments and at the national scale was analysed and proposals for improved environmental flow protection were formulated. Extending the quantitative modelling results (section 4.2.1) with stakeholder perceptions (section 4.2.2) allowed the mapping of multiple dimensions which influence and can contribute to successful environmental flow protection (Hargrove and Heyman, 2020; Martin-Ortega et al., 2015; Stoate et al., 2019). The proposals for improving environmental flow protection were identified from the regulatory and organisational gaps defined by stakeholders as well as from mechanisms they suggested and endorsed. Where applicable, it was also evaluated how well mechanisms from ICM, EBA and adaptive management have been implemented or how their uptake could be encouraged.

4.2.1 Water Balance Modelling

To assess the implications of the NFW's environmental flow scenarios, a simple time series water balance model was developed in R. For every day the residual flow was calculated as natural flow plus climate change impact minus abstraction plus return flow (6).

$$\text{residual flow} = \text{natural flow} + \text{CC} - \text{abstraction} + \text{return flow} \tag{6}$$

CC - Streamflow changes under climate change "over-abstracted" if residual flow < EFI
"over-discharged" if residual flow > high-flow EFI

For every day the EFI was compared to the residual flow to determine if the EFI was met or not. When comparing the residual flow to the EFI for each day, the flow was considered as over-abstracted if the flow fell below the EFI. Vice versa if the flow was beyond the "high flow" - EFI the flow was considered as over-discharged. If it fell between the EFI

and the "high-flow" - EFI, residual flows and therefore water use of this day was within the limits set by the EFIs. Daily flows from the period 2001-2017, when abstraction rates and therefore natural flows are known, were taken as baseline. Both abstraction rates and return flows were held stable as observed during the baseline. Changes in demand (e.g. for growing populations) were therefore not explicitly considered. The NFW scenarios vary in the way climate change is considered in the calculations for the EFI's natural flow baselines and in the ASB taken for determining the EFIs (see section 4.2.1.2). The results were assessed on monthly scale. The focus of the evaluation was on;

one: change in over-abstraction (share of abstraction tapping into those flows protected for the environment as allocated by the EFI) and over-discharge (share of return flow exceeding the new EFI for return flows)

two: required changes to current water use strategies to meet the EFI scenarios (with regard to both abstractions and return flows)

Calculations were undertaken for the time period 2061-2080 (far future in Chapter 3) with reference to the baseline period on daily scale and aggregated to monthly scale for the analysis. This future period was chosen as it most clearly depicts the difference between the four climate ensembles and respectively scenarios.

4.2.1.1 Case Study Catchments

To represent environmental flow change and adaptation options across England's diverse river types identified in Chapter 2, a total of five catchments representative of each of the groups were modelled (Table 4.1 & Table C.1 in section C.1.1). Figure 4.1 shows their locations and Figure 4.2 details their water use structure. The main criteria guiding the choice of catchments was data availability - the catchments' CAMS should be fully accessible and flow records should be complete between 2001 and 2017. Furthermore, they should be located in England and have a catchment area of at least 100 km^2. Using these criteria three catchments of groups 2, 3 and 5 were found. Due to the varying hydroclimatic and water management regimes between the study catchments, subsequent modelling represents a range of impacts across England.

Table 4.1: Catchment classification (as identified in Chapter 2), catchment area, Abstraction Sensitivity Band (ASB) and dominant water use in the five case study catchments (NRFA (2019c)[a], NRFA (2022b)[d], NRFA (2022g)[e], NRFA (2019f)[h], NRFA (2022d)[j], Environment Agency (2018d)[b], Environment Agency (2020b)[c],Environment Agency (2020e)[f], Environment Agency (2018a)[g], Environment Agency (2020a)[i]).

	Idle	**Dearne**	**Darwen**	**Rother**	**Yare**
Catchment class	1	2	3	4	5
Catchment size (km^2)	529	118	128	346	231
ASB (band)	moderate (2)	moderate (2)	high (3)	moderate (2)	moderate (2)
Abstraction sources	public water supply & irrigation[a,b]	industry, irrigation[c,d]	public water supply, irrigation & industry[e,f]	public water supply& irrigation[g,h]	public water supply & irrigation[i,j]
Return flow sources	-	wastewater treatment & minewater[c,d]	wastewater treatment[e,f]	-	-

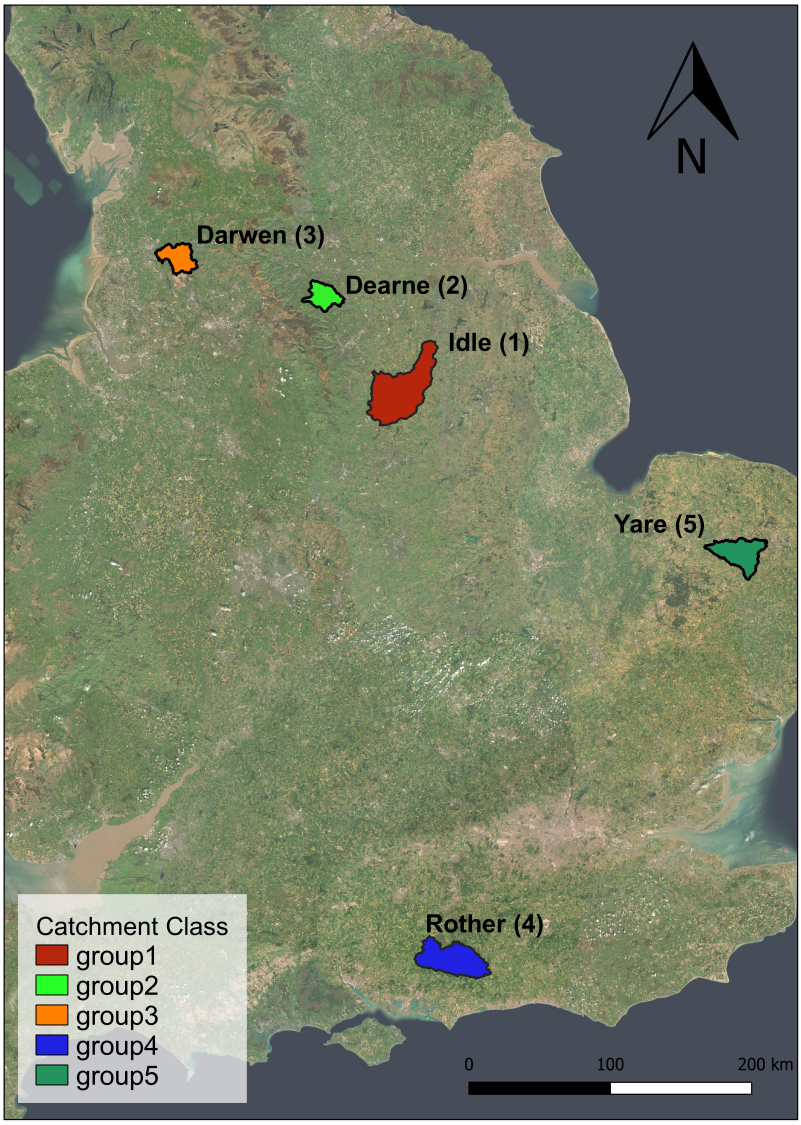


Figure 4.1: Location of case study catchments in England and their catchment class according to Chapter 2.

The Idle and Rother were once again used to represent groups 1 and 4, while the Dearne is part of group 2, the Darwen represents group 3 and the Yare is part of group 5. As shown in Figure 4.2, in the Idle, water withdrawals are tapping into the EFI across the whole flow duration curve while in the Yare and Rother over-abstraction mainly occurs during low flows. The Darwen and Dearne are predominantly affected by return flows (discharge rich), particularly during low flows.

The current EFI distinguishes three ASBs from 3 – "high" to 1 – "low", reflecting varying perceived sensitivity of waterbodies to changes from natural flow, and hence differing in allowable abstraction at four points on the FDC; Q_{30}, Q_{50}, Q_{70} and Q_{95} (Environment Agency, 2020f; Hall, 2008). While the EFI for all other catchments is allocated according to Band 2, abstractions in Darwen are restricted under the more sensitive ASB 3 (Environment Agency, 2020e).

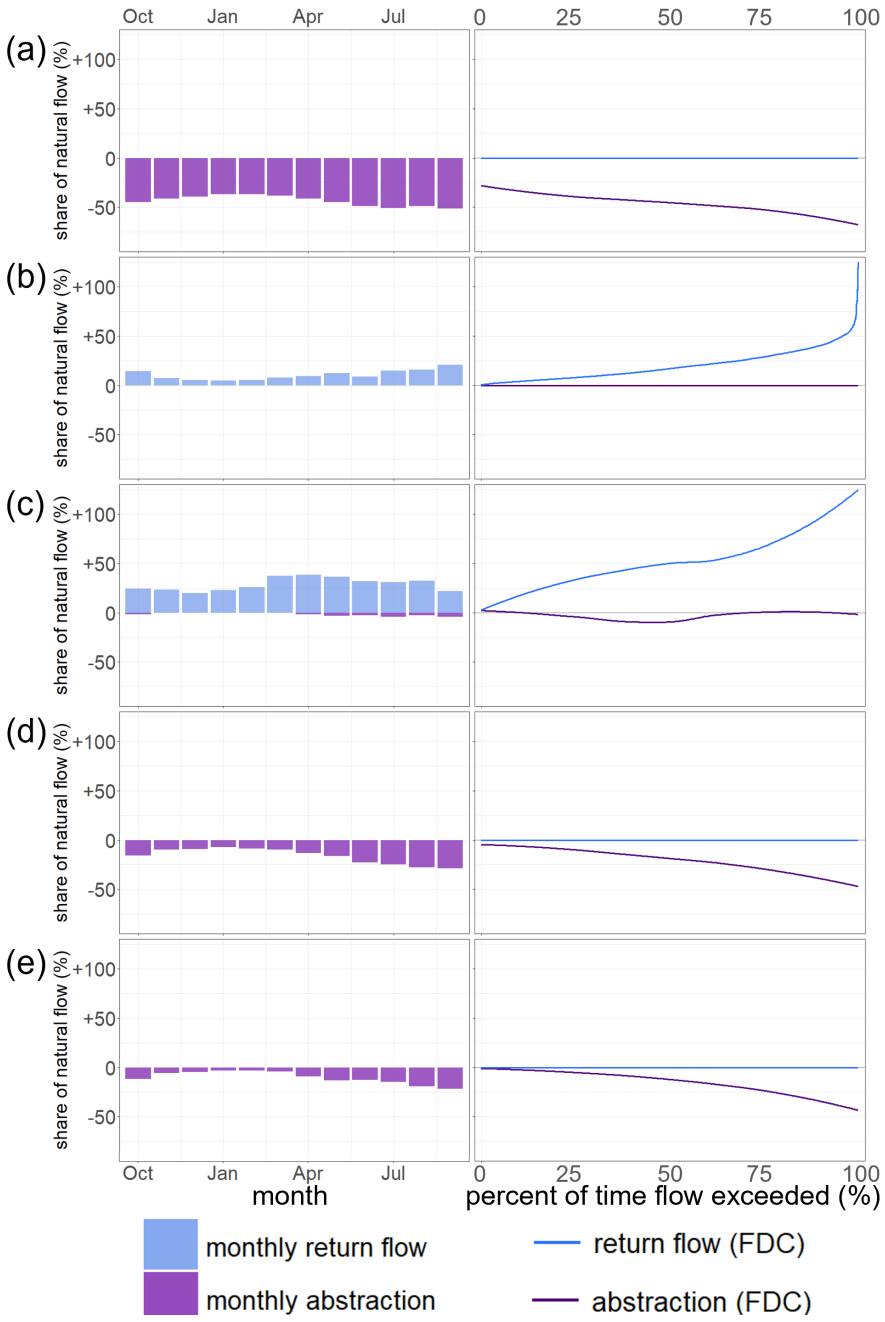


Figure 4.2: Mean monthly abstraction and return flow (left column) and abstraction and return flow across the flow duration curve (FDC, right column) for the (a) Idle, (b) Dearne, (c) Darwen, (d) Rother and (e) Yare for (2001-2017), in percent (%) of natural flow.

The Dearne is abstracted for industrial use but the main influences stem from wastewater treatment discharges and mine water drainage (Environment Agency, 2020b; NRFA, 2022b). Return flows most strongly affect low flows (Figure 4.2). As reflected by its classification as catchment of group 2, the Dearne receives limited rainfall (766 mm per year, which is at the lower end of the range observed in group 2 catchments) and natural regimes display distinctive extreme flow ranges and considerable low flow and high

flow events throughout the year. It has a base flow index of 0.54[5], which is larger than in Darwen and Yare but lower than in the Rother and Idle. Only around a quarter[6] of rainfall contributes to runoff generation. This predominantly rural catchment is covered by 55% grass- and woodland and 28% arable farming (NRFA, 2022a). Historically a strongly polluted river there have been considerable restoration efforts and juvenile salmon were discovered in the river in 2015 (Environment Agency, 2015).

Human influences on natural flow regimes in the Darwen consist of small abstractions for public water supply, industry and irrigation mainly at median flows (Figure 4.2) (NRFA, 2022g). Return flows from wastewater treatment works, particularly during low flow periods influence this catchment, with largest volumes in spring and summer. Typical for flashy coastal catchments of class 3, the Darwen has a low base flow component of only 0.41[5], high rainfall rates of around 1199 mm per year and some steep slopes in the headwaters. Roughly a quarter of its area around the towns of Blackburn and Darwen is urban with other land covers primarily grassland (54%) and woodland (11%) (NRFA, 2022f).

The Yare is mainly affected by groundwater abstractions for agricultural uses (NRFA, 2022d). Patterns of water use are similar to the Rother with highest shares of natural flow abstracted at low flows. Like other catchments from group 5, this chalk catchment in Norfolk has flat reliefs, on average only rising 18.5 m/km, low rainfall rates of 635 mm per year, only 35%[6] of rainfall contributing to runoff generation and a high base flow component of 0.53[5]. The land cover in this rural catchment is dominated by arable farming (73%) and grassland (17%) (NRFA, 2022c).

4.2.1.2 Climate Change and Environmental Flow Scenarios

In order to assess how flow allocation may change in the future, five environmental flow scenarios were compared across four climate change scenarios. The design of the climate change scenarios is outlined in detail in section C.1.2. For Idle and Rother, the analysis undertaken in Chapter 3 provided the detailed climate change scenarios. Catchments representing the three remaining groups (2, 3 and 5) utilised climate scenarios from the Enhanced Future Flows and Groundwater (eFLaG) project (Hannaford et al., 2022) which uses UKCP18 derived data. The eFLaG dataset was chosen as it provides climate scenarios under UKCP18 that are directly comparable to those obtained in Chapter 3. Furthermore, it covers a large number of English catchments which simplified the choice of suitable case studies.

The climate change scenarios are named after their degree of influence on streamflow:

- **high**: high-end emissions mean scenario UKCP18
- **medium high**: high-end emissions mean scenario euro-CORDEX$^{\text{Idle \& Rother}}$ / 50th percentile of mean UKCP18$^{\text{Dearne, Darwen, Yare}}$

[5] bfih in Chapter 2
[6] shost in Chapter 2

- **medium**: medium emissions mean scenario euro-CORDEX$^{\text{Idle \& Rother}}$ / 15th percentile of mean UKCP18$^{\text{Dearne, Darwen, Yare}}$
- **low**: low emissions mean scenario euro-CORDEX$^{\text{Idle \& Rother}}$ / 5th percentile of mean UKCP18$^{\text{Dearne, Darwen, Yare}}$

As outlined in Chapter 1, the EFI signifies the allowed “deviation from natural flow” (Acreman et al., 2008; UKTAG, 2013) and distinguishes four Abstraction Sensitivity Bands (ASBs). Equation 10 and Table 4.2 describe how (changes to) the EFIs are calculated across the environmental flow scenarios. In three of the scenarios - “Fulfill”, “Maintain” and “Enhance-Maintain” - environmental flows are allocated based on natural flow as it evolves under modelled climate change and is quantified in river flow and groundwater balance tests (7). In the “Integrate” and “Enhance-Integrate” scenarios, the natural flow during the baseline period remains the reference flow, so that scenario modelling shows how climate change impacts can be “integrated” into existing policies (Environment Agency, 2020d; WRSE, 2020).

$$\text{nat.flow}_{\text{new}} = \begin{cases} \text{nat.flow}_{\text{old}} & \text{for scenarios with integration of CC} \\ \text{nat.flow}_{\text{old}} + \text{CC} & \text{for scenarios without integration of CC} \end{cases} \tag{7}$$

$$\text{EFI}_{\text{old}} = \text{ASB}_{\text{old}} * \text{nat.flow}_{\text{old}} \tag{8}$$

$$\text{EFI}_{\text{new}} = \text{ASB}_{\text{new}} * \text{nat.flow}_{\text{new}} \tag{9}$$

$$\Delta\text{EFI} = \text{EFI}_{\text{new}} - \text{EFI}_{\text{old}} \tag{10}$$

$\text{nat.flow}_{\text{new}}$ - Future natural flow/scenario EFI baseline

$\text{nat.flow}_{\text{old}}$ - Current natural flow

CC - Streamflow changes under climate change

ASB_{old} - Current Abstraction Sensitivity Band

ASB_{new} - Scenario Abstraction Sensitivity Band

EFI_{old} - Current Environmental Flow Indicator

EFI_{new} - Scenario Environmental Flow Indicator

The scenarios furthermore vary in the ASBs. Additionally to current ASB allocation rules, the (stricter) percentage allowable abstraction according to the Common Standards Monitoring (CSM) Guidance (JNCC, 2016) that distinguishes four flow ranges; $>Q_{10}$, Q_{10} to Q_{50}, Q_{50} to Q_{95} and $<Q_{95}$ was also considered in two of the scenarios "Enhance-Maintain" and "Enhance-Integrate". This method allocates environmental flow for three different river sizes based on annual mean flow (headwater: $<0.62 m^3 s^{-1}$, river: 0.62-$40 m^3 s^{-1}$, large river: $>40 m^3 s^{-1}$).

Table 4.2: Environmental Flow Scenarios and their respective assumptions for the Environmental Flow Indicator (EFI), Abstraction Sensitivity Band (ASB), natural flow baseline and exemplary change in EFI calculated based on the change in ASB and climate change effect on streamflow (as signified in bold; positive change implies the EFI becomes stricter).

Scenario name	**Purpose**	**EFI & ASB change**	**EFI baseline** (see Equation 7)	**Example** (see equations (8) to (10))
Fulfill	Good status cannot be achieved everywhere under shifting climate and demand has to be "fulfilled"	next lower ASB	"new" natural flow under climate change	ASB 2 (old) = 15% ASB 1 (new) = 20% climate change = -10% change in EFI = **-15**%
Maintain	Regulatory approach remains the same, climate change is not considered	ASB remains the same	"new" natural flow under climate change	ASB 2 (old) = 15% ASB 2 (new) = 15% climate change = -10% change in EFI = **-10**%
Integrate	Achieve the same level of flow protection while protecting from climate change effects	ASB remains the same	baseline natural flow levels, flows are protected from climate change impacts	ASB 2 (old) = 15% ASB 2 (new) = 15% climate change = -10% change in EFI = **+10**%
Enhance-Maintain	Higher protection can be achieved but the environment must adapt to climate change	allocated according to the highest CSM protection for the respective class of river	"new" natural flow under climate change	ASB 2 (old) = 15% CSM (new) = 10% climate change = -10% change in EFI = **-5**%
Enhance-Integrate	Improve the outcomes for the environment and protect from climate change impacts	allocated according to the highest CSM protection for the respective class of river	baseline natural flow levels, flows are protected from climate change impacts	ASB 2 (old) = 15% CSM (new) = 10% climate change = -10% change in EFI = **+15**%

The proposed scenarios (Table 4.2) increase in strictness of environmental flow protection from the “Fulfill” to the “Enhance-Integrate” scenario. The first four scenarios “Fulfill”, “Maintain”, “Integrate” and “Enhance-Maintain” were designed directly based on the four suggestions made in the National Framework (Environment Agency, 2020f; WRSE, 2020). The fifth scenario, “Enhance-Integrate” differs from the fourth, “Enhance-Maintain” only in that it does not protect natural streamflow from the impacts of climate change.

Regulation in England as well as the modelling in this thesis has largely focused on activities lowering natural flows such as abstractions and impoundments. The EFI is defined as a lower flow limit aimed at preventing over-abstraction and does not consider return flows (Environment Agency, 2018b). Regulatory limits for restricting activities that artificially increase river flow, “return flows”, do exist however only under water quality considerations as discharges largely stem from wastewater treatment works (Environment Agency, 2018c). However, the high flow regime plays an important role in fish migration and spawning, channel habitat diversity, sediment regime and floodplain connection (Acreman et al., 2009; Bunn and Arthington, 2002). Altered high flow characteristics have been shown to reduce species abundance and density (Dunbar et al., 2010; Suren and Jowett, 2006), change in high flow timing might affect synchronised fish spawning and/or migration (Bunn and Arthington, 2002). Therefore, to reflect the implications for required changes to return flows under varying EFIs and changing climate, a "high flow" - EFI was set for every day. The limit for allowed discharges/return flows was set at the same magnitude above the natural flow as the limit for allowed abstractions is set below the natural flow. For example under ASB 2 abstractions are allowed to lower natural flow at Q_{50} by 20%; return flows would therefore allow an increase by the same percentage above the natural flow at Q_{50} (see also Equation 6).

4.2.2 Semi-structured in-depth Stakeholder Interviews

Stakeholder consultation through interviews facilitated the ground-truthing of the results from the water balance modelling and was chosen to overcome the disconnect between society and science (Tress et al., 2005). A total of 25 stakeholders interviews were conducted between March 2021 and October 2022. The focus was on stakeholders engaged in managing and improving freshwater habitats or in the protection of nature more generally. This included employees of any of the private English water companies and of Non-Governmental Organisations (NGOs), stakeholders working for environmental consultancies advising on water infrastructure and river restoration as well as employees of any of the regulatory bodies working in water policy, regulation and planning. Interviewees were recruited using connections within the EA and through snowballing. All interviews were conducted through the online video calling platform Zoom.

Table 4.3: Profiles of interview participants (WA=Water Company/Authority, NGO = non-governmental and not for profit organisations, F = Farmer, PC = Private Consultancy, R = Regulator, LG = local government). Names of people and identifying roles and/or names of organisations are anonymised as per conditions of consent.

Institution	**Role/Team**	**in text**
South East Water	Environment	WA1
South East Water	Water Resource Planning	WA2
South East Water	Environment	WA3
Severn Trent	Water Resource Planning	WA4
Southern Water	Water Resource Planning	WA5
Affinity Water	Asset Strategy	WA6
Portsmouth Water	Catchment & Environment	WA7
Thames Water	Catchment Management	WA8
SES Water	Water Resource Planning	WA9
Drainage Board	Environmental Officer	NGO1
RSPB	Conservation Officer	NGO2
The Rivers Trust	Policy and Science	NGO3
Regional Rivers Trust	Acting Trust Manager	NGO4
Regional Rivers Trust	Water and Land Stewardship Officer	NGO5
Wildlife Trust & Water Company	Agricultural Catchment Advisor	NGO6
Canal & River Trust	Principal hydrologist	NGO7
Farm & Drainage Board	Water Advisor (Farm) & Vice Chairman (Drainage Board)	F1
APEM	Freshwater Biology	PC1
Atkins Global	Water Management	PC2
Small private environmental consulting company	CEO and founder	PC3
Natural England	Senior Hydrologist	R1
Environment Agency	Water Strategy Manager	R2
Environment Agency	Water Resources Planning	R3
Environment Agency	Environment Planning	R4
County Council	Water Resources Manager	LG1

In-depth interviews lasted up to one and a half hours. A set of pre-determined questions (appendix section C.2) was used but the interviewer was allowed to explore particular themes or responses further (Babbie, 2020). The interview plan was informed by previous preliminary work using an online questionnaire with 30 respondents that determined perceptions of future climate change impacts, the main shortcomings of the current water management system and priorities for future freshwater use (included in appendix section C.3).

The interviewer first introduced herself and outlined that the research was aimed at understanding how environmental flow protection can be improved under climate change and non-flow pressures and to establish how local practitioners can be better supported at improving the outcomes for the environment at the catchment scale. The first set of questions was aimed at detailing the respondent's roles and responsibilities within their organisation and they were asked to describe their day-to-day work and ongoing projects. If applicable they were asked to name specific catchments they work in and the water management issues and ongoing projects in these areas. Depending on ongoing and past projects mentioned, the interviewer encouraged the respondent to reflect further on these projects' background, collaboration with project partners and water management and/or environmental issues of relevance. The next set of questions aimed to outline environmental challenges respondents had encountered, water company-specific solutions and their feasibility and the range of planning applied in abstraction management. Respondents were then asked to reflect on adaptation to decreasing water availability and what it meant for their organisation, their work, project partners and clients. The final set of questions explored what support they wished to receive in improving the outcomes for the environment and climate change adaptation and where they recognise scope for more support for others. Furthermore, they were encouraged to elaborate where they see a lack of support for adaptation to climate change and for improving the outcomes for the environment. If applicable perceptions about collaboration with the regulator were collected.

Interview responses were analysed in two different ways; using a structural code system (DeCuir-Gunby et al., 2011) and open coding of emergent themes (Strauss and Corbin, 1998). The former approach was applied to ground-truth and extend upon the issues uncovered in the previous chapters and make proposals for addressing them. The first chapter developed a new catchment classification that allows to match natural and near natural with hydrologically altered catchments and emphasised the wide variety of catchment types present in England and the associated difficulties for one-fits-all approaches for their management. Themes guiding the structural coding analysis were therefore problems with current environmental flow protection (and the EFI) and solutions for more flexible protection across very different catchment types. The second chapter undertook a detailed climate impact analysis of two highly influenced catchments under a range of climate scenarios and emphasised the wide range of uncertainty and high variability of potential outcomes under different future pathways. Themes guiding the structural coding analysis to extend on the second chapter's results were therefore the respondent's

perceptions of local scale climate impacts including compound effects (i.e. combined effects of human uses and climate) and the challenges for achieving better outcomes for aquatic environments under these effects.

Open coding is a method of grounded theory (Corbin and Strauss, 1990) and serves to conceptualise and categorise core ideas emerging from the interviews (Vollstedt and Rezat, 2019). While analysing the responses, new themes emerged and new codes were delineated and included in the investigation. Once a stable code system had been developed, sub-codes disclosing central concepts, patterns, differences or consistencies in the data were established. Finally, each code and sub-code was analysed and described in depth. To manage, analyse, store and code these interviews, the software package NVIVO version 20.1.6 was used.

4.3 Results

The water balance modelling results are presented and discussed first in section 4.3.1. The modelled changes in over-abstraction and over-discharges and required changes in demand are illustrated using two representative catchments for simplicity.

Five main themes emerged during the stakeholder consultation and structure the presentation and discussion of the results. The respondents' perceptions of the main shortcomings in water management and governance pertaining to environmental flow protection are outlined and discussed first (section 4.3.2) before proposals for their solution are presented (section 4.3.3). In line with accepted social science practice, only those quotes from the interviews best illustrating the results are included and solely key results are discussed in more detail (e.g. Martin-Ortega et al. (2019), Okumah et al. (2021), Larson and Brumand (2014)).

4.3.1 Water Balance Modelling

The climate change and environmental flow balance modelling has been used to assess (**one**) the changes in over-abstraction and over-discharge between the baseline and the modelled future and (**two**) the required changes to current water use strategies to meet the EFI scenarios. The results for (**one**) are illustrated using the Idle because as a catchment with strong existing over-abstraction, it is a good example of how changes in water availability and allocation rules alone can imply strong changes. The results for (**two**) are illustrated using the Yare to highlight the importance of seasonal water use adaptation.

4.3.1.1 All Scenarios require Changes to current Water Use

The results indicate that achieving the levels of environmental flow protection outlined by the scenarios cannot be attained without considerable changes to current water use. Largely due to high existing pressures not even the "Fulfill" scenario which embeds the strongest reductions in the amount of water protected for the environment (pink line on Figure 4.3 and Figure 4.4) can be achieved without reductions in water appropriation. It implies decreases in over-abstractions and over-discharges under low and medium climate change impacts but these are small, never beyond -15% (Figure 4.3, see figures Figure C.3 to Figure C.6 in section C.1.3.1 for remaining catchments).

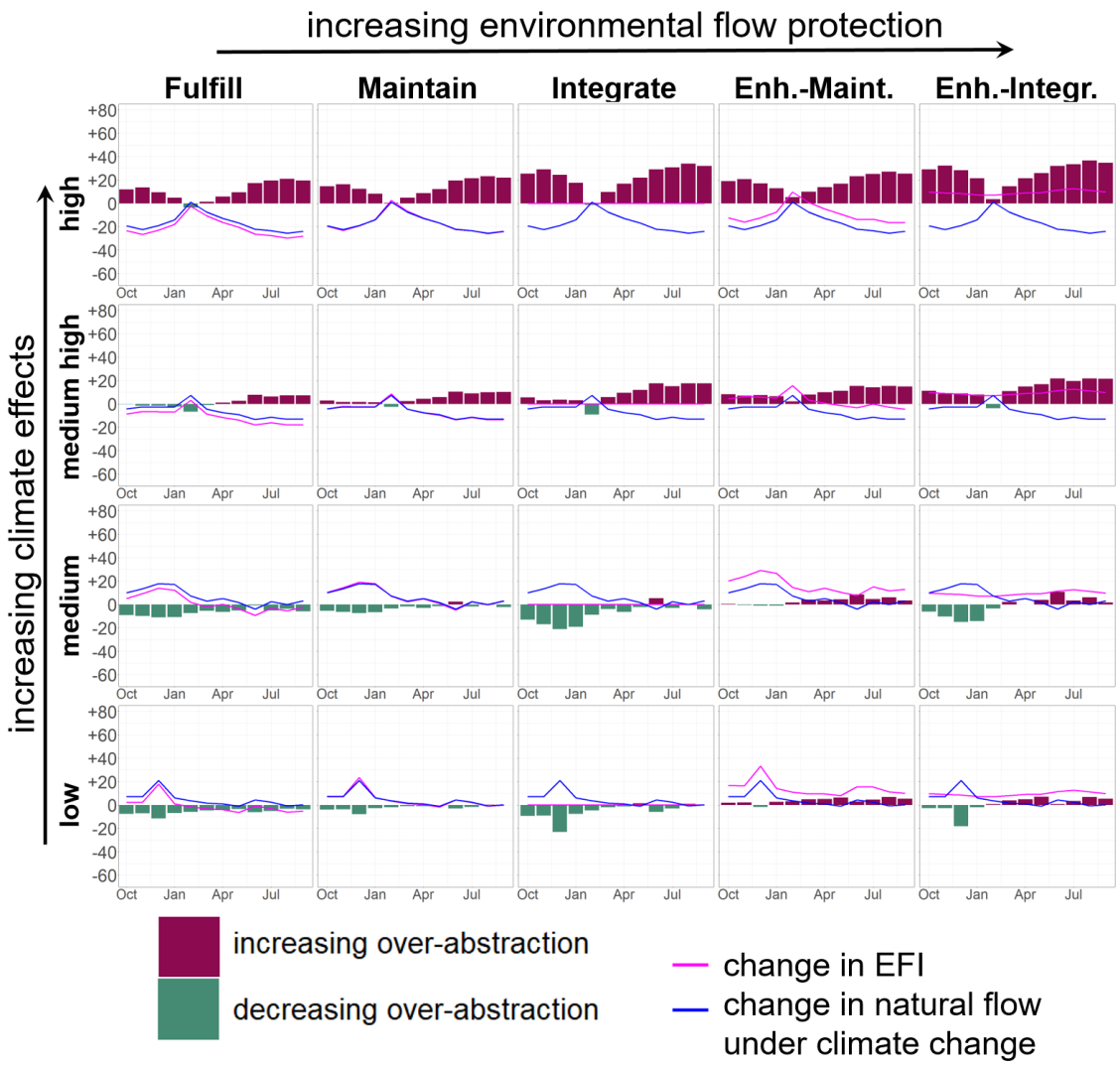


Figure 4.3: Change in mean monthly share of over-abstracted environmental flows under five environmental flow and four climate change scenarios, in percent (%) for the Idle.

The analysis of (**two**) the required changes to current water use strategies to meet the EFI scenarios, indicates that to achieve the “Fulfill” scenario under high climate change impacts, reductions in abstractions and return flows are required in all modelled catchments, particularly in summer. Under the strong water availability decreases under high climate impacts in September, abstractions in the Yare would have to reduce by 50% (Figure 4.4). In the catchments most strongly affected by water use, Idle and Darwen, abstraction and respectively return flows would have to decrease across almost the whole year across all climate change scenarios to attain levels of protection prescribed by “Fulfill” (see figures Figure C.7 to Figure C.10 in section C.1.3.2 for the remaining catchments). Nevertheless, required changes under the “Fulfill” scenario are variable across the year. This scenario allows considerable increases in water appropriation in catchments where existing over-abstraction is mainly affecting low flows such as the Yare (Figure 4.5). In this catchment, monthly abstraction would be allowed to increase

by beyond 320% from current levels from December to March under all climate change scenarios (Figure 4.4).

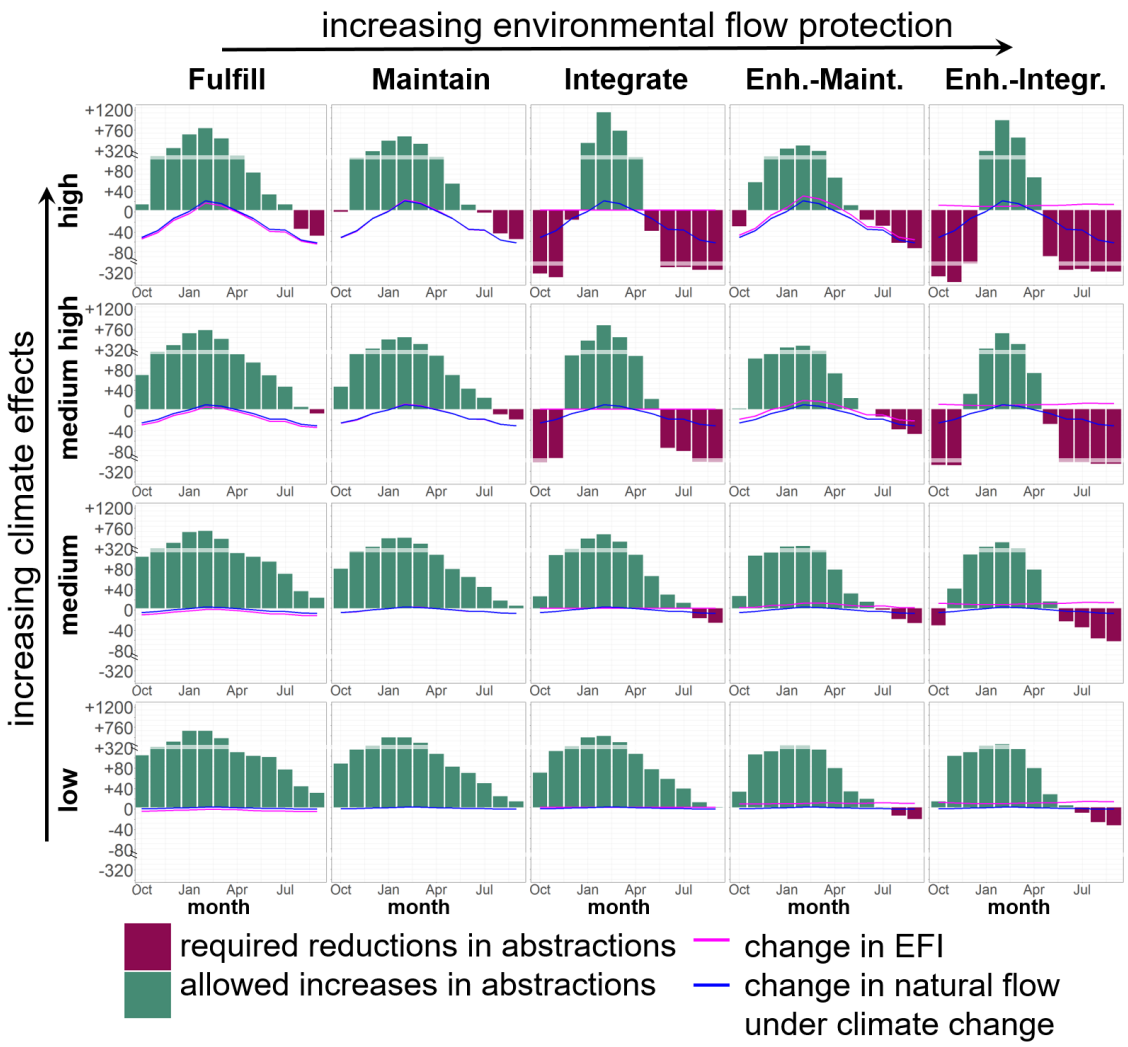


Figure 4.4: Mean monthly required reductions and allowed increases in abstractions to stay within the Environmental Flow Indicator (EFI), in percent (%), for the Yare. Note the broken y-axis scale.

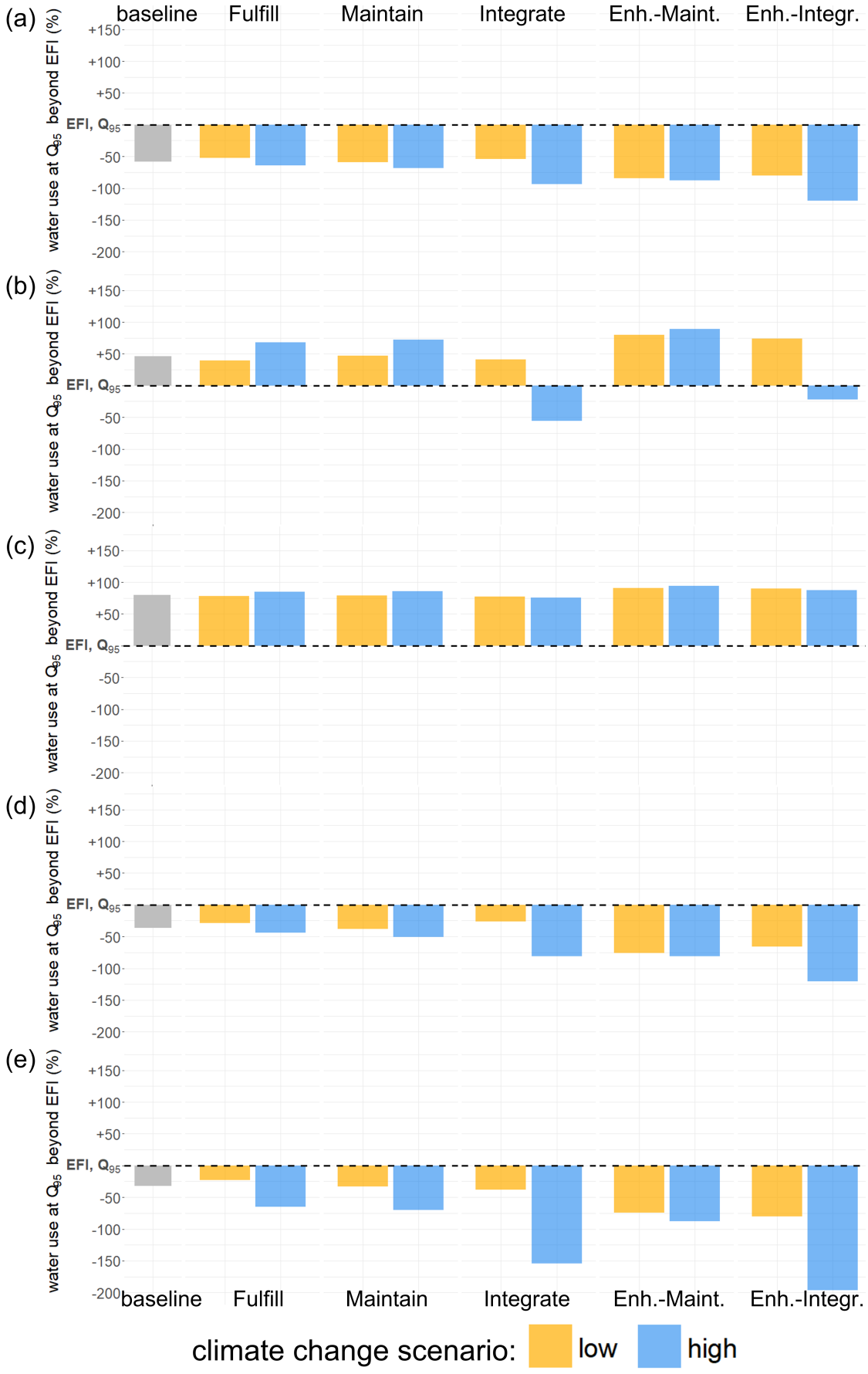


Figure 4.5: Comparison of required reductions in water abstraction/return flow to meet the Environmental Flow Indicator (EFI) at Q_{95} under the "low" and "high" climate change scenario for (a) Idle, (b) Dearne, (c) Darwen, (d) Rother and (e) Yare. In the "Integrate" and "Enhance-Integrate" scenarios the EFI is set for the Q_{95} of natural flows during the 2001-2017 baseline (in percent %).

4.3.1.2 Not integrating Climate Change not necessarily results in more Water for Human Uses

Scenarios without protection from climate change ("Fulfill", "Maintain" and "Enhance-Maintain") allow some large decreases to the share of water protected for the environment during months with decreasing water availability such as from May to November in the Yare (Figure 4.4). The "Maintain" scenario is very similar to the "Fulfill" scenario in (**one**) changes to over-abstraction and over-discharge. The largest differences between the two scenarios are observed under "high" and "medium-high" climate change impacts when stronger changes to water use are needed to maintain current protection, particularly in summer (e.g. Figure C.9). "Enhance-maintain" has more consistent outcomes across varying climate change impacts than the other environmental flow scenarios. This scenario allows less water use increases during autumn and spring than "Maintain" and "Fulfill". Two main observations can be drawn from a comparison between these three scenarios and the two that "integrate" climate change; the first is that the allowed increases in water use are not generally larger and mainly differ in summer under high climate change impacts. Correspondingly, the reduced environmental protection during summer low flows is probably the largest shortcoming of these three scenarios as they imply less protection when rivers need it the most (Font et al., 2021). Even for short durations allowing more abstractions during low(er) flows can be harmful (Hayes et al., 2017). In basins experiencing an increase in water temperature as well as a decrease in (low) flows, the effects on river water quality could be detrimental (Mosley, 2015; Vliet et al., 2013). Particularly in catchments with high existing anthropogenic pressures and/or sensitive freshwater habitats these EFI scenarios might therefore not be advisable.

4.3.1.3 Integrating Climate Change in Environmental Flow Allocation might support a better Balance between the Environment and Human Uses

The modelling suggests that in some catchments protecting flows from climate change impacts might attain better outcomes for meeting EFIs and balancing different water needs than not integrating it. While the question of if and how streamflow should be protected from climate change cannot be answered with a simple methodology such as used here (notably without a sensitivity analysis of the outputs to key scenario assumptions (e.g. George et al., 2011; Letcher et al., 2007)), it provides a good starting point for discussions with stakeholders and regulatory authorities regarding future water management in England (Assaf et al., 2008; Heikkila, 2017).

Both scenarios that aim to protect environmental flows from future climate change ("Integrate" and "Enhance-Integrate") imply increases in over-abstraction driven by decreasing streamflow under climate change (e.g. $\sim$80% flow decreases for both scenarios in September in the Yare Figure C.6). On the other hand, climate change driven water availability increases, "bonus water" during (winter) floods (Defra, 2016b), contribute towards fulfilling water demand if these flows can be stored or utilised during this time. They therefore suggest dynamic changes to water use to accomplish all three; environ-

mental flow protection, demand fulfilment and protection from climate change. Under the “Integrate” scenario, changes are driven by climate impacts only as environmental flows are allocated at the same rates as during the baseline period 2001-2017. Therefore, over-abstraction is decreasing where climate change leads to increasing water availability e.g. from -18 to -21% in December in the Idle under low and medium climate change impacts (Figure 4.3). Conversely, over-discharge is declining where climate change leads to streamflow decreases e.g. from 3 to 9% in September in the Darwen. These two scenarios therefore indicate large potential for meeting EFIs if water abstractions are shifted to those seasons with water availability increases, such as from summer to winter and vice versa from winter to summer in catchments largely affected by return flows. This is particularly relevant for catchments with clear seasonality increases such as Rother or Yare (Figure 4.4). Depending on return flow water quality (Diamantini et al., 2018) and temperature (Vliet et al., 2016), streamflow reductions through climate change could subsequently be buffered. The feasibility of this change in timing of water use will depend on storage capacity (Scanlon and Smakhtin, 2016) and highlights the relevance of continued (flow) measurements (separating effects of climate change) (Burt et al., 2008).

4.3.1.4 Protecting Flow Regimes from Climate Change and Water Use is particularly difficult in Summer

The findings (Figure 4.3 & Figure 4.4) emphasise that protecting river flows from the combined pressures of water use and climate change is difficult, particularly in summer when low flow conditions prevail and demand is highest (Environment Agency, 2020d). As depicted in Figure 4.5 for Q_{95}, across all scenarios, abstractions would have to reduce by at least a fifth in the Yare, a quarter in the Rother and a half in the Idle while return flows during low flows in the Darwen would have to decrease by at least 76%. Under the “Enhance-Integrate” scenario, to protect flows from climate change while achieving the CSM standards, reductions in abstractions of up to 118% would be required during August in the Idle, up to 123% in the Rother and up to 311% in the Yare. This scenario would hence be very difficult to attain in some of the catchments as abstractions would have to cease completely and stored river water or transfers from outside the catchments would be necessary (Hutchins et al., 2018). The findings for Q_{95} in the Dearne are more variable than for the other catchments due to its natural flow regime and water use patterns. Return flows are mainly affecting low flows which, typical for its catchment class, occur throughout the year. The return flows buffer decreasing (low) flows under climate change, to the extent that under high climate change for both “Integrate” and “Enhance-Integrate” scenarios, over-discharge at Q_{95} is removed (Figure 4.5 b)).

4.3.1.5 Requirements for Adaptation vary across Catchments

Chapter 3 discussed potential changes to water management in the Idle and Rother in detail, including the need for more groundwater sensitivity assessments. The extension with environmental flow scenarios has emphasised the importance of reducing abstrac-

tion in both catchments and suggested a shift in abstractions from summer to winter in the Rother. This might also be suitable in the Yare. Water abstractions are mainly required for agricultural use in this catchment and indicate the possibility to reduce pressure due to irrigation water abstraction by improving water use efficiency (Gong et al., 2022) and moving to less water sensitive crops (Malhotra, 2017; Peyster, 2016). The importance of groundwater for maintaining base flows in the Yare and similar catchments of group 5 also implies the need to further analyse groundwater sensitivity to climate change. The Darwen is part of catchment group 3; the flashiness in natural flow regimes of this group indicates the need to protect from (too) homogenous flow regimes which can impact ecological integrity (Moyle and Mount, 2007). The findings indicate a water surplus across almost all scenarios in this catchment. Depending on feasibility, this suggests that catchments such as the Darwen might become relevant as source of inter-basin water transfer (NAO, 2020), especially where climate change leads to net water increases. In the Dearne, the results indicate that protecting low flows can be better achieved with environmental flow allocation that accounts for climate change ("Integrate" & "Enhance-Integrate"). Use of excess return flows for artificial groundwater recharge through injection wells (Karim and Ali, 2017) or infiltration basins (Peters, 2020) might be appropriate in both Darwen and Dearne. This would help to maintain distinctive low flow periods typical for both catchments' groups' natural regimes and which are important for instream biota (Romaní et al., 2017).

It should be noted that this study assessed a stable baseline (2001-2017) and strong climate change impacts for all catchments. These impacts are all derived from UKCP18 projections and therefore likely represent drier scenarios than those under other projections such as euro-CORDEX (Murphy et al., 2018; Pastén-Zapata et al., 2020). Due to data constraints, this study applied more detailed and dynamic climate change scenarios only for the Idle and Rother catchments. Furthermore, depending on data records and availability, the choice of baseline for determining levels of current water use and protection that should be "maintained" or which form starting points for "integrating" climate change might vary across different catchments and result in less extreme changes in water availability. This study was constrained by naturalisation records, based upon 1990-2007 data (Environment Agency, 2009). As outlined in more detail in section 4.3.3, water use has been decreasing over recent years (Ofwat, 2012) while rainfall shows an upward trend (Met Office, 2021a, 2023). This suggest a very conservative naturalisation and a potential overestimation of overabstraction. On the other hand, the modelling did not consider the likely reversal of this (decreasing) demand trend in the future. Rates of abstractions and return flows are unlikely to remain at current rates (Environment Agency, 2019b; NAO, 2020). Therefore, it is overall more likely that future over-abstraction and over-discharge were underestimated than overestimated as abstraction and return flow rates will likely increase (particularly in catchments required for public supply such as the Rother) to fulfil demand of rising populations (Environment Agency, 2020d).

These results emphasise the need for a balanced, systematic approach to define large scale environmental flow requirements (for example based on classifications such as developed in Chapter 2) to then guide case by case decision making based on local priorities and climate change considerations. This study has suggested environmental flow limits for return flows and assessed them separately from limits for abstractions. Further research is needed on the ecological impacts of return flows under climate change, particularly with respect to water quality and temperature (Vliet et al., 2016; Wen et al., 2017). The reality in most catchments is complex as they are usually affected by both abstractions and return flows.

It was highlighted that for environmental flow protection to be rendered climate smart, demand patterns have to be adapted by focussing on reductions in water abstractions, particularly during summer. In catchments such as Idle and Darwen it is unlikely to achieve both full environmental flow protection and demand fulfilment without water transfer from outside the catchments and respectively removal of water from the catchment or into aquifers. This falls in line with the findings of the NFW undertaken at the national scale. Across the country water transfers between water companies are expected to contribute 646 million litres per day by 2045 (NAO, 2020). Mainly catchments in areas with increasing water availability under climate change and with naturally higher rainfall rates, such as groups 3 and 4 from Chapter 2, suggest themselves as sources of water for these transfers. The Darwen is one of them from group 3 and particularly recommends itself because water use largely consists of return flows. While dependent on water storage options, in some catchments such as the Rother or the Yare, climate-driven changes in seasonal water availability indicate high potential for adaptation through dynamic water use changes shifting demand between seasons.

4.3.2 Stakeholder Perceptions of main Shortcomings in current Environmental Flow Protection

The respondents' perceptions on major limitations of current water management and governance that hinder good environmental flow protection are summarised in Table 4.4 and discussed below. They are structured along five main themes that emerged during the interviews and set the scene for the proposals for their solution discussed in the next section (section 4.3.3). While collated for England, many of these concerns likely also apply to other regions.

Table 4.4: Respondents' perceptions of the shortcomings of current water management and governance in England

1. **A lack of data hinders efficient decision making.** Limited knowledge on the interactions between flow, ecology, water abstraction, climate change, groundwater and surface water and on related sensitivities as well as insufficient data access and sharing represent barriers for flexible and confident decision making. Information is often not available at high spatio-temporal resolution.
2. **Water use is high, projected to increase and not sufficiently restricted.** Water consumption is not decreasing strongly enough and comprehensive regulation of water use efficiency is missing. New housing developments increase pressure on drainage and water quality, often in regions with pre-existing water stress. Unlicensed small abstractions are harmful. Leakage is a major problem and there is little public awareness on the environmental effects of water use.
3. **Insufficient funding, coordination and alignment of planning processes hinder ICM.** The EA is not able to deliver sufficient monitoring, enforcement and coordination. EA working groups often do not align in their aims. Policy design is lacking in clarity allowing its misuse. Land use and management is not sufficiently considered in freshwater protection. Land use lock-in dynamics have developed, particularly as flooding is seen as the primary concern. WINEP and its funding is inflexible and maladapted to align across different organisations. There is a lack of financial investments in high risk/high reward environmental improvements. The abstraction licensing system is not fit for purpose.
4. **Collaboration is fragmented and local knowledge not sufficiently exploited thus limiting adaptive capacity.** A large number of groups and initiatives work in parallel instead of integrated, meaning their knowledge is not appropriately operationalised. Independent support for businesses is limited. The EA's double roles of enforcement and engagement present a barrier for engagement. CaBA is successful but lacks funding, legitimacy and standing.
5. **Maladapted land use increases climate change risks to people, biodiversity and ecosystem services.** Synergies and multiple benefits provided by restoring ecosystems (EBA) are often not realised. Maladapted land use and development particularly in floodplains and is kept up by grey infrastructure. Environmental assessments in rivers largely focus on single aspects such as flow or water quality.

4.3.2.1 A Lack of Data hinders efficient Decision Making

Respondents highlighted how a lack of regional and local data and appropriate models was often the reason for incomplete understanding of the relationship between flow (alteration) and ecosystem functioning. This resonates with the findings by Pahl-Wostl et al. (2013) who showed limitations of systematic approaches for the determination of environmental flow requires the use of very basic hydrological analyses to represent environmental requirements in large scale water assessments and models. Respondents diagnosed this to be due to the lack of more sophisticated broadly applicable methods and data, reflected in the use of AQUATOR (Oxford Scientific Software, 2008) and other water resource system models applied by water supply companies in England. The respondents disapproved of their limited representation of groundwater processes and lack of coupling with distributed groundwater models used by the regulator (Shepley et al., 2012). This in many regions limited understanding of groundwater and groundwater sensitivity to pressures from climate change and abstractions was stressed during the interviews. This is consistent with the literature that confirms the present understanding of groundwater pressures as particularly “wicked” due to its invisibility, often longer response times and lack of high quality data and groundwater modelling (Jakeman et al., 2016). This is particularly problematic as groundwater makes up around 30% of England’s water supply with chalk representing the most important aquifer (UKRI, 2022). Compared to other aquifers with significant inter-granular flow such as sandstone, chalk has a higher sensitivity to climate change including droughts (Ascott et al., 2019) and floods (Hughes et al., 2011).

A lack of baseline data was highlighted during several interviews, as illustrated by quotes such as: “*There’s often not a lot of good background data to know what the river is doing*” (WA5). Interviewees also pointed to the fact that particularly headwaters of streams were often not sufficiently understood or as put by one interviewee: "*The headwater resource has been massively impacted, and massively under monitored, under resourced, just basically fallen off the radar*." (R1). This is not least due to the WFD not requiring headwaters to be treated as "bodies of surface water” for monitoring (European Commission, 2000). Furthermore, the lack of access (rights) to data and the time and cost intensive procurement of data was regarded as a major limitation for improving the outcomes for the environment. The respondent working as Water Resources Manager for a county council (LG1) described their experience with procuring water company data: "*We don’t have enough hair left on our heads to pull out to get through all the regulations and hurdles needed (. . .). That particularly applies to the water industry. Getting water company data can be quite challenging*”. Interviewees furthermore saw scope for more citizen science supporting data collection. Robins et al. (2017) also criticise this, highlighting that approaches to collecting, processing and sharing data in a stringent way as exist for wildlife surveys are missing.

4.3.2.2 Water Use is high, projected to increase and not sufficiently restricted

The interviewees from water companies explained that water use efficiency increases had driven demand decreases in recent years. At 139 litres per person per day (l/p/d), water use efficiency in England however still lacks behind many other European countries such as Spain, the Netherlands, Germany and Poland (EurEau, 2020). Moreover, respondents emphasised that sooner or later population growth would likely override any water efficiency increases, for example in 10-15 years in SES Water's supply area (WA9, SES Water (2022)). The projected water demand increases are highly spatially variable with the south and south-east affected most strongly (Environment Agency, 2020d). To provide housing to growing populations, the Government wants to deliver 300,000 new homes per year and local planning authorities are tasked with finding the land (Wilson and Barton, 2022). In several interviews respondents criticised that freshwater availability and sensitivities were not considered in decisions on where and how new housing developments were built, pre-existing water stress was not appropriately accounted for. Furthermore, rules for drainage and flood protection were too lax as was the regulation on water use efficiency in new builds (see also section 4.2.3). Interviewees outlined that to achieve the efficiency standards of 125 l/p/d, current regulation The Building Regulations (2010) allows to offset (high) water use (e.g. through power showers) in the main bathroom by adding bathrooms with less water intensive appliances and averaging the use.

Additionally, Interviewees saw leakage as a major challenge. The regulators reported that 21% of water (3,170 Ml/d) put into public supply was lost to leakage in 2018-2019 (Environment Agency, 2020d; Ofwat, 2019b). This is largely due to the high age of the network (UK Water, 2022) but also due to lack of investment since privatisation (Buse and Bayliss, 2022; Lobina, 2019). There was no progress in leakage reduction between 2011 and 2020 (Ofwat, 2022f). Thames Water, the worst performing company on leakage lost more than twice as much water (22,200 litres per km of pipe per day) than then next company, Affinity Water (Committee of Public Accounts, 2020). Leakage is very expensive to reduce (PWC, 2019) and respondents from water companies reported some disagreement between their employers and Ofwat on how prescribed levels of leakage reduction could be achieved. Furthermore, one interviewee diagnosed a major challenge (that also pertains to the lack of enforcement power and the maladapted abstraction licensing system, see next theme) arising through the unknown combined environmental impact of small unlicensed and uncontrolled abstractions of less than 20 m^3/d do not require a license (Defra, 2016a). An observation that recently received some media coverage (Salvidge, 2022). Lastly, respondents saw a lack of awareness in public behaviour, highlighted by this quote; "*I think there's such a disconnect between how the general public use water and understanding where it comes from*" (WA1).

4.3.2.3 Insufficient funding, coordination and alignment of planning processes hinder ICM

Several major shortcomings were attributed to the regulator's lack of funding. "*They* [*the EA] *simply don't have the resources to do the monitoring that they used to do or even the monitoring that's really required*" (PC1) and "*They do seem over reliant on hoping for private investments to save the world*" (NGO3). Additionally to fees and charges, the EA is largely funded by Defra (68%) (Environment Agency, 2021a). The impacts reported by the respondents correspond to the real-term reductions of 63% in EA funding over the last 10 years reported by Rose (2020). The regulators also acknowledge the significant decrease in surface-water quality and macroinvertebrate monitoring in England (Defra, 2022d; Environment Agency, 2022b). One EA employee highlighted how the lack of resources hindered investigations in providing more granular detail beyond WFD classifications. Furthermore, respondents from water companies reported that the environmental expectations set by the EA and those set through Ofwat's price reviews often did not align. Respondents also saw room for improving the EA's coordination of work with the public, in particular with regards to transparency of processes such as permitting. Moreover, they observed that the aims of different EA working groups often lacked integration as explained by LG1: "*The separation of water quantity and water quality is completely artificial and not particularly helpful. It needs an integrated approach, and different bits of the Environment Agency go in the corners and work on each different part of that separately by themselves and it feels like they don't talk to each other enough.*"

Respondents also highlighted that current policy allowed the misuse of regulatory tools for purposes it was not designed for which had led to lock-in dynamics. This has also been reported in the literature; intransparent planning processes (Ison et al., 2015) and cognitive frames (Lin and McDonough, 2014) with flooding as the dominant concern had encouraged the management of flood defences as land drainage (encouraging agriculture on previously flooding land) although they were meant to solely protect infrastructure. Additionally, several respondents outlined the lack of Sustainable Urban Drainage Systems (SuDSs) (Flood and Water Management Act, 2010) leading to drainage and pollution issues in their catchments. They worried about the outcomes for freshwater systems through new developments should (obligatory) SuDSs not be reinstated after it was removed following the lobbying from developers. This is supported by findings such as those by Vilcan and Potter (2020) who analysed the lack of policy clarity on SuDSs and found that the institutional void left by the state led to their uptake becoming dependend on power relations and negotiations between local authorities and developers, the so-called "strengthened planning system" led to suboptimal outcomes. Two respondent from the EA remarked how collective water planning systems were missing for sectors other than the water sector itself, their hands were hence tied in more urban environments. This corresponds with findings by a report to Ofwat (Ong and Cuttle, 2021) that particularly criticises inconsistent mechanisms and incentives for environmental improvements across sectors and that fragmented regulation prevents innovation. Inter-

viewees also recognised a lack of land integration in the work of water companies and highlighted how Ofwat did not provide enough support for wider catchment work.

Moreover, they reported that the WINEP was inflexible and often did not fit with the time line of other initiatives outside of water companies and therefore was not conducive to cooperation. Interviewees found the WINEP process too slow and hence not fit for dealing with climate change impacts and was "*dysfunctional*" (LG1). The implementation of solutions often took 15 years and the process was "*hideously complicated*" (R1). Instead, WINEP and AMP led to short termism and water companies pursuing projects that had guranteed delivery. This is consistent with the diagnosis of the National Audit Office NAO (2020) which found that while fixed-term planning cycles provided certainty for investors they were not conducive to improving system resilience. This is closely related to another limitation; the way environmental improvements are financed.

Interviewees saw little possibility for current fixed term planning to achieve enhancements beyond retaining the status quo. One reason for this was seen in the backlog on investments, particularly in infrastructure. A respondent from the EA highlighted that that was part of the reason for failing Combined Sewer Overflows (CSOs) that caused the current water quality crisis (OEP, 2022). Investing in environmental improvements was often extremely expensive as R3 explained: "I think in East Anglia they say to meet the EFI everywhere requires 50% cut to groundwater abstraction. But that's about 900 mega litres a day of water you'd have to find and reengineer your entire supply system to accept that water and build all the schemes to deliver it. It is billions and billions and billions of pounds that come with their own environmental impact and social impact." This is a generational equity issue and avoiding future costs to wider society relies on these investments (Hatchwell and Rose, 2020). Furthermore, the respondents outlined that established methods of assessment applied in investment planning were not appropriate to account for high risk and uncertainty: "*The game is who accepts the financial risks, the water companies, the customers, government? Somebody has to carry the can if it doesn't work out. That's currently the blocker to a lot of this stuff, to take a leap of faith on something that's unproven, particularly at a large scale, you need somebody underwriting that risk*" (R3). This shortcoming falls in line with what has been discovered by the OECD (2022). Should highly risky assessments go wrong this would moreover reflect extremely bad on the EA: "*We would be hammered in the public*" (R4). Not allowing uncertain outcomes has led to a lock-in dynamic: no one is taking (financial) risk that (often uncertain) catchment based approaches entail. This resonates with the findings by Williams (2011) who found institutional barriers and risk aversion preventing the adaptive management required to overcome high uncertainties. Water companies and the wider water sector might miss high reward and innovative mitigation approaches at the cost of the environment and the tax payer.

Lastly, the limitations of the current abstraction licensing regime were highlighted, the main issues respondents flagged were related to previously outlined lack of data and flexibility within the EA. It is very difficult for the EA to retain appropriate levels of mon-

itoring and metering over abstractions, including on the compliance of exemptions of small abstractions, also reported by Salvidge (2022). Some regulations such as the the definition of “catchments closed for further abstractions” (e.g. the Thames Environment Agency (2019c)) were criticised as too rigid preventing all investigations into changing abstraction regimes and improving the environment. Furthermore, there have been some unwanted effects of licensing exemptions: “*Trickle irrigation has been seen as a very efficient irrigation technique, that the government wants to encourage rather than license. And it was quite small at that time too in terms of demand but the result of that exemption from licensing has been that there has been major investment in it, and it's become the dominant water user*” (NGO5).

4.3.2.4 Collaboration is fragmented and local Knowledge not sufficiently exploited thus limiting Adaptive Capacity

There are many high-class initiatives and actors working on improving the outcomes for freshwater environments but through several examples outlined during the interviews it became clear that their knowledge was often not well operationalised. Respondents highlighted that the fractured nature and wide range of different initiatives engaged in catchment based work was a challenge: “*I think there's too many groups. So you're not actually getting a single voice representative of that environment, there's hundreds of these small groups. I know CaBA tries to sweep them up together but there's maybe an image problem. Because they're not at one of the large groups so they're not like the Wildlife Trust or an NGO*” (R4). Interviewees pointed out that CaBA's lack of integration and (statutory) power as well as severely limited funding hampered the exploitation of its full potential. Robins et al. (2017) highlighted this limitation with catchment partnerships not yielding a formal mandate and having no authority over allocation of EA resources. The EA is only expected to show “due regard” to partnerships' advice (Defra, 2013). The lack of legitimacy and standing highlighted by the respondents has previously been described by Smith et al. (2015) and evidently persist. One EA employee criticised the incentives created through current CaBA regulation requiring matched funding from non-governmental sources and explained that partnerships therefore tended to follow the money rather than focus on the issues needing the most improvement. Robins et al. (2017) reasoned along similar lines and extended the argument; the multitude of organisations made it moreover extremely difficult to interact and engage with institutional arrangements in order to influence how water resources are managed.

Three respondents described the difficulties for businesses, in particular farmers, to receive truly independent support. Farmers pay for every acre an advisor walks and “*most of the advice on fertiliser is driven by the fertiliser industry, not by the industry trying to actually reduce its inputs*" (NGO6). This is alarming as nutrient pollution is one of the biggest threats to river health in Europe (Carvalho et al., 2019; Posthuma et al., 2020). Agriculture has been estimated to account for 72% of fine sediment emissions to the aquatic environment in England and Wales with locally significant additional inputs from river channel banks, urban areas and wastewater discharges (Zhang et al., 2014).

One respondent criticised that farmers had to pay for support and that the National Agricultural Advisory Service (NAAS), now Agricultural Development and Advisory Service (ADAS) (HC, 1997), had been privatised. A previously government-run agency, NAAS used to support a network of farm advisors around the country offering free agricultural advice. Moreover, the EA's double roles of enforcement and engagement was viewed negatively by respondents as filling these two roles was hard to reconcile in some contexts. This compromised the function of the EA, particularly where it was important to proactively engage people. While more engagement increases complexity of decision making processes it is vital to integrated learning (Jacobs et al., 2016).

4.3.2.5 Maladapted Land Use increases Climate Change Risks to People, Biodiversity and Ecosystem Services

Several common land uses in England such as vineyards, polytunnels and intensive farming of floodplains were seen critical by interviewees. One respondent explained that problems for water quality were rarely due to crude problems such as sewage input to rivers (point sources) but many were instead related to land use and agriculture (diffuse sources). Several respondents described the challenges of gaining control over runoff and thus over sedimentation, flooding and fertilizer input into rivers. It was reported that "*more intense summer rainfall events running off the polytunnel surfaces, uncontrolled, cause muddy flooding into roads and damaging infrastructure*" (LG1). The nutrient-rich soils of floodplains had incentivised arable farming facilitated through "grey" flood protection schemes (i.e. hard or engineering approaches) creating a system sensitive to climate change with adverse effects on freshwater ecosystems. Previous research has illustrated infrastructure's large effect in locking in unsustainable patterns of development and preventing EBAs through its shaping of behaviours, expectations and preferences (Thacker et al., 2019; Wesselink et al., 2015). Maladapted land uses had often caused a slow shift in biological baselines and one respondent explained how this had led several nature reserves to lose their protected status. Furthermore, several interviewees reported that maladapted land uses in their catchments such as arable farming on wet meadows had led to short-term solutions dominating interventions such as desilting to improve environmental flow outcomes and water abstraction. "*The whole Isle of Axholme should actually be underwater naturally. So the fact that we've reclaimed it, we're now always working to maintain the false environment*" (R4).

Interviewees criticised that water company assessments were rarely holistic, often focusing solely on flow or water quality. "*The water companies are only interested in the things that affect drinking water standards. And not really looking at the wider implications of herbicides and pesticides on flora and fauna in the river*" (NGO4). Non-flow pressures (such as sediment trapping) from old or mismanaged infrastructure was often not sufficiently considered. One respondent from the EA explained how only recently the full scale of CSOs' effects had been uncovered through the uptake of new monitoring targets. Three respondents highlighted the problems their catchments faced through road runoff: "*A lot of the highways' drains are not managed properly, and you've got*

that really high intense rainfall summer which is washing everything off the roads into the river and this contains contaminants which are highly toxic from tyres and catalytic converters" (WA3).

4.3.3 How can Environmental Flow Protection be improved?

Based on the interviewees' responses, this study makes five proposals for improving environmental flow protection across diverse catchment types characterised by complex, multifaceted pressures (summarised in the overview in Table 4.5) and comments specifically on their application in the England setting. Overlap exists between some of the themes; however each point is sufficiently distinctive to warrant separate discussion. The solutions outlined here address the shortcomings outlined in the previous section and make reference to enhancing ICM, adaptive management and EBA.

Table 4.5: Five proposals for improving environmental flow protection

1. **Close knowledge gaps for regionalisation.** Provide and facilitate more and improved monitoring, telemetry, real-time information gathering and sharing, regional modelling and public data access. Thus, provide evidence with increased spatio-temporal resolution to support efficient and unbiased decision making.
2. **Maximise potential for demand reductions.** Tackle water leakage, increase roll-out of (smart) metering and support efficiency increases. Widen consultation on the location of new housing developments. All underpinned by campaigns to raise awareness of water as a finite resource. Thus, mitigate the effects of growing populations and embed behavioural changes.
3. **Strengthen institutional support for Integrated Catchment Management (ICM).** Provide adequate financial support for the EA while improving the coordination within and between regulators. Strengthen focus of existing policy and implement new policy focusing land integration. Shorten and adapt funding cycles to integrate risk and allow for uncertain outcomes. Modernise the abstraction licensing system. Align top-down national regulatory goals with bottom-up collective action.
4. **Champion adaptive capacity.** Clarify different actors' responsibilities and roles across scales, emphasise shared goals and support cooperation. Strengthen and adopt strategies of successful schemes. Harness and enhance adaptive capacity.
5. **Build resilience by embedding and restoring natural processes.** Restore rivers and their floodplains and protect natural processes. Establish and integrate exchange processes between land and water and embed more holistic management including non-flow pressures. Maximise and profit from resilient Ecosystem-Based Approach (EBA) realising multiple benefits beyond environmental flow protection.

4.3.3.1 Close Knowledge Gaps for Regionalisation

a) Provide and collect data with higher spatio-temporal resolution

To address existing as well as emerging challenges, interviewees regarded the collection and provision of more data with higher spatio-temporal resolution as crucial. The literature agrees that balanced, efficient and unbiased decision making is ensured by reliable and timely information about the river basin and is at the heart of ICM (Ludwig et al., 2014; McDonnell, 2008; Poff et al., 2010). For improving flexibility to react to variable conditions, dependable information was stressed as indispensable in several interviews. This corresponds to Pandya and Sharma (2021) who outline that readiness for highly regionalised climate change impacts relies on better forecasting and monitoring.

Main means highlighted as integral for achieving this were; extended and improved baseline and headwater monitoring, more gauging stations, real time telemetry of surface- and groundwater and remote sensing. More monitoring was identified as important to better characterise baseline conditions of groundwater, surface water and the ecology to then support interventions. The Natural Environment Research Council (NERC) - funded UK Drought and Water Scarcity Programme has recognised enhanced fundamental monitoring as central in tackling groundwater drought (https://aboutdrought.info/) and NERC is also leading on a £38 million project to establish UK-wide monitoring, open-access data and research infrastructure for flood and drought modelling (CEH, 2022). Furthermore, aligning with other studies including Harwood et al. (2018) and King et al. (2015), respondents emphasised that monitoring can ensure environmental flows have the desired outcomes and demonstrate their benefits. Several respondents called for improved monitoring of headwater streams to support restoration efforts such as the removal of structures. The importance of headwater wetlands is immense for both biodiversity (Brown et al., 2019) and climate change adaptation (Shuttleworth et al., 2019) in England. One regulatory intervention to achieve larger monitoring coverage suggested by Ascott et al. (2020) lies in including stipulations on new abstraction licenses to require monitoring. Furthermore, respondents stressed the importance of collecting different types of information together for closing knowledge gaps in process understanding. In places with monitoring, data collection often was not done at the right frequency and not for the right combination of plants and/or invertebrates.

For improving water quantity and quality data collection in surface- and groundwater bodies, the need for more flow gaugings and real time telemetry was identified. Real time data collection through sensors, transmission through telemetry and online data provision relied on investments in new technologies. As pointed out by one EA employee "*reliable access to real time level flow data (...) would be a big leap from where we are now*" (R3). However, it would facilitate more dynamic water use which was seen as decisive in the face of climate change. Respondents highlighted the opportunities real time flow data collection and online provision offers for ensuring that environmental flows are met as abstractors could be notified directly; one respondent suggested that farmers could be texted when they can take however much they want during floods but also

when all abstractions have to cease to maintain Hands-off-Flows (HOF) and another highlighted the potential for water trading. The Canal and River Trust already employs a Supervisory Control and Data Acquisition (SCADA) network to monitor water levels and facilitate some automation in pump and sluice operation (NGO7, Canal & River Trust (2022)). The regulator has recognised the large potential of real time information on water quantity and quality and the Catchment Systems Thinking Cooperative (CaSTCo) project aims to improve the quality and density of water sensor networks won funding from Ofwat (Ofwat, 2022b).

Several opportunities for the implementation of remote sensing were outlined. When used for continuous water quality monitoring, water companies could for example be informed when they needed to stop abstracting. Additionally, one respondent saw its high potential for proactive monitoring of algal blooms. Currently, algal blooms are only treated when they are reported (Environment Agency, 2017). Algal blooms can pose health risks to humans and aquatic habitats through release of toxins and oxygen depletion (Brooks et al., 2016; Cheung et al., 2013). With regards to river flow, a water company employee highlighted the importance of remote sensing for understanding combined abstraction pressures on water courses particularly during drought. They told of the successes their company had: "*We're using satellite imagery that they'll plot onto a GIS layers and it comes down to two metres resolution. And off that actually from the vegetation changes you can pick up leaks, you can pick up where people are abstracting it gives us a better idea of what's going on in our catchments*" (WA3). This might become instrumental in gaining control over harmful unlicensed abstractions. Also, the large potential for citizen science in supporting data collection and monitoring including algal bloom and groundwater droughts was highlighted by several interviewees (see below).

b) More and improved integrated regional modelling

The interviewees emphasised the importance of regional modelling for closing knowledge gaps. They stressed that models play a crucial role in improving the understanding of land-water interactions and combined pressures from abstraction and climate change. Furthermore, in line with the literature (Kaushal et al., 2017; Sanz, MJ and De Vente, J and Chotte, Jean-Luc and Bernoux, Martial and Kust, G and Ruiz, I and Almagro, M and Alloza, JA and Vallejo, R and Castillo, V, 2017) they emphasised its role in guiding climate change adaptation for example through land use change. For evaluating the effects of land use change on water resources integrated models have proven effective, however they require spatially explicit input data and should be site-specific (Mensah et al., 2022) such as a model developed for the Sherwood Sandstone aquifer which has been used to evaluate climate change and land use scenarios (NGO2, Zhang and Hiscock (2010)).

The complex processes involved in the development and progression of droughts were one area mentioned where integrated surface-groundwater models are applied to increase understanding. The sensitivity to altered recharge conditions (Hellwig et al.,

2021), effects of climate change (Hughes et al., 2021) and exchange processes between different types of groundwater and surface waters (Hare et al., 2021) have to be established. Interviewees emphasised that groundwater processes can have large implications for ecology under drought and particularly in perennial rivers and reaches the implications of changing rainfall and groundwater recharge have to be understood. One respondent emphasised the complex interaction of intermittent streams with groundwater that affects flow timing, frequency and duration: "*it gets really complicated as you get variations in geology and as you're getting variations in morphological stress*" (PC2). Respondents reported using models to inform the flexible conjunctive use of ground – and surface water abstraction. They could also support the process understanding within complex aquifers for example the effects of abstractions on the pressurisation in chalk. One respondent highlighted that due to the non-linear and heterogeneous nature of groundwater some processes manifest only during droughts and not at higher flows.

Lastly, a number of respondents talked about their involvement, sometimes in cooperation with the EA, in the development of regional hydro-ecological models. Water company interviewees praised the use of statistical models fed with local data, including expert technical knowledge to separate abstraction effects from other processes. If sufficiently robust, models such as developed by Bradley et al. (2017), are used for regulatory decisions regarding abstraction licencing including setting local flow constraints, both now and under new demand scenarios in the future. The EA is using very coarse models in setting local EFIs. The respondents therefore stated that the main aim of developing regional scale models was to detangle main pressures on freshwaters and improve the EA's models. Subsequently, these new or refined models were often used to justify a change in abstraction regime, this is illustrated by such quotes as: "*At the time we faced quite a lot of challenge as to 'why are you bothering doing this', and so on and so forth. But by doing that test, and going back and looking at what the model actually did, it transpired that the model needed to be updated and refined quite significantly. Now, after the refinement of the model, the EFI was halved*" (WA6). This suggests that water companies are largely incentivised to invest in improving models through new abilities or in specific models incorporating a particular catchment's features where abstraction limits set through the EFI are perceived as too limiting. Where levels of abstraction are within water company requirements, they have fewer incentives to invest in models. While not explicitly conveyed during the interviews, this finding indicates the importance of incentivising the development of models in other areas, particular in those of high ecological value (Saintilan et al., 2009) and where impacts of abstraction are poorly understood (Mansour et al., 2012; Tait et al., 2004).

c) More information sharing and public access to data

To save time, reduce costs and bring together good practice, many interviewees indicated a need for more free access and quicker processes of data procurement. The provision of information and knowledge, both local and scientific, is an important part of Adaptive Governance (Chaffin et al., 2014). Defra along with several of the interviewees

see the EA as the key responsible for providing data and evidence at the catchment scale (Defra, 2013). The literature describes such boundary organisations for connecting different actors of the water sector (Gustafsson and Lidskog, 2018) as substantial in facilitating information sharing and its subsequent use in successful impact across a range of scales, fields and types of stakeholders (Ferré et al., 2022; Victor et al., 2017).

Two interviewees emphasised that consistent procedures that allow for people to go out in field and pursue citizen science needed to be developed and supported by public funding. A few examples do exist where public engagement and data collection are integrated. In the Wye catchment, the EA is using citizen science with the aim to collect data on high temperatures and algal blooms to tackle phosphate pollution (Environment Agency, 2022c). The catchment monitoring co-operative by CaBA aims to foster citizen science by bringing together local communities, NGOs, businesses and public bodies to establish a coordinated and cost-effective environmental monitoring programme (The Rivers Trust, 2021).

Respondents stressed the value of catchment scale combined datasets such as those maintained by CaBA which comprises a large online database on catchment information for supporting local and national initiatives. This dataset is gradually being merged into shared information platforms usually established at the catchment scale (e.g. Partnership, West Cumbria Catchment (2022) or River Eden Catchment Partnership (2022)). It doesn't require additional software and, by extending the datasets with narratives, facilitates to prepare, present and make the complex evidence base understandable for a wider audience (Collins et al., 2020). Despite easy access and applicability, the respondent working at the Rivers Trust stressed that due to limited awareness, the regulators were not exploiting its full potential when setting up new initiatives: "*Defra created CaBA and when creating nature recovery, they weren't aware of the CaBA data set*" (NGO3).

One respondent recommended more public environmental information sharing, such as on licensed abstraction volumes, without time consuming freedom of information requests. Lange et al. (2019) also highlighted that to enable innovative and transparent licensing agreements, access to critical datasets was needed for catchment partnerships. Ofwat has recognised the problem of lack of open access data and its relevance for climate change adaptation and environmental protection and is assessing the possibilities of open data in the water industry (Ofwat, 2021).

4.3.3.2 Maximise Potential for Demand Reductions

a) Tackle leakage

The interviewees recognised that a high degree of water recovery is possible through tackling leakage in the supply network and also emphasised the high importance of leakage reductions for water companies' drought resilience and credibility during drought when customers are asked to use less. A report by the National Audit Office (NAO) NAO (2020) sees leakage reduction as the most significant contribution to decreasing

the gap between demand and supply. Water companies have committed to reduce leakage by 50% until 2050 from 2017/18 levels (Environment Agency, 2020d). Ofwat estimates leakage to reduce by 16% during AMP7 (2020–25) (NAO, 2020). In 2022, 11% of these reductions had been achieved although with large differences between companies (Ofwat, 2022a). Ofwat admitted to the Committee of Public Accounts (2020) that the plan for reducing leakage, while not impossible, was difficult to achieve, realising some companies' targets relied on as yet unknown and untested methodologies.

As two interviewees pointed out, smart networks – pressure sensors extended with Artificial Intelligence (AI) – offer large opportunities for reducing leakage. This has been very effective elsewhere, notably in Singapore (Allen et al., 2012) and Las Vegas (Boulos et al., 2014). Its success is due to the reduction in response time as leaks are noticed and located quicker than with traditional methods (UK Water, 2022). United Utilities is leading on an "AI and Sewer Defect Analysis Project" supported by the Ofwat Innovation Fund (Ofwat, 2022e). One respondent highlighted the importance of investment in such technological advances that make it simpler to fix leaks such as sending robots into pipes. Since repairing leaks is very expensive for water companies (PWC, 2019), the interviewed water company employees emphasised that Ofwat needed to support innovation and collaboration to tackle it. WA9 conceded that water companies also needed to provide support for leakage reduction on customer side where around a third of leakage occurred; "*They* [*customers] *are responsible for their pipe work from the property boundary so from the footpath. So any leak that happens on a pipe from that point onwards is their responsibility though we would generally help them with that*".

b) Quicker and increased rollout of metering

Respondents described the many benefits that metering and particularly smart metering, continuous measuring of water consumption combined with online controls, of household water use would realise. Water charges in England rely on a mix of metered and fixed charge billing (Ofwat, 2022l). As of March 2021, 56.4% of water customers had a water meter fitted (Environment Agency, 2022h). WA2 pointed out that South East Water: "*just completed an eight year compulsory customer metering programme and water efficiency programme, which has actually driven demand downwards*". This resonates with findings by Ornaghi and Tonin (2017) who showed that in addition to improving the detection of leakage, metering reduced water use by between 16% to 20%.

The following advantages of (smart*) metering were highlighted during the interviews:

1. demonstrates effect of interventions such as improved fittings
2. facilitates to untangle drivers of demand e.g. holiday periods and weather events
3. supports the reduction of leakage on customer property
4. shows customers how they compare to other households, encouraging water saving
5. helps customers reduce demand through details on drivers for their use*

6. in combination with agile communication (creating a smart network) it can help steer demand for example through direct texting when demand reductions are needed during low flow and drought conditions*

One respondent pointed out that smart meters were not only useful for private households but also in industry and on irrigation pumps. Salvidge (2022) discusses this as an option for supporting compliance under licensing exemptions. The Water Industry Act (1999) represents the legislative framework for switching to metered water services for private customers including their installation free of charge. Several respondents talked about the compulsory metering programs rolled out by water companies which they have the right to do in regions with serious water stress (Environment Agency, 2021d). Southern Water, Thames, Affinity Water, South East Water and Anglian Water have been running compulsory metering programs with Thames Water rolling out smart meters to all its customers (Hutton, 2019). The move to (smart) meters is however not without criticism including concerns about data privacy (Salomons et al., 2020) and increasing prices(Chawla et al., 2020). Thames Water has been investigated by Ofwat regarding its use of meters that exclude third party providers (Ofwat, 2022g).

c) Support efficiency increases

The design of appliances, (mandatory) water labelling, effluent reuse for agriculture and rainwater harvesting for housing developments were all identified by interviewees in having large scope for efficiency increases. One respondent called for stronger government policy for efficiency design standards for home appliances. Research has shown that improving water use efficiency of home appliances reduces water use significantly (Carragher et al., 2012; Willis et al., 2013). Another respondent highlighted that this should be supported by clear rules through both more regulation as well as improved enforcement as current regulation left loopholes. They outlined that achieving the efficiency standards of 125 l/p/d use The Building Regulations (2010) should not rely on offsetting. This undermined the effect of efficient fittings and might misrepresent the actual (higher) use.

The advantage of water labelling was seen in similar incentives for consumers as the labelling applied for energy using devices. Higher public awareness for energy saving than for water saving was also reported by the Committee of Public Accounts (2020). As part of the 25 year Environment Plan, the introduction of a mandatory water label for products was announced in 2021 (EA, Defra &, 2021). Moreover, according to respondents, effluent reuse in agriculture could realise multiple benefits by using nutrient rich final effluent from water treatment works for aquifer recharge while pulling out nutrients and/or direct use for irrigation and fertilizing. Due to its environmental and health related risks this should be underpinned by good agricultural practices and measures reducing chemicals at the source particularly those with persistent, bioaccumulative and toxic and persistent, mobile and toxic properties (Helmecke et al., 2020). Higher water reuse within new developments on the other hand could only be achieved through stricter regulation of per person use caps, LG1 recalled: "*One particular new development where we*

got the local authority and everybody on board, the landowner as well, to deliver 90 litres per person per day as the objective for the development. It's a level that would require some form of water reuse within the development, it couldn't be achieved just with low flow fittings and houses and things like that. It was actually overruled by the planning inspector. They said no, we can't do 90 litres per person per day, it's got to be 110". While the UK Government (2010) requires all new dwellings to achieve a water efficiency of 125 l/p/d, local authorities can adopt 110 l/p/d in 'water stressed areas'. Usually sustainable urban drainage (discussed in section 4.3.3.3) is also required. Respondents wished for more stringent rules and support in these areas. Ofwat encourages water companies to incentivise developers through reductions to their water infrastructure charges. Water recycling is incentivised by some companies such as Thames Water and SES Water (Ofwat, 2022n).

Respondents also saw large scope for water use efficiency increases through rainwater harvesting in greenhouse and polytunnel systems. They described multiple benefits this could realise, particularly combined with water recycling such as flood protection and preventing sediment scouring and erosion. These systems could realise self sufficient water supplies, particularly as within-system water recycling was often already in place. The H2OSource2Sea project two respondents were involved in is working with farmers on polytunnel adaptation (Kent Wildlife Trust, 2019).

d) Wider consultation on housing developments

A suggestion made by interviewees and in a similar way taken up by official government reports (WSBF, 2020) relates to optimising the spatial distribution of increasing water demand by facilitating more diverse statutory consultation for major planning applications. While there are many competing interests involved, interviewees from water companies highlighted that this would make water provision easier and cheaper for them. The report to Government by the Westminster Sustainable Business Forum (WSBF, 2020) outlines that to better use local planning and flood authorities they could be brought together within catchment groups to then give these groups more power in the planning processes as statutory consultees. One interviewee pointed out that this could be realised through CaBA which additionally brought land owners, environmental groups and local communities to the table.

e) Campaigns to raise awareness for value of water as a finite resource

A recurring theme discussed in the interviews was that for the success of the previously outlined approaches, they needed underpinning with campaigns to raise awareness for water as a finite resource. One respondent suggested price increases to incentivise water savings. In February 2023, a price increase of 7.5% in households' average annual water bill was announced, the largest increase in over 20 years and a move criticised by consumer rights groups (Clark, 2023; Sandercock, 2023). For example many countries in Europe have higher water prices than England, however the majority

of these countries also have higher water use efficiency (EurEau, 2020). This suggests that it might be more equitable to first reduce leakage and enhance efficiency of fittings.

Furthermore, some authors argue that higher prices disproportionally benefit investors Bayliss et al. (2022) and Buse and Bayliss (2022). Other approaches around engagement and education were favoured among the interviewees and one stated: "*things like citizen science, for example, just to reconnect the general public back to their environment so I think in terms of the demand that aspect is needed really*" (WA1). One EA employee praised what the extensive media coverage of the 2022 drought had accomplished for public awareness on climate change. However, they also emphasised the need for more education on invisible progression of climate change for example that a drought was not over after a few days of rainfall. They furthermore pointed out that both, increased reporting on environmental issues and the recent extreme events in Europe, had positively influenced awareness on the effects of human activities on their environment. This included longstanding unsustainable land uses such as agriculture on drained land. They explained that it was vital for the EA to control the narrative around the data they published and that they should dare to become more forceful with their messaging. Otherwise "*we give the data and then we let people that have an agenda put the story to the data and I don't think generally those stories match the actual real world*" (R4). Previous research has shown that to achieve the desired public engagement and counteract misinformation, appropriate framing and communication of scientific data is crucial (Grainger et al., 2016; Iyengar and Massey, 2019). Another interviewee was optimistic that the timing for campaigns on reduction of water use was right and emphasised: "*I think it's a massive opportunity at the moment with young people to really, really embed behavioural changes (. . .) young people they're very, very clued up in terms of climate change and green agenda, environments*" (WA4). This falls in line with the growing literature on the younger generation's larger online exposure, more active engagement in the fight against climate change (Hamilton et al., 2019; Tyson et al., 2021) and more sustainable lifestyle compared to previous generations (Brand et al., 2022).

4.3.3.3 Strengthen institutional Support for Integrated Catchment Management (ICM)

a) Provide adequate financial support for the regulator

The respondents agreed that the EA required adequate financial support to fulfil its role of operationalising Defra's environmental policies. As outlined in section 4.3.3.1, this is instrumental to increase flexibility, confidence, responsiveness and openness to innovation. Interviewees mainly focused on how more financial support would increase the EA's ability to collect data, to undertake surveys and to realise their role in enforcing regulation. They highlighted how more in-house data collection would render the EA more flexible in terms of environmental flow allocation due to more confidence in ecological correlations. This would allow to refine regulation and to move away from blanket rules

such as those of “closed catchments” where no further abstraction licenses are given out (e.g. Environment Agency, 2019c). Respondents were also confident that more EA-led investigations would render the institution more open to innovation. They highlighted the role of the EA and its employees as what Gustafsson and Lidskog (2018) identify as a boundary organisation – points of contact and facilitators of knowledge exchange in regional to national scale projects and groups. To fulfil this role, respondents saw large scope through more staff who would increase responsiveness. This would also facilitate more support to catchment groups and more appropriate enforcement (e.g. for farming rules for water, that the EA should guide, advice and enforce on (Defra, 2022c)) to close the environmental enforcement gap (Rose, 2020). These three opportunities offered through more financial support – more confidence in underlying relationships, more openness to innovation and more enforcement reflect in the following quote: “*One of my farmers wanted to clean a watercourse up and divert it through a wetland where it was on its original course. He’s been tied up with red tape yet the Highways Agency’s new road drains aren’t working properly*" (NGO6). Monitoring data from the wetland was found to have been missing, and the outcome of innovative approaches suggested by the farmer were uncertain as there were no staff available to assess the potential benefits and the Highway Authority did not fulfill its duties agreed upon with the EA (Environment Agency & Highways Agency, 2009).

The literature agrees that to effectively accomplish their mission, regulatory agencies require adequate funding (Metzenbaum and Vasisht, 2015). In the long run this saves money as the right priorities for environmental resilience can be set and further deterioration (as stated in the WFD) can be prevented. The EA undertook an extensive consultation on changes to water resources charges and a new charging scheme has come into force in April 2022. This new scheme increased charges and changed the banding of abstraction volumes (R2, Environment Agency (2022a,c)). With regards to funding environmental improvements, the interviewees highlighted the need to emphasise multiple outcomes beyond the main environmental focus. To achieve this, Cubi-Molla et al. (2021) advises the establishment of a formal method and public valuation to guide the allocation of budgets between UK government departments.

b) Improve coordination within and between regulators

Respondents saw scope for improving the interaction with, within and between the regulators. A successful link between the regulators’ strategic decision making and operational practice requires improved communication and dialogue (Falkenmark et al., 2004). Several water company employees described how the low bills focussed by Ofwat needed more realism regarding the environmental protection priorities set out by the EA. They emphasised their need for certainty in planning. This falls in line with findings by Helm (2020), who described the same disconnect between the foci of Ofwat and the EA. Interviewees also called for an increase in transparency of within-EA processes to project partners and the public, as clearly explained by one: “*planning permission (. . .) need to be a lot more transparent, the time stamp for example when it is submitted*

on this date to such and such a person, here are the contacts, and some sort of regular online bit, like when your parcel is delivered and you type in a number and you know where your parcel is" (NGO5). In line with Lange and Gouldson (2010) interviewees explained how important transparency is for trust in and cooperation with the regulator.

Furthermore, interviewees suggested integrating and assessing compatibility and goals of different thematic areas within the EA. For example water quality and quantity should not be treated separately and one respondent wished for more exchange between people working on the two themes within the EA. Furthermore, flood defence and biodiversity and their respective compatibility required more oversight (discussed in section 4.3.3.5).

c) Strengthen focus of existing policy & support land integration through new policy

Respondents called for a stronger emphasis on land use and management integration in the governance and regulatory frameworks for water and for Ofwat to support innovations aiming to enhance integrated water management. For a more focussed policy design supporting land integration, one respondent emphasised the need for long-term land use planning and the importance of reestablishing natural processes (as discussed in the last theme). They found it important to clearly communicate policy aims to manage expectations (such as land drainage for roads and not for naturally flooding areas). This is well in line with the literature; Ison et al. (2015) reason that the framing of water policy matters greatly and Pahl-Wostl (2007) emphasises that reducing differences in mental frames is important for creating a common understanding.

The new innovation fund set up by Ofwat (Ofwat, 2022e) was well received by respondents as it supported independent ideas (both the AI project by United Utilities and CaSTCo by the Rivers Trust are funded through it). Additionally, one respondent wished for Ofwat to force water companies to more catchment-wide approaches and said: "*Ofwat (. . .) increasingly realised that the water industry has to do more with regards to wider catchment pollution and not just simply continue with the old narrow way of water company working*" (NGO3). The interviewees evaluate the Environmental Land Management Schemes (ELMS) (Defra, 2021a) as positive because of its focus on incentives, sustainable land use change and realising multiple benefits. This falls in line with Environmental Land Management Schemes (ELMS)' advantages highlighted by Klaar et al. (2020). ELMS replaced the EU's Common Agriculture Policy framework providing financial support of farmers that was primarily based on the amount of land farmers farmed UK Parliament (2022). Instead, ELMS use payment for ecosystem services, the exchange of value for land management practices aiming to provide or ensure ecosystem services (Salzman et al., 2018). Farmers and other land managers may be paid for delivering clean and plentiful water or adaptation to climate change (Defra, 2021a). One interviewee from the EA highlighted that, while some details were not fully established yet, ELMS could become the suitable mechanism for convincing respective stakeholders of the environmental, economic and social benefits of environmental improvements

(e.g. flooding land) and in this way realising the three pillars of sustainability. However, five respondents criticised that it was not implemented quick enough. Furthermore, they were not certain if the compensation for farmers, particularly those growing high value irrigated crops, was always appropriate and therefore if ELMS actually changed water needs. Moreover, respondents called for clarifications on how ELMS, CaBA and nature recovery complemented each other and operated side by side.

With regards to the WINEP, interviewees highlighted that more flexible AMP cycles were needed to increase responsiveness and implementation of long and short-term improvements. This way the process would better align with the other sources of funding that environmental groups rely on and thus encourage cooperation. Ofwat has come to a similar conclusion and is considering the exclusion of some performance issues (such as raw water quality exclusions in the calculation of peak week production capacity (Ofwat, 2022d)) from the price review to develop longer/more rapid processes where appropriate (Ofwat, 2021b). The respondents also emphasised the significance of SuDS in mitigating the effects of increasing populations on water demand and drainage. Two respondents called for the original intention of Schedule 3 ("the establishment of a SuDS Approving Body (SAB) to be set up within the local authority alongside their lead local flood authority duty. SAB approval will be required before construction of drainage systems can commence on new and redeveloped sites" , Flood and Water Management Act (2010)) to become obligatory. This is also endorsed by a range of private and public bodies working in the water sector including the British Hydrological Society who wrote a joint letter to the Prime Minister calling for Schedule 3 to be implemented in the Flood and Water Management Act (CIWEM, 2022).

One EA employee suggested a statutory collaborative and collective water planning system across policy sectors. They explained how this would provide actors outside the water sector with an overarching remit and a platform to consult and advocate legislation and with collective negotiation power to generate investment and hence enhance their voices. This resonates with the literature. Similar action was highlighted by Williams (2020) whereby quantifiable water targets for example in statutory land use planning can lead to adoption of more integrated urban water management practices. Schaub et al. (2022) found that the integration of water with other policy sectors avoids conflict and realises synergies, but requires formulation and implementation of suitable policy mixes (Kern et al., 2019; Rogge and Reichardt, 2016). The respondent outlined that agricultural, business or urban water management plans could then be developed. Another suggestion made during the interviews was to change the law making food security a statutory target as this would free money for water resilience in agriculture.

d) Financial boost for transformation processes under uncertainty

Throughout the interviews, it became clear that achieving ICM and climate resilient environmental flow protection would be difficult without significant (public) investments. Not least the water quality crisis caused by CSOs had shown the immense investment backlog which prevented rendering water supply systems climate ready. Respondents

recommended that investments should be made with sensible weighting of all options including those with uncertain outcomes yet potentially high rewards. With regards to renovating and replacing sewers, R4 recommended a focus on those threatening the most vulnerable places: "*You focus on things that cause the most harm the most often and by doing that, you will then get into a much better place*". To overcome cautious and inflexible catchment-based planning, several respondents suggested a move away from solely outcome based approaches allowing WINEP investments with uncertain, more open results. Water companies should be allowed to take risks and fail as innovation required risk taking and learning from mistakes. To overcome the current barrier (lock-in) of no one carrying financial risk, a public body might have to assume the risk. This corresponds to Lütkenhorst et al. (2014) and Kern and Markard (2016) who find that high uncertainty and lock-ins require comprehensive government intervention to advance sustainability. One respondent explained this well: "*There is a culture of allowing that at some places, investments is not going to work and we're going to fail sometimes. On the flip side, if that's 25% and the other 75% is successes, you should have outweighed it*" (R3). One respondent suggested the need to address issues in public water supply first as this was deemed most important by society and provided flexibility to fix other problems with public supply as a potential part of the solution.

e) Adapt the licensing system

Respondents came up with several suggestions to modernise the abstraction licensing system. Adaptive management of abstractions supported by improved data collection (particularly more baseline monitoring/real-time data) was seen as crucial to achieve the flexibility needed to face climate change. Furthermore, several respondents called for licensing and monitoring of unlicensed abstractions to remove harmful incentives (e.g. cress farming in Kent). Some licensing exemptions have been removed, yet abstractions of less than 20m^3/day remain exempt (Environment Agency, 2014a). Furthermore, to relieve pressure from headwaters, several respondents advocated for abstractions to be moved downstream where possible. This was an easy approach to improve sustainability while maintaining similar levels of deployable output. Also, despite not being included in the WFD, ephemeral streams should be taken up in guidance and monitoring. Additionally, water company employees criticised that neither HMWB nor flow augmentation schemes were well represented in current regulation. Several respondents emphasised the importance of adapting low flow guidance under climate change similar to the guidance available for high and flood flows (Environment Agency, 2016b) for example by drawing from past low flow periods (e.g. during the years 1976, 2018 or 2022).

Respondents especially wished for more holistic drought planning and explained that overwriting the water management plans during droughts was problematic as this was when rivers needed the protection. This is highlighted by quotes such as the following: "*In a drought, you follow a totally different set of rules.' And it's only in a drought maybe that the rivers got any stress in a drought that it needs any kind of protection. It is madness*" (PC2). Grecksch (2018) agrees that currently available water scarcity and

drought management options in England are limited and more proactive approaches relying on preventing rather than reacting to droughts are needed to face challenges ahead. Due to their slow onset and fuzzy definition, planning for droughts is harder than responding to them (Raikes et al., 2019). The literature agrees on the importance of monitoring, early warning systems and proactive measures reducing drought impacts during times of sufficient water availability (Finnessey et al., 2016; Wilhite et al., 2014).

Lastly, three respondents emphasised the importance of guidance for climate resilience in each catchment. NGO3 explained that: "*We need quantifiable targets for resilience across each and every catchment, how much do we need to re-wild, how much water do we need to hold back to support more sustainable water resources*". One respondent favoured a rigorous reform through a catchment shares approach as it created incentives for everyone to solve challenges for supply and demand. This approach relies on water abstraction rights based on percentage shares of available water instead of on physical volumes (Stern, 2013). Stern (2013) see advantages in the incentives it creates for trading water and its flexibility to changing conditions while existing abstraction licenses can be continued and Erfani et al. (2015) have shown its scope for improving environmental protection.

4.3.3.4 Champion Adaptive Capacity

a) Clarify responsibilities and roles

Power sharing and leadership by individual actors such as through catchment managers or site officers who can make decisions locally was seen as crucial by the respondents. The interviewee from Natural England praised their organisation's former approach of having responsible officer at each (protected) site with local knowledge. This is consistent with Rouillard and Spray (2016)'s analysis on cross-scale working in catchment management. They describe that on-ground change relies on such trusted intermediaries who develop relationships with key actors and are effective in closing gaps across levels of governance. By focussing on these key social connectors who operationalise local knowledge, the fit between ecosystems and the governance system is enhanced (Folke et al., 2005; Olsson et al., 2007; Rouillard and Spray, 2016). One of the respondents, NGO6, was such a key connector integrating knowledge of farmers with that of the water company and the Wildlife Trust they work for. The uptake and success of programs such as Farming Rules for Water program (Defra, 2022c) requires support by such trusted intermediaries. This way two-way synergies could be realised; more efficiency and economic benefit for farmers and a reduction of diffuse pollution of freshwater.

To increase adaptive capacity and governance and respond to local challenges, respondents indicated the need to clearly define roles and responsibilities. They not only referred to individual actors, but also endorsed a clear delineation of the remit of the many semi-independent groups working at multiple spatial scales. This resonates with the literature that describes these groups as necessary to not hamper the self-organising

functions of communities (Folke et al., 2004; Nelson et al., 2007). The importance of strengthening Rivers Trusts and other organisations leading on CaBA was also underlined by several interviewees. These organisations had a good track record in facilitating cooperation as explained by NGO5 working for a Rivers Trust: "*The trusts act as a facilitator, and we're not a statutory body, we can access different types of funding and support*". They can bring groups focused on individual sites together with their strategic overviews and embody water-related memory and Robins et al. (2017) propose that any new UK water policy with focus on catchment partnerships models should grant them a leading role. Furthermore, CaBA brings local communities on board and one respondent reported that politicians tended to listen when these made their complaints heard. Besides, soil nutrient management guidance was needed across the country with more free independent support for farmers from beyond the EA or water companies. Governmental initiatives such as Catchment Sensitive Farming (CSF) from Natural England, Defra and the EA address this issue and provide free training, advice and support in selected priority areas (UK Government, 2020). Davey et al. (2020) found that CSF led to a reduction in instream suspended solids and orthophosphate. Lastly, the EA should be replaced in instances where it has a double role and also acts as "policing" regulator. Interviewees, both from the EA and outside, described their good experience with third party advisors and highlighted how replacing the EA was particularly important for increasing engagement from landowners who were often wary of the regulatory arm of the agency. "*We find that the third party advisors, so catchment sensitive farming officers or water company advisors, (. . .) they have probably better conversations with landowners*" (R4).

b) Emphasise common goals and support cooperation

A main red thread throughout the interviews was the praise for cooperating and working together. As a key aspect for supporting adaptive capacity, this facilitates the coproduction of operational knowledge (Lemos, 2015) and respondents emphasised that cooperation should be a central element of all further initiatives. In the context of finding a balance between water uses, NGO6 emphasised: "*For me, especially with a national framework and direction of travel, it's working together, it's all water abstractors working together to come up with solutions that will protect supply, whether for the customers, the farmers or industry or the environment*".

Respondents saw a large scope for improving the five-year price review and AMP cycle in a way that fosters more exchange and establishes trust. Apart from a need for more flexible timelines of delivery to ensure environmental groups' further engagement (see section 4.3.3.3), interviewees suggested that failure to reinvest and to deliver the environmental objectives set out in the WINEP needed prosecution. This corresponds with their suggestions for more dynamic targets (see section 4.3.3.3). Ofwat is considering to update some performance measures from the price review to develop longer-term processes or to respectively facilitate more rapid action where needed (NAO, 2020). Furthermore, interviewees indicated that CaBA should be supported through greater

funding and legitimacy (see next theme). It has large potential and a good track record of harnessing local adaptive capacity. Each CaBA partnership has an EA catchment coordinator who serves as a link to specialists within the EA and for informal communications when things go wrong but also when for example more water company collaboration is needed (Defra, 2013). The way CaBA cooperates with the EA is a good example of linking up top down with bottom-up approaches (Rouillard and Spray, 2016) through engagement and collaboration across sectors and actors, including local communities and land owners (Biswas, 2004; Molle, 2006). This reflects in what the interviewee from the Rivers Trust pointed out; CaBA's National Support Group encouraged catchment partnerships to work together with local and regional groups, build as diversified a partnership as possible and not see each other as a threat. All involved organisations needed to back the CaBA host agreement. Examples where CaBA or other types of partnerships had been established brought up in the interviews include the Action for the River Kennet (ARK, 2022), Friends of the Ems (Greening Westbourne) and the Holistic Water for Horticulture Project (The South East Rivers Trust, 2022a). Interviewees commended the feedback mechanism (Medema et al., 2008), personal relationships and understanding (Stankey, 2005) these projects created. Learning cycles (Pahl-Wostl, 2007) were established, also through the CaBA database.

The priority catchment project was also well received as it improved lines of communication through regular meetings, facilitated exchange of good practices, fostered mutual trust and compromise and engaged landowners. R4 highlighted its positivity: "*The feedback from some of the members of that group was that they liked the positivity of the priority catchment group that they weren't getting in a lot of the other groups*". The respondents prioritised projects with the aim to activate social memory on more integrated resource use in the past (Olsson et al., 2007) (see section 4.3.3.5). They wished for conversation spaces to explore such topics as provided through the UK Environment Link for networking among organisations with an interest in the environment. One respondent was involved in the UK Environment Link's Blueprint for Water (WCL, 2020) and reported of responding to government consultations together with other NGOs. They highlighted that "*when we responded as the Rivers Trust, we also respond as this coalition, the blueprint for water because it's a powerful voice*" (NGO3).

c) Support and strengthen successful schemes

The respondents indicated that more and extended priority catchment-type projects were needed, as these leveraged funding and pooled resources but needed follow up to ensure long-term engagement and exchange. Their short duration made it difficult to harness commitment beyond the project end. One respondent said they didn't have funding to deliver a trial for water trading they had envisioned. Also, as discussed above, CaBA is well established in harnessing regional adaptive capacity yet could be much more impactful. One respondent highlighted: "*More money for CaBA will mean it can play a more active role in all these initiatives - ELMS, Nature recovery, drainage and wastewater management plans, natural flood risk management etc. and act as a con-*

venor and catalyst for action" (NGO3). Reliable funding would cover the time it costs to establish relationships and support long-term engagement. Investment in capacity building is required for meaningful engagement (Lowndes et al., 2006). Moreover, one respondent highlighted that people needed reliable jobs. Appropriate funding can hence prevent the institutional amnesia (Pollitt, 2000) that ensues when people leave insecure jobs taking their knowledge with them. The funding, around £1.5m a year across all catchment partnerships, is limited compared to what similar Australian initiatives receive (CaBA, 2022b; Robins and Kanowski, 2011). To make catchment partnerships' foci more independent from non-governmental money, the government, for example Defra would need to steer a move away from (fully) matched funding and increase its public funding yet that was "*a popular idea in the general public, less so in political circles*" (R4).

Furthermore, CaBA's legitimacy should be enhanced, potentially through regulatory remit. The catchment groups did not have the ability to deliver and those that did - water companies, EA, local authorities didn't have to follow their advice. They had soft power but their legitimacy was insufficient. Collins et al. (2020) recommend integrating CaBA into the water governance framework and, similar to respondents, indicate that its lack of regulatory power might potentially create confusion as to their role and purpose. The findings are in line with Robins et al. (2017) who recommend that community led and nested catchment based planning and management should be at the heart of all nation-wide water policy. While requiring a significant structural shift, all relevant institutional arrangements should then be aligned to conform with this water policy. In drafting a catchment page for each of the respective partnerships, CaBA has on the one hand yielded some influence during the second and currently running third cycle of River Basin Management Planning (Defra, 2021a), it however requires more systematic integration within the WFD process. Fritsch (2019) found that this policy disconnect has not yet been closed by officially employing CaBA in the WFD public participation processes.

4.3.3.5 Build Resilience by embedding and restoring Natural Processes

a) Seize synergies realised through restoration and process management

Respondents saw large opportunities to realise multiple benefits beyond environmental flow protection and become more climate resilient through: stage zero restoration and ecological recovery, natural processes management and reconnecting rivers to their floodplain. This way multiple benefits could be realised, in particular improvements in flood defence, water storage, water quality, sediment regimes, biodiversity and climate adaptation.

The stage zero restoration concept goes beyond solely re-meandering straightened rivers and focusing on in-channel restoration but aims to rehabilitate a more resilient mosaic of freshwater habitats (Bowles et al., 2020). PC2 highlighted: "*Stage zero restorations makes perfect sense from a water resources perspective as well as from a flood risk and a biodiversity perspective*". Natural process restoration and manage-

ment was also seen as providing large opportunities for realising synergies. Examples named during the interviews included the restoration of natural morphology for more different flow types, the restoration of more natural shapes of riverbanks which provided more biodiversity also through more bank side vegetation, marginal vegetation and more in-channel habitats. Furthermore, natural bankside trees controlled temperature and dissolved oxygen. Several respondents highlighted the large opportunities offered by Natural Flood Management (NFM) i.e. getting wood back into catchments, woody debris in the channel and establishing trees along rivers and streams. Studies have shown net positive benefits of NFM (Iacob et al., 2014). The need to extend the restoration of riparian vegetation was also emphasised due to their importance as habitats and for managing soils in the catchment, in addition to their link between terrestrial and aquatic systems. Both are well established in the literature (Fernandes et al., 2014; Iacob et al., 2014). The role of restoring peat hydrology such as through the removal of gripping in reducing water treatment costs and mitigated the effects of flooding was highlighted in several interviews. Respondents also outlined the large scope for restoring natural sediment regimes to reduce the need for desilting. NGO3 emphasised that: "*CaBA is quite strong on nature-based solutions, wetland, reedbeds, trees, riparian buffer strips all of this managing soil in the catchment, both in the urban and rural environment. I think the country as a whole needs step changes funding this, to make it properly climate resilient*". Since successful restoration and process management requires control over the contiguous land surrounding the river, respondents highlighted the significance of acquiring and transferring land from other uses. Adams et al. (2005) outlined that this might be easier with large institutional owners than where (multiple) land owners require incentives to give up land (e.g. through ELMS section 4.3.3.3).

b) Establish and integrate exchange processes between land and water

Three main proposals for accounting for and integrating exchange processes between land and water and thereby strengthening resilience to climate change (Falkenmark and Rockström, 2010) were outlined during the interviews: rendering land use and agricultural regimes compatible with geographies, enhance natural aquifer recharge through adapted land use and learn and draw from historic land uses.

Interviewees favoured a move to less water intensive crops to reduce irrigation demand. A wide range of crops suitable for England are drought resistant including corn and a range of wheat species (Peyster, 2016). Moreover, improving the match between soil type and crops would not only allow reduced irrigation demand but also enhance environmental protection. NGO2 explained: "*Sandy soils are grade three. So in lot of areas they wouldn't be seen as very good soils, and they're the sorts of soils where as conservationists we might say - are there opportunities for conversion to semi-natural habitats because they're not very profitable. But with the addition of water, they'd be used by the farmers as the equivalent of grade one, so top quality agricultural soils*". Respondents called for incentivising less and more adapted soil movement such as reduced tillage and conservations agriculture that have been shown to significantly lower soil

erosion (Seitz et al., 2018). The need for improved pesticide management for example through Integrated Pest Management (IPM) was highlighted. It is hoped that IPM might become part of the Sustainable Farming Incentive of ELMS in 2023 (Defra, 2022b). IPM considers the entire ecosystem (Smith, 1962) and strives for pest management that is economically, environmentally and ecologically sustainable (Higley and Pedigo, 1996). Respondents outlined the relevance of riparian vegetation for biodiversity and as buffer strips intercepting nutrient and sediments, similarly described in the literature (Anbumozhi et al., 2005; Feld et al., 2018). One respondent saw large opportunities provided through vertical farming as it reduced land use and therefore enabled nature regeneration and water retention. While some challenges remain in particular with regards to energy efficiency and profitability, with increasing population densities vertically produced crops are gaining in momentum (Butturini and Marcelis, 2020; Van Delden et al., 2021).

Land use adaptation's effect on aquifer recharge was another opportunity highlighted during several interviews. Due to less evapotranspiration and irrigation water demand, modelling undertaken for the Sherwood Sandstone aquifer "*shows that there's a significant positive natural aquifer recharge if you shift from arable and conifer plantation to wood pasture*" (NGO2). One respondent was involved the ProWater project and reported its aims; by restoring soils, wetlands and natural land cover, aquifer recharge and water retention in the landscape shall be improved (The South East Rivers Trust, 2022b). These considerations will increase in significance as Hughes et al. (2021) see potentially strong climate change-driven decreases in groundwater recharge during summer across Britain. Particularly in catchments with high baseflow component such as Idle and Rother, the protection of environmental flows will depend on mitigating the effects of climate change on groundwater (Hellwig et al., 2021; Hutchins et al., 2018). The literature reports a range of further opportunities that could be realised through adapting land use. It has for example been shown to increase the capacity of hydropower dams, reduce sediment fluxes and enhance water provision to cities (Chung et al., 2021).

The historical land uses advocated by several interviewees focused on floodplains. One respondent described maps from the 1840s showing species rich hay meadow covering the whole river valley. Respondents reported a multitude of ecosystem services these forms of low intensity farming well adapted to regular flooding allowed to realise including biodiversity, warming of soils, sediment capture and natural flood protection. These are also well established in the literature (Lawson et al., 2018; Warner et al., 2017).

c) More holistic management including non-flow pressures

Respondents had considerable expertise on different non-flow processes and pressures in rivers that demanded more attention if environmental flow protection shall be enhanced. For example, they stressed that built structures (weirs, bridges etc.) that led to direct and indirect sedimentation and flow restriction required more consideration. Furthermore, several respondents reported that highway drains had led to sedimentation and pollution issues in the catchments they worked in. For containing these inputs, two

respondents emphasised that the Highway Authority responsible for their management (Highways Act, 1980) had to improve maintenance of drains. Moreover, approaches to curb diffuse agricultural pollution sources stemming from the application of pesticides, herbicides and fertilisers were discussed. As part of Sustainable Farming Incentive, the suggestions by one interviewee could be realised; replacing some harmful compounds such as the slug repellent metaldehyde while adapting and enhancing application modes for nitrate fertilisers. Storr et al. (2019) additionally recommend to provide more information on the economics and effects of cover crops to UK farmers to limit sedimentation input into rivers. To address challenges of sedimentation, fertilizer input and flooding through runoff, respondents suggested to define high risk land use areas that act as vectors for transport into rivers, as one respondent vividly describes for the Rother: "*So you could even have a field that's on a hillside that's not very close to the river, but it is very well connected to the river*" (NGO4). Furthermore, water companies' and other water infrastructure such as CSO, storm drains and cesspits, needed to be managed appropriately, taking into account the risk they presented for rivers, particularly in flooding areas. To curb pollution through CSOs, one respondent suggested to extend sewer outflows with constructed wetlands, this way sewers could first spill into a controlled environment and be pre-filtered before entering waterways. However, retaining control over water quality was challenging in wetlands. Anglian Water is testing an integrated constructed wetland for wastewater treatment on the Ingol (R4, Norfolk Rivers Trust (2018)). The scope of these secondary and mixed interventions in addressing the challenges of CSO and other sources of pollution likely requires more research.

4.4 Conclusion

Sustaining environmental flows is central for achieving water resilience. Population growth and climate change amplify the importance of strategies for overcoming wicked water management problems. Applying two strands of data and using England as a case study, this multidisciplinary study illustrated the deficiencies of current water management and governance in protecting the freshwater environment from existing and emerging pressures from climate change and population growth. Suitable for informing decision making elsewhere, it elicited five main proposals for attaining more integrated, adapted and ecosystem based environmental flow protection alleviating existing and bracing for emerging pressures.

The time series modelling has shown that, depending on existing demand patterns and climate change, the protection of environmental flows might become exceedingly difficult. In all five case study catchments the five environmental flow scenarios require strong changes to current demand patterns. Supporting environmental flows will require water use reductions and, as previously demonstrated by the NFW, in some catchments water transfers from outside the catchment area might be required to fulfill demand. Some of the scenarios suggested by the NFW allow considerable increases in water abstraction during times of climate induced streamflow decreases and might hence not be advisable in many catchments. The protection of summer streamflow requires decision makers' particular attention as existing overabstraction is high and further reductions in flows through climate change and/or abstractions might exacerbate safeguarding freshwater habitats. Depending on appropriate storage infrastructure and monitoring practicalities, environmental flow allocation that integrates and accounts for climate change's effect on flow regimes might achieve both, protect (more) water for the environment and make fulfilling demand easier in some catchments. Limits to return flows were assessed for two catchment. Shifting return flows between seasons might alleviate climate change effects and catchments with high return flows might be appropriate sources of inter-basin transfers. Case by case studies on sensitivities and climate change effects are required to balance environmental with societal needs.

Stakeholder consultation served to put the water management challenges identified in the modelling into a broader context. It uncovered the comprehensive social and political dimensions relevant for strengthening environmental flow protection. A lack of data and information on surface and groundwater processes was found to hinder efficient decision making. Interviewees described improved monitoring and data collection, regional modelling, data sharing and access as central for closing these knowledge gaps and for providing the evidence base for innovative and confident decision making across scales. The high levels of water use that are projected to increase driven by population growth and insufficient water efficiency restrictions were also seen as problematic. The interviewees recognised high scope to alleviate pressure on water resources through leakage reductions, metering and efficiency increases. Wider consultations on the lo-

cation of new housing developments were endorses as were campaigns raising public awareness on the value of water.

Another major shortcoming was seen in inadequate coordination, integration, funding and alignment of (land and water) planning processes. This reflects in the EA not being able to provide enough in-house data collection and enforcement, in unclear policy and land use lock-ins. Institutional support for ICM can be enhanced through increasing the EA's financial support, coordination of within and between regulatory planning processes, clarifying policy focus and developing new policy for land integration and through a shift to allowing uncertain outcome in environmental improvements through financial support. Interviewees determined limited adaptive capacity to be due to fragmented collaboration and insufficient application of local knowledge. Suggestions for augmenting it included clarifying different actors' responsibilities and roles and more power sharing. Fostering cooperation and enhancing successful schemes of which there are a plethora in England was also regarded favourable. Another important shortcoming relates to ecosystem based management; respondents highlighted that land use practices, particularly in floodplains, were often not well adapted to geographies thus increasing climate change risks to people, biodiversity and ecosystem services. There is considerable scope for establishing resilience and realise a multitude of synergies by embedding and restoring natural processes and ecosystems, learning from historic land uses, integrating land use and exchange processes in water management, extending the management focus beyond single pressures and treating the river and its floodplain as one integrated system.

This study outlined that reversing existing and protecting the environment from emerging pressures stemming from population growth and climate change depends on adequate financial resources for establishing and maintaining the necessary knowledge base, for providing regulatory support and enforcement as well as for supporting groups that harness local and regional engagement and knowledge from stakeholders. The success of ICM, adaptive management and EBA requires solid integration of these groups within the national regulatory decision making processes.

Chapter 5. Concluding Remarks

After a summary of how this thesis has addressed the research objectives and contributed to environmental flow science, section 5.2 provides a broad overview of the English water industry's private ownership structures and their environmental and social implications, before section 5.3 outlines areas of future work this thesis has uncovered.

5.1 Synopsis

This thesis has assessed three dimensions of environmental flow protection; natural flow variability, climate change uncertainty and policy, governance and social operating space of water management. The results provide integral insights for achieving the balance between sustaining human well-being and safeguarding resilient freshwater ecosystems.

The aim of Chapter 2 was i) to determine large-scale patterns of natural flow regime, climatic and geographic variability in English catchments and ii) to describe new targets for environmental flow protection and starting points for local-scale assessments in altered regimes. With a larger coverage than previous analyses, this is the first systematic study representing natural variability in a holistic manner while specifically including altered regimes. Against the background of variable pressures, shifting baselines and ecology, this chapter developed a framework for informing decision making on priorities in water management and environmental protection.

The first aim, i), was achieved by developing a new classification across a total of 875 catchments including 126 natural and near-natural catchments. Five natural catchment groups were distinguished: 1. Dry, large, lowland catchments; 2. Small, dry, central catchments; 3. Flashy, coastal catchments; 4. Medium and large, wet, Western catchments and 5. Dry Southern and Eastern catchments. These classes were determined using Ward's clustering of 16 hydrological, climatic and physical descriptors and describe a high share of England's natural flow regime variability. The second aim, ii), was achieved by detailing the natural flow regimes' typical features such as pronounced high and low flows in group 3 and a high constancy and predictability in group 5. The altered catchments were sorted into the natural catchment classes based on descriptors that are not affected by human activities with an efficiency of 67%.

The aim of Chapter 3 was i) to determine climate change impacts on hydrological indicators used in environmental flow management under a range of climate change projections and emissions scenarios and ii) to establish the implications of different types of climate change uncertainty for these projections. To address these aims, Chapter 3 applied catchment-scale hydrological climate impact modelling for two catchments from two different groups established in Chapter 2. Expanding on the previous chapter, this is the first study assessing the hydrological impacts under UKCP18 in altered catchments and the first to compare UKCP18 to similar RCM projections. The climate impacts might apply more widely to other catchments of the same groups and emphasise the implica-

tions of uncertainty for decision making in catchments with large pressures from water use. In both catchments current environmental flow protection has failed and not facilitated to protect from severe over-abstraction.

Assessing high emissions scenarios to achieve i), seasonality increases with strongly decreasing summer and increasing winter streamflow were found in the coastal catchment of group 4 and pronounced streamflow decreases across most of the year were projected in the lowland catchment of group 1. Projections under low and medium emissions scenarios were more variable and generally wetter. In the coastal catchment high flows are projected to increase and low flows are projected to decrease under all assessed ensembles and emissions pathways. In the lowland catchment patterns are similar under low and medium emissions, while projections under high emissions entail decreasing flows across the whole FDC. Examining ii) it was found that under the assessed climate ensembles, GCM parameter uncertainty translates into a higher range of projected changes and into a stronger hydrological response than GCM structural uncertainty. The ensemble chosen for assessing parameter uncertainty, the UKCP18 Regional Projections, show a particularly dry streamflow response, highlighting their limited suitability as standalone projections. Shifting abstractions from summer to winter was suggested as robust adaptation in the coastal catchment yet particularly in the lowland catchment, the strong reductions projected for summer streamflow indicate the need to focus efforts on low flow protection.

The aim of Chapter 4 was i) to evaluate the performance of environmental flow allocation scenarios under climate change across different types of catchments and ii) to delineate shortcomings of the current water management system and articulate, in a participatory way with stakeholders, opportunities for overcoming the climate change adaptation gap and water management challenges to improve environmental flow protection in England. Chapter 4 broadened the focus of the preceding chapters by extending the narrow view of pressures on freshwaters beyond flow and climate change aspects by identifying other physical non-flow pressures and socio-economic drivers of water use. It represents the first multi-disciplinary study focussing on strengthening environmental flow protection against the background of a range of existing pressures and emerging climate change and population growth.

To address i), this chapter used stakeholder engagement and a simple water model to study five catchments representative of the five regime types distinguished in Chapter 2. Evaluating environmental flow allocation scenarios under the climate change impacts established in Chapter 3, it expanded on both previous chapters integrating their results. It was shown that balancing existing pressures from abstractions (and return flows) and emerging pressures from climate change is difficult under all assessed environmental flow scenarios. Not protecting future flows from climate change effects does not necessarily imply more water availability for human uses. Furthermore, the results suggest that it might conversely be beneficial to integrate climate change. While dependent on dynamic changes in the seasonal water use subject to storage infrastructure, integrating

climate change might facilitate protection of flow regimes from the combined pressures of for example decreasing water availability and abstraction during summer.

Through a consultation of 25 stakeholders, a variety of shortcomings in the current English system of managing environmental flows were delineated to address ii). Suitable proposals for addressing these shortcomings and improving ecosystem outcomes across different types of catchments could be drawn. The first proposal is to close the knowledge gap for regionalisation to overcome a lack of data hindering efficient decision making. The second proposal is to maximise the potential for demand reductions to relieve pressure from freshwater systems while the third is to strengthen institutional support for ICM which is hindered by insufficient funding, coordination and alignment of planning processes. The fourth proposal is to champion adaptive capacity for example through strengthening successful schemes already operating in England such as CaBA. This is required to overcome the limitations of fragmented collaboration and application of local knowledge. Finally, stakeholders endorsed embedding and restoring natural processes to realise synergies of biodiversity and climate change adaptation and overcome maladapted land use.

5.2 Privatisation and its Implications

The ownership structure of England's water industry and in particular the associated financial and regulatory infrastructure are important aspects impacting the success of environmental flow protection. England is unique in that Chile and Wales are the only other countries where the water sector is fully privatised (Bayliss et al., 2020; Hall and Lobina, 2019). Privatisation and its influence on water management and environmental flow protection was discussed during the interviews but not in sufficient detail to allow recommendations and a conclusive examination of the topic. Several respondents work in close collaboration with and nine directly for water companies, which may have prevented them from openly discussing the issue.

In many catchments, public water supply is the largest or only water user and, driven by population growth, this sector will see the largest demand increases (Defra, 2023; Environment Agency, 2020d). The water industry therefore plays a crucial role in addressing existing and preparing for emerging pressures on freshwater ecosystems. Water companies' environmental improvements, their infrastructure investments and maintenance, their effective engagement in ICM and other (broad scale) decision making processes and their contribution to the realisation of the proposals made in Chapter 4 are crucial to attain sustainable and reliable water supply and sourcing.

After a period of little public investment in infrastructure upgrades, state-owned water and sewerage utilities were privatised by the Thatcher government in 1989 (Act, Water, 1989). Today, most water companies are owned by private equity investors who use financial engineering to boost shareholder returns using complex corporate structures often involving tax havens (Bayliss et al., 2020; O'Brien et al., 2019; Pryke and Allen, 2019). At least 72% of the English water industry is held by international investment

funds (Leach et al., 2022). The following section describes the main challenges for environmental flow protection, sustainability and equitable water supply arising from the ownership and financial structures of water companies and from the regulatory environment. Structured along the system's main shortcomings, suggestions for overcoming these challenges are briefly reviewed.

A main criticism is that the current system of water company financing and reinvestment is built for short termism instead of environmental sustainability (Lobina, 2019) such as envisioned through the out by the 25-year Environment Plan (Defra, 2018). There is growing literature, most recently by Bayliss et al. (2022), demonstrating that investors in water companies leave the sector severely indebted with negative consequences for both environment and social equity. Since privatisation in 1989, the nine English water companies have accrued debts in order of £56bn while shareholders have received £72bn in dividend payments (Horton, 2022). Increasing debt goes hand in hand with (rising) finance costs (Lobina, 2019). For example over the past decade around a quarter of Southern Water's revenue has been used to cover net finance costs (Southern Water, 2022, c.f.).

The sector relies on what is termed financial engineering to boost shareholder dividends often hidden by complex water-related financial products (Loftus and March, 2019a; Pryke and Allen, 2019). One mechanism of financial engineering is that dividends are paid at the expense of infrastructure modernisation (Harvey, 2022; NAO, 2020) and by growing debt (underwritten by future water bill payments) thereby increasing finance costs (Bayliss et al., 2022; Hall, 2022; Morgan and Nasir, 2021). Moreover, gaming and asset sweating are central strategies. Gaming is a strategy of systematically overestimating required investments so Ofwat allows higher customer prices resulting in windfall gains (Lobina, 2019). In this context, asset sweating describes the use of infrastructure in a way that minimises cost and maximises profits by not investing (enough) in their maintenance, modernisation and replacement (Colley, 2022; O'Brien et al., 2019). Reconfiguring infrastructure assets in this way, maximising wealth extraction and providing revenue streams for investors is commonly referred to as financialisation (Loftus and March, 2019a; Stockhammer, 2010). As a result, the sector is highly geared (has a high ratio of debt to equity) (Helm, 2020).

5.2.1 Environmental Concerns

Many of the environmental issues highlighted in Chapter 4 as well as the poor ecological and chemical status of many water bodies can be attributed to the sector's financial and operational structures and the resulting limited (re)investments in environmental improvements and infrastructure. Moreover, this lack of investments also threatens sustainable freshwater development in the future. The EA's chair, Emma Boyd, called the sector's performance on pollution in 2021 "shocking", "unacceptable" and "a breach of trust" (Environment Agency, 2022h). Since privatisation, no new reservoirs have been built in England, yet 30 would be required to protect from drought (Bawden,

2022). Six reservoir projects have been accepted in the 2019 Price Reviews including reservoir extensions and repurposing of quarries, however no supply increases will be realised before 2025 (Environment Agency, 2022g; NAO, 2020). The head of the National Farmers' Union furthermore warns that a lack of reservoirs could lead to increased over-abstraction of groundwater due to a lack of surface water during droughts (Harvey, 2023).

Lobina and Hall (2008) argue that public ownership would have allowed larger investments if the growth rate of 8% in investments observed during public ownership between 1985 and 1989, before privatisation, would have been kept up. Since 2002, Scottish Water, which remained in public ownership, has invested almost 35% more per household than English water companies while Scottish customers pay on average 14% less for their water bill (Yearwood, 2018). At the same time, the status of rivers is signficantly better in Scotland with 48% rivers attaining good ecological status in 2019 versus only 16% in England. An additional 8% of Scottish rivers attain high ecological status, a status no river in England has reached (JNCC, 2021). At 40%, the share of rivers with good or high ecological status in the EU, where water supplies are in public ownership, is also much higher (European Commission, 2019).

Renationalising these companies, while popular (it was favoured by 63% of respondents in a 2022 poll (Conner, J. and Smith, F., 2022)) would certainly be complex, not least because of the conglomerate of international investors requesting compensation (Jessop and Shackleton, 2019). In a similar case concerning the bank Northern Rock, the European Court of Human Rights however ruled that there is no right to full market-value compensation in a nationalisation if there are "legitimate objectives in the public interest such as those pursued in measures of economic reform or measures designed to achieve greater social justice" (p. 12 ECHR, 2012). Also, UK law allows parliament to set its own rules in case of renationalisation giving them high flexibility on the terms of compensation and "primary legislation cannot be overturned by UK courts" (Moodys (2017) as cited by Hall (2019) and Mercer and Whitfield (2018)).

Hall (2019) see potentially great advantages of a renationalisation for environmental protection due to cheaper borrowing for investments through the state as well as greater public control over public policy for sustainable management. A renationalisation is currently only backed by the Green party (Laville, 2022).

5.2.2 Regulating the Water Industry

Regulation of a natural monopoly such as the water industry is central for guaranteeing equitable and fair outcomes (Tollison and Wagner, 1991). The complex institutional and governance setting in England (Robins et al., 2017) and the blurry interactions between the regulator Ofwat and the water sector are not well equipped to achieve this purpose (Bayliss and Hall, 2017; Buse and Bayliss, 2022; Yearwood, 2018). On the contrary, Helm (2020) highlights that regulation has contributed to the sector's poor (environmental, efficiency and social) performance by failing to adequately address mar-

ket failures. Against the background of limited environmental performance and lack of (re)investment, regulation is falling behind in tackling existing and emerging challenges (Lobina, 2019; Salvidge, 2022). Moreover, regulation has become increasingly complex with each Price Review adding about two new regulatory mechanisms (Helm, 2020).

Fines issued through Ofwat have little effect in the face of an immense backlog of water infrastructure investment. The worst performing water company, Thames Water (see section 4.3.2), was fined £120m for failing to cut leakage in 2018 (Ofwat, 2018) and four years later it was required to return £50m to customers for underperformance across environmental targets (Ofwat, 2022i). Thames Water's shareholders received dividends of £32.9m in 2021 (Thames Water, 2021) and £37.1m in 2022 (Thames Water, 2022). Using what Hall (2022) calls a misleading 'round trip' rhetoric, Thames Water claims that these dividends are "used solely to service group debt obligations" (p. 12 and 97 Thames Water, 2022) omitting that these dividends are not paid (back) to Thames Water Utilities Ltd but that these service debts are owed to other companies within the conglomerate of parent companies. Other companies including Southern Water, Yorkshire Water and Anglian water use similar misleading rhetoric to conceal dividend payments (Hall, 2022).

In addition, water companies have been extracting profits irrespective of Ofwat's price levels and Ofwat has recognised that allowing price increases on customers does not lead to investment into better services, infrastructure and environmental improvements but rather increases shareholder returns (Bayliss et al., 2022). Privatisation was initially implemented to relieve public debt and remove the water industry from public expenditure (Helm, 2020). Instead the current system is expensive for the state and inefficient for tax payers as well as future generations as water charges are not reinvested but instead largely "lost" to shareholders and private water companies pay higher interest rates than the state (Yearwood, 2018). Ofwat is struggling to set price controls that curb excessive value extraction by shareholders (Bayliss and Hall, 2017). Starting in the 1990s, by focussing regulation on prices instead of on companies' corporate practices and financialisation it has created incentives to pay for investments with debt instead of company capital (equity) (Bayliss and Hall, 2017; Helm, 2020).

Helm (2008, 2020) argues that not the ownership structure but the poor regulation is to blame for the sector's performance and suggests a change in the calculation of the allowed rate of return. The rate of return is an important element in regulation of natural monopolies such as water utility and determines the price that allows the companies a "reasonable" return on their monopoly (Tollison and Wagner, 1991). Helm (2020) suggest a split cost of capital approach instead of the currently applied average cost of capital approach to calculate the allowed rate of return. In the split cost approach the allowed cost of debt is different across different parts of the business (e.g. infrastructure and operational side) which would reduce (allowed) finance cost and incentives for debt and therefore better capture benefits for customers (Helm, 2008). Furthermore, the Environment Agency (2022h) calls for courts to impose higher fines as these can be un-

limited for environmental crimes (Environment Agency, 2022f). In this context, economic policy needs to back investment appraisals to extend beyond economic cost-benefit and account for ecosystem services such as realised through enhanced environmental flow protection. Infrastructure needs to support more flexible and circular water use, integrate EBA and allow a larger distinction between water of different sources and qualities (Sadoff et al., 2020).

An alternative to full nationalisation is a semi-nationalisation with the state as the largest owner or shareholder. In this position the state could easily tighten its control and curb financial engineering, reduce tax avoidance and enhance (re)investment. There are few examples for semi-nationalisation of former privately owned companies to clearly outline potential pathways that successfully achieve this.

5.2.3 Social Concerns

Shareholder value, as opposed to public service, is the main guiding principle for water companies' financial and ownership structures (Bayliss et al., 2022; Zwan, 2014). Risks faced by investors are commonly overestimated at the expense of water customers (Wild, 2018).

Ofwat itself (p. 2 Ofwat, 2017) recognises a system bias towards investors in the regulatory architecture which is not only failing in terms of adequate environmental protection and sustainability but also with regards to social equity and protection. Since privatisation, water prices have risen by 40% in real terms and a survey in May 2022 indicated that half of customers were expecting to struggle to pay utility bills in the coming year (Ofwat, 2022c). Water prices have been shown to contribute to destitution (Fitzpatrick et al., 2016). Partly due to the immense debt levels of Thames Water, its customers in London are paying for Thames Tideway with an additional charge on their water bills (Loftus and March, 2019b). Some of Ofwat's performance metrics, such as rewarding companies with higher prices if per capita water consumption reduces, moreover imply that the customer's bills increase as a reward for consuming less (Bayliss et al., 2020). Stricter regulation has previously improved the social performance of the sector when in 1999 under the Labour government the disconnection of customers was banned which had previously tripled (Lobina, 2019). Ofwat aims to increase transparency and reign in the high gearing which is underwritten by customers (Hall, 2022; Ofwat, 2022h). Gearing metrics have been considered in the Price Review 2019 and profits beyond a 74% of gearing shall be returned to customers (Ofwat, 2019a).

These changes in regulation must be reinforced by a shift in policy narratives from a framing of efficiency, competition and individual responsibility to universal and socially equitable provision (Bayliss et al., 2020; Lawson et al., 2020). Sustainable yet fair policy and regulation have to signal water scarcity while capturing equity trade-offs (Sadoff et al., 2020). A potential strategy would lie in allowing companies higher water prices but only while they pay for every litre lost through leaks and only where they support low income groups in the purchase of water efficient appliances.

Given these barriers to modernisation of the water sector, it can be concluded that the challenges uncovered in this thesis are unlikely to be adequately addressed within the current system. The proposals for enhancing environmental flow protection drawn in Chapter 4 particularly those referring to water abstraction and policy will have to be underpinned by structural changes to the financial, regulatory, policy and potentially also ownership infrastructure of the water industry.

5.3 Further Research Directions

The results of this thesis highlight several areas for further work, some of which have been detailed in Chapter 2 to 4's discussions. The most important among them are briefly summarised and extended with a focus on aspects integrating results of all three chapters.

5.3.1 Chapter 2

To fully operationalise and maximise the use of Chapter 2's hydrological framework for informing large-scale policy and environmental flow management as well as local-scale restoration potential, the functional relationships between climate, flow and ecology need to be established in detail.

The overarching questions are:

1. How does climate modulate flow regimes?
2. How do flow regimes influence ecology?

and connecting 1. and 2.:

3. What is the freshwater ecosystems' ecologic vulnerability to climate change?

Extending the knowledge base on how climate affects flow regimes would be useful for enhancing the framework to match altered flow regimes more reliably. The strongest climatic determinants of flow regime characteristics Roo et al. (2015) found were aridity index, precipitation seasonality, transformed mean annual precipitation, potential evapotranspiration seasonality and mean annual potential evaporation. If the classification or (due to limited data coverage with climate indicators) parts of it could be extended by climate indicators, e.g. from the CAMELS dataset (Coxon et al., 2020), the performance of the LDA (currently at 67% correctly matched catchments determined through a leave-one-out-cross validation) could be improved. Moreover, such a hydrologic framework enhanced with more climatic indicators could support catchment- to national-scale climate change adaptation. A range of climate ensembles including the euro-CORDEX project (Jacob et al., 2014) provide bias corrected climate projections for precipitation, temperature, humidity, evapotranspiration and other climate variables across a range of scales. Some provide large scale hydrological projections including river discharge (e.g. ECMWF, 2021). The climate-related sensitivities of flow regimes in different (types of) catchments, particularly in those important for water demand, could be established. This could either be done directly through the large scale hydrological scenarios or indirectly through determining climate indicators and their influence on regime elements. While this cannot replace detailed catchment-scale climate impact analyses such as undertaken in Chapter 3, it could guide further research priorities and/or the determination of new priority catchments. The overarching question could be approached by refining questions such as; Where will the largest regime shifts occur? Which flow regime

elements characteristic of certain regime types require more protection? What does climate change mean for water abstraction planning and water transfer?

The framework developed in Chapter 2 provides a template for extrapolating generalised flow-ecology relationships from where they are known to those catchments with similar flow regimes. Protecting the same amount and timing of water adapted to ecological needs of one catchment should support similar ecology in another catchment with a similar regime type. However, the drivers of variation of flow-ecology relationships across different flow regime types are rarely fully understood (Bruckerhoff et al., 2019). Flow-ecology relationships are complex and often nonlinear - the thresholds of flow decreases that cause disproportionately large variations in biological response are difficult to determine (Poff and Zimmerman, 2010; Rosenfeld, 2017). Furthermore, the transferability of flow-ecology relationships can be limited due to variations in local context such as land use (Bisselink et al., 2018; Chen and Olden, 2017).

These complexity of flow-ecology relationships and the importance of local context mean that to make full use of the hydrological frameworks developed in Chapter 2, complex relationships and dependencies have to be untangled. A focus could lie on species traits and the definition of ecological guilds, groups of species that use the same type of environmental resources in a similar way (Simberloff and Dayan, 1991). Species traits are a good predictor for ecological response and therefore for the delineation of environmental guilds with comparable biological traits and response to changes in flow regime (for example habitat preference and intra-annual flow variability (Macnaughton et al., 2016)) (Bejarano et al., 2018; Lytle et al., 2017; Palmer and Ruhi, 2019; Tonkin et al., 2018). Species traits and these guilds could serve to transfer flow–ecology relationships accounting for the broad ecological response across several species (Chen and Olden, 2017). This managing for variability accounts for the uncertainty of future climate changes (Hiers et al., 2016). Furthermore, by comparing flow and ecology of natural catchments with those in altered catchments within the same group, degrees of alteration and sensitivities across different flow regime descriptors could be determined. This could be applied to refine flow-ecology models on the effects of flow alteration across guilds and other ecological descriptors such as spawning and recruitment, assemblages, density or community composition.

Chapter 3 described some strong impacts of climate change that environmental flow protection must take into account and highlighted the importance of a robust knowledge base on freshwater ecosystems' ecologic vulnerability to hydro-climatic changes. Strategies for flow protection have to account for species and ecosystem response to changes in magnitude, timing, variability, frequency and duration as well as to individual extreme events (Poff, 2017; Thompson et al., 2018). Therefore, the way uncertainty in future hydrologic ranges is represented in freshwater ecosystem protection is an important determinant of their success. Understanding existing flow-ecology relationships remains the cornerstone (Acreman et al., 2014). The measures provided by the three approaches, ICM, EBA and adaptive management including effective monitoring are

central to recognise climate-induced flow regime changes and to evaluate potential transitions in ecosystem states. Priorities should be established integrating diverse sources of knowledge and on the appropriate spatial scale. These could be EBAs managing for resilience sustaining key processes and/or managing for variability allowing for a wide ecological response to shifting conditions.

5.3.2 Chapter 3

Several of the research needs uncovered in Chapter 3 relate to modelling capabilities. Improving these capabilities is critical for reducing uncertainty and enhancing the process understanding in freshwater systems' climate response. In both case study catchments assessed in Chapter 3, low flows are projected to decrease under high emissions. The performance of SWAT+ in simulating observed low flows was however not consistent across catchments and climate input data. Due to their ecological importance, low flow protection is an important element of environmental flow protection and the main target of many flow restoration efforts (Hughes et al., 2014; Richter et al., 2017; Walker et al., 2021). A good representation of low flows can for example be achieved through a focus on groundwater representation (e.g. Tashie et al., 2022).

The flow regimes of both case study catchments used in this chapter are influenced by groundwater. As a major source of freshwater in some parts of England, around a third of withdrawals for public water supply stems from groundwater (UKRI, 2022). Globally, 70% of freshwater withdrawals are used in irrigation (Siebert and Doll, 2010). While poorly conceptualised in the UN Sustainable Development Goals (SDGs), groundwater protection is therefore closely related and contributes to several SDGs (Guppy et al., 2018). However, also highlighted in section 4.3.2.1, groundwater management is particularly wicked. As interviewees in Chapter 4 have indicated, an enhanced understanding of groundwater processes through improved modelling capabilities is therefore invaluable for informing sustainable abstraction and environmental flow management.

In Chapter 3, the immense role that land use (change) plays in climate change adaptation has been discussed in detail. While its effects on flow regimes are often hard to detangle (Mensah et al., 2022; Trolle et al., 2019), land use change offers immense scope for climate change adaptation (Qi et al., 2018). An evaluation of possible land use adaptation options represents one of the most useful new research avenues, potentially with a focus on groundwater recharge and in combination with a stakeholder consultation to closer delineate realistic land use conversion scenarios.

5.3.3 Chapter 4

More conceptual and theoretical work is required to realise all proposals made in Chapter 4. First, it should be established how the EA's regulatory support for environmental flow protection can be rendered fit for purpose. Its role as a boundary organisation with high influence over the transfer of scientific information into impact (Ferré et al., 2022) makes its success crucial for water management's responsiveness to climate change.

In this context, the political barriers for the provision of adequate financial resources for climate change adaptation of freshwater systems for the EA and beyond need to be identified. Climate change adaptation is costly, yet future costs of no, low and too little adaptation are likely higher and involve considerable risks to ecosystems and societies (e.g. Rising et al., 2022).

Moreover, in many areas, environmental and human requirements cannot both be fulfilled. Next to stringent regulation, decision support mechanisms for water managers need to be developed and implemented. In this context more work is needed to determine how existing financial mechanisms and schemes such as ELMS and nature recovery can best align and be operationalised for sustainability improvements. They need to incentivise appropriate mitigation of increasing abstraction pressures required for increasing populations and promote water use efficiency across sectors.

Another important aspect requiring more research is dilution as a practice to obtain acceptable levels of water quality (Vliet et al., 2021). Growing populations do not only need more water, wholesome water provision also relies on more wastewater treatment. Not least the failing of CSOs has emphasised the shortcomings of a focus on dilution for attaining acceptable water quality (Gündüz, 2015). Freshwater is simply not available at the immense quantities a business-as-usual management of discharge water quality would necessitate, especially considering the substantial health risks to both the natural environment and humans. Next to the importance of stricter regulation of the water industry discussed above and a shift in agricultural and reuse practices discussed in Chapter 4, further work is needed on the requirements of wastewater regulation and treatment for growing populations, particularly in areas with increasing population densities.

Several aspects of the key role the public plays in achieving resilient freshwater ecosystems have been described in Chapter 4. In England, 2022 was a year of extensive reporting on water-related issues across media outlets spurred by the unprecedented failures of CSOs and a string of extreme climate events such as a prolonged drought. Across society, this has created and increased awareness of water as a finite resource and represents large opportunities to expand public acceptance and participation in environmental protection (Berry et al., 2019). Many useful research topics that build on Chapter 4's results lie in the field of environmental democracy which is concerned with how environmental sustainability can be achieved without compromising democratic practices and values (Goodin, 2013). Rivers convey and show global changes in the local environment. In this context it could be closer established how the current impetus of public awareness can create agency for citizens to take part in rendering their local environment more resilient. It needs to be established how awareness can be converted into action such as participation within the CaBA process to safeguard a valuable and diverse environment. Moreover, social research on the design of campaigns that aim to embed behavioural changes and create incentives for water use reduction would be beneficial. Enhancing environmental protection and restoring natural processes of-

ten requires strong modifications of landscapes, for example the removal of manmade structures that prevent low lying floodplains from periodically flooding or the rewetting of peatlands. More work is therefore also needed on the policy and institutional infrastructure that benefit support and acceptance of such large interventions (O'Donnell et al., 2017). For attaining resilience, (small) changes can become an important primer for the system to later transform in the "right" direction (Shrivastava et al., 2020).

Lastly, extending on all three chapters in an inter-disciplinary way, stakeholder preferences could inform more sophisticated modelling across the different catchment types and/or in (new) priority catchments. A multitude of potential foci are possible. Different rules for (a) environmental flow allocation could for example be assessed across varying (b) ecological sensitivities, (c) adaptation options and (d) climate change scenarios.

The foci could include the following:

(a) Environmental flow protection scenarios could be refined using priorities for protection of specific regime elements such as defined in Chapter 2, in terms of monthly volumes or timing or according to supply priorities.

(b) Stakeholder consultation could inform realistic representation of local ecological sensitivities to evaluate performance of environmental flow scenarios in safeguarding different flow regime aspects across catchments.

(c) Adaptation options for different catchment types including land use scenarios, changes in licensing and water storage infrastructure could be delineated and their performance across different designs such as storage volume or land use type could be evaluated.

(d) To improve the representation of uncertainty between climate scenarios and large scale climate modes, such as the North Atlantic Oscillation, the performance of different GCM simulations (within an MME such as eCX) could be evaluated and weighting or sub-setting could be applied to more closely match large-scale climate modes and local hydrology.

This advanced modelling could employ a storyline approach (Shepherd et al., 2018) or an evaluation of options for general decision support.

5.4 Conclusion

Water management and freshwater ecosystem protection face unprecedented challenges. Optimal environmental flow allocation is based upon local-scale assessments of flow regime and ecology and their sensitivity to changes and, if applicable, on the feasibility of restoration of flow and non-flow factors important for safeguarding healthy riverine ecosystems. Protection strategies for example of a certain timing and amount of flow are best determined using collaborative approaches integrating stakeholder knowledge and preferences. Environmental flow implementation moreover strongly benefits from continuous monitoring and cyclic learning and feedback processes.

It is unrealistic to undertake such detailed assessments for all catchments within a country and decision makers will often have to prioritise anthropogenic water demand over environmental flow considerations. Using England as a case study, this thesis has described some large-scale guidance to represent natural variability in a new template for classifying natural and modified catchments. It has determined climate change implications for streamflow and flow duration statistics under a range of scenarios for two case study catchments representative of common regime types. A main focus lay on the hydrological response under climate ensembles sampling the two largest sources of climate change uncertainty. Lastly, it has evaluated potential new scenarios for allocating environmental flows under climate change and outlined shortcomings in the policy, governance and social settings that water management is operating in. Proposals for enhancing environmental flow protection informing environmental policy and water management in England and more widely were formulated.

This thesis advances the understanding on environmental flow protection, key for achieving freshwater resilience.

Bibliography

10th International River Symposium (2007). The Brisbane Declaration - Environmental Flows Are Essential for Freshwater Ecosystem Health and Human Well-Being. In: Brisbane, Australia (3rd - 6th September 2007).

Abbaspour, K. C., Vaghefi, S. A., and Srinivasan, R. (2018). A Guideline for Successful Calibration and Uncertainty Analysis for Soil and Water Assessment: A Review of Papers from the 2016 International Swat Conference. *Water* 10 (1). doi:artn610.3390/w10010006.

Abbott, B. W., Bishop, K., Zarnetske, J. P., Minaudo, C., Chapin, F. S., Krause, S., Hannah, D. M., Conner, L., et al. (2019). Human Domination of the Global Water Cycle Absent from Depictions and Perceptions. *Nature Geoscience* 12 (7), pp. 533–540. doi:10.1038/s41561-019-0374-y.

Acreman, M., Aldrick, J., Binnie, C., Black, A., Cowx, I., Dawson, H., Dunbar, M., Extence, C., et al. (2009). Environmental Flows from Dams: The Water Framework Directive. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* 162 (1), pp. 13–22. doi:10.1680/ensu.2009.162.1.13.

Acreman, M., Arthington, A. H., Colloff, M. J., Couch, C., Crossman, N. D., Dyer, F., Overton, I., Pollino, C. A., et al. (2014). Environmental Flows for Natural, Hybrid, and Novel Riverine Ecosystems in a Changing World. *Frontiers in Ecology and the Environment* 12 (8), pp. 466–473. doi:10.1890/130134.

Acreman, M. and Dunbar, M. J. (2004). Defining Environmental River Flow Requirements - a Review. *Hydrology and Earth System Sciences* 8 (5), pp. 861–876.

Acreman, M., Old, G., and Laizé, C. L. R. (2013). Environmental Flows and Abstraction Reform in the UK. In: Centre for Ecology and Hydrology. London, United Kingdom: Department of Environment, Food & Rural Affairs.

Acreman, M. C. and Ferguson, A. J. D. (2010). Environmental Flows and the European Water Framework Directive. *Freshwater Biology* 55 (1), pp. 32–48. doi:10.1111/j.1365-2427.2009.02181.x.

Acreman, M., Dunbar, M., Hannaford, J., Mountford, O., Wood, P., Holmes, N., Cowx, I. A. N., Noble, R., et al. (2008). Developing Environmental Standards for Abstractions from UK Rivers to Implement the EU Water Framework Directive. *Hydrological Sciences Journal* 53 (6), pp. 1105–1120. doi:10.1623/hysj.53.6.1105.

Act, Water (1989). C. 15. UK Public General Acts. URL: https://www.legislation.gov.uk/ukpga/1989/15/contents.

Adams, W. M., Perrow, M. R., and Carpenter, A. (2005). Perceptions of River Managers of Institutional Constraints on Floodplain Restoration in the UK. *Journal of Environmental Planning and Management* 48 (6), pp. 877–889.

Addor, N. and Melsen, L. A. (2019). Legacy, Rather Than Adequacy, Drives the Selection of Hydrological Models. *Water Resources Research* 55 (1), pp. 378–390. doi:https://doi.org/10.1029/2018wr022958.

Aitken, G., Beevers, L., and Visser-Quinn, A. (2022). Euro-Cordex: A Multi-Model Ensemble Fit for Assessing Future Hydrological Change? *Frontiers in Water*, p. 112.

Ajjur, S. B. and Al-Ghamdi, S. G. (2021). Evapotranspiration and Water Availability Response to Climate Change in the Middle East and North Africa. *Climatic Change* 166 (3), pp. 1–18.

Allam, A., Tawfik, A., Yoshimura, C., and Fleifle, A. (2016). Simulation-Based Optimization Framework for Reuse of Agricultural Drainage Water in Irrigation. *Journal of Environmental Management* 172, pp. 82–96. doi:10.1016/j.jenvman.2016.02.022.

Allen, C. R., Cumming, G. S., Garmestani, A. S., Taylor, P. D., and Walker, B. H. (2011). Managing for Resilience. *Wildlife Biology* 17 (4), pp. 337–349. doi:10.2981/10-084.

Allen, M., Preis, A., Iqbal, M., and Whittle, A. J. (2012). Case Study: A Smart Water Grid in Singapore. *Water Practice and Technology* 7 (4). doi:10.2166/wpt.2012.089.

Alrawashdeh, M. J., Radwan, T. R., and Abunawas, K. A. (2018). Performance of Linear Discriminant Analysis Using Different Robust Methods. *European Journal of Pure and Applied Mathematics* 11 (1), pp. 284–298.

Anandhi, A., Frei, A., Pierson, D. C., Schneiderman, E. M., Zion, M. S., Lounsbury, D., and Matonse, A. H. (2011). Examination of Change Factor Methodologies for Climate Change Impact Assessment. *Water Resources Research* 47 (3).

Anbumozhi, V., Radhakrishnan, J., and Yamaji, E. (2005). Impact of Riparian Buffer Zones on Water Quality and Associated Management Considerations. *Ecological Engineering* 24 (5), pp. 517–523.

Anderson, E. P., Jackson, S., Tharme, R. E., Douglas, M., Flotemersch, J. E., Zwarteveen, M., Lokgariwar, C., Montoya, M., et al. (2019). Understanding Rivers and Their Social Relations: A Critical Step to Advance Environmental Water Management. *Wiley Interdisciplinary Reviews: Water* 6 (6), e1381.

Andrews, T., Andrews, M. B., Bodas-Salcedo, A., Jones, G. S., Kuhlbrodt, T., Manners, J., Menary, M. B., Ridley, J., et al. (2019). Forcings, Feedbacks, and Climate Sensitivity in Hadgem3-Gc3.1 and Ukesm1. *Journal of Advances in Modeling Earth Systems* 11 (12), pp. 4377–4394. doi:10.1029/2019ms001866.

Archfield, S. A., Kennen, J. G., Carlisle, D. M., and Wolock, D. M. (2014). An Objective and Parsimonious Approach for Classifying Natural Flow Regimes at a Continental Scale. *River Research and Applications* 30 (9), pp. 1166–1183. doi:10.1002/rra.2710.

ARK (2022). Action for the River Kennet. URL: http://www.riverkennet.org/ (Accessed: 13.10.2022).

Arnell, N. W. (2011). Uncertainty in the Relationship between Climate Forcing and Hydrological Response in UK Catchments. *Hydrology and Earth System Sciences* 15 (3), pp. 897–912. doi:10.5194/hess-15-897-2011.

Arthington, A. H. (2012). Environmental Flows: Saving Rivers in the Third Millennium. Vol. 4. Univ of California Press. ISBN: 0520273699.

Arthington, A. H., Kennen, J. G., Stein, E. D., and Webb, J. A. (2018a). Recent Advances in Environmental Flows Science and Water Management-Innovation in the Anthropocene. *Freshwater Biology*. doi:10.1111/fwb.13108.

Arthington, A., Bhaduri, A., Bunn, S. E., Jackson, S. E., Tharme, R. E., Tickner, D., Young, M., Acreman, M. C., et al. (2018b). The Brisbane Declaration and Global Ac-

tion Agenda on Environmental Flows (2018). *Frontiers in Environmental Science* 6. doi:10.3389/fenvs.2018.00045.

Ascott, M. J., Bloomfield, J. P., Karapanos, I., Jackson, C. R., Ward, R. S., McBride, A. B., Dobson, B., Kieboom, N., et al. (2020). Managing Groundwater Supplies Subject to Drought: Perspectives on Current Status and Future Priorities from England (UK). *Hydrogeology Journal* 29 (3), pp. 921–924. doi:10.1007/s10040-020-02249-0.

Ascott, M. J., Mansour, M. M., Bloomfield, J. P., and Upton, K. A. (2019). Analysis of the Impact of Hydraulic Properties and Climate Change on Estimations of Borehole Yields. *Journal of Hydrology* 577. doi:10.1016/j.jhydrol.2019.123998.

Assaf, H., Beek, E. van, Borden, C., Gijsbers, P., Jolma, A., Kaden, S., Kaltofen, M., Labadie, J. W., et al. (2008). Generic Simulation Models for Facilitating Stakeholder Involvement in Water Resources Planning and Management: A Comparison, Evaluation, and Identification of Future Needs. In: *Developments in Integrated Environmental Assessment*. Ed. by A. J. Jakeman, A. A. Voinov, A. E. Rizzoli, and S. H. Chen. Vol. 3. Elsevier. Chap. 13, pp. 229–246. doi:https://doi.org/10.1016/s1574-101x(08)00613-3.

Babaeian, F., Delavar, M., Morid, S., and Srinivasan, R. (2021). Robust Climate Change Adaptation Pathways in Agricultural Water Management. *Agricultural Water Management* 252, p. 106904. doi:https://doi.org/10.1016/j.agwat.2021.106904.

Babbie, E. R. (2020). The Practice of Social Research. Cengage learning. ISBN: 0357360842.

Badgley, G., Fisher, J. B., Jiménez, C., Tu, K. P., and Vinukollu, R. (2015). On Uncertainty in Global Terrestrial Evapotranspiration Estimates from Choice of Input Forcing Datasets. *Journal of Hydrometeorology* 16 (4), pp. 1449–1455. doi:10.1175/jhm-d-14-0040.1.

Bailey, S. (2012). Principal Component Analysis with Noisy and/or Missing Data. *Publications of the Astronomical Society of the Pacific* 124 (919), p. 1015. doi:10.1086/668105.

Balian, E., Lévêque, C., Segers, H., and Martens, K. (2008). Freshwater Animal Diversity Assessment. Developments in Hydrobiology. Springer Netherlands, p. 640. ISBN: 978-1-4020-8258-0.

Barbour, E. J., Holz, L., Kuczera, G., Pollino, C. A., Jakeman, A. J., and Loucks, D. P. (2016). Optimisation as a Process for Understanding and Managing River Ecosystems. *Environmental Modelling Software* 83, pp. 167–178. doi:https://doi.org/10.1016/j.envsoft.2016.04.029.

Bárdossy, A., Kilsby, C., Birkinshaw, S., Wang, N., and Anwar, F. (2022). Is Precipitation Responsible for the Most Hydrological Model Uncertainty? *Frontiers in Water* 4. doi:10.3389/frwa.2022.836554.

Barrios-Ordóñez, J. E., Salinas-Rodríguez, S. A., Martínez-Pacheco, A., López-Pérez, M., Villón-Bracamonte, R. A., Rosales-Ángeles, F., Guerra Gilbert, A., and Sánchez Navarro, R. (2015). National Water Reserves Program in Mexico. Experiences with Environmental Flows and the Allocation of Water for the Environment. *Technical note BID-TN-864. Interamerican development Bank, water and sanitation division, Mexico City, Mexico*.

Bateman, I. J. and Mace, G. M. (2020). The Natural Capital Framework for Sustainably Efficient and Equitable Decision Making. *Nature Sustainability* 3 (10), pp. 776–783.

Bawden, T. (2022). UK Needs 30 New Reservoirs to Protect Water Supply from Drought after Failing to Build One in 31 Years. The i Newspaper, London, United Kingdom. URL: https://inews.co.uk/news/environment/uk-needs-30-new-reservoirs-protect-water-supply-drought-31-years-1793414 (Accessed: 17.2.2023).

Bayliss, A. C. and Jones, R. C. (1993). Peaks-over-Threshold Flood Database. Institute of Hydrology. ISBN: 0948540478.

Bayliss, K. and Hall, D. (2017). Bringing Water into Public Ownership: Costs and Benefits. In: University of Greenwich, Faculty of Business. http://gala.gre.ac.uk/id/eprint/17277.

Bayliss, K., Mattioli, G., and Steinberger, J. (2020). Inequality, Poverty and the Privatization of Essential Services: A Systems of Provision Study of Water, Energy and Local Buses in the UK. *Competition Change* 25 (3-4), pp. 478–500. doi:10.1177/1024529420964933.

Bayliss, K., Van Waeyenberge, E., and Bowles, B. O. L. (2022). Private Equity and the Regulation of Financialised Infrastructure: The Case of Macquarie in Britain's Water and Energy Networks. *New Political Economy*, pp. 1–18. doi:10.1080/13563467.2022.2084521.

Bejarano, M. D., Jansson, R., and Nilsson, C. (2018). The Effects of Hydropeaking on Riverine Plants: A Review. *Biological Reviews* 93 (1), pp. 658–673.

Belmar, O., Velasco, J., and Martinez-Capel, F. (2011). Hydrological Classification of Natural Flow Regimes to Support Environmental Flow Assessments in Intensively Regulated Mediterranean Rivers, Segura River Basin (Spain). *Environmental Management* 47 (5), pp. 992–1004. doi:10.1007/s00267-011-9661-0.

Benestad, R. (2004). Empirical-Statistical Downscaling in Climate Modeling. *EOS, Transactions American Geophysical Union* 85 (42), pp. 417–422.

Berg, M. and Allen, D. (2007). Low Flow Variability in Groundwater-Fed Streams. *Canadian Water Resources Journal* 32 (3), pp. 227–246.

Berry, L. H., Koski, J., Verkuijl, C., Strambo, C., and Piggot, G. (2019). Making Space: How Public Participation Shapes Environmental Decision-Making. In: JSTOR.

Berry, P., Yassin, F., Belcher, K., and Lindenschmidt, K.-E. (2017). An Economic Assessment of Local Farm Multi-Purpose Surface Water Retention Systems under Future Climate Uncertainty. *Sustainability* 9 (3), p. 456.

Best, J. (2018). Anthropogenic Stresses on the World's Big Rivers. *Nature Geoscience* 12 (1), pp. 7–21. doi:10.1038/s41561-018-0262-x.

Bestgen, K. R., Poff, N. L., Baker, D. W., Bledsoe, B. P., Merritt, D. M., Lorie, M., Auble, G. T., Sanderson, J. S., et al. (2020). Designing Flows to Enhance Ecosystem Functioning in Heavily Altered Rivers. *Ecological Applications* 30 (1), e02005.

Beven, K. and Binley, A. (1992). The Future of Distributed Models: Model Calibration and Uncertainty Prediction. *Hydrological Processes* 6 (3), pp. 279–298. doi:10.1002/hyp.3360060305.

Beven, K. and Binley, A. (2014). Glue: 20 Years On. *Hydrological Processes* 28 (24), pp. 5897–5918. doi:10.1002/hyp.10082.

Beven, K. and Smith, P. (2015). Concepts of Information Content and Likelihood in Parameter Calibration for Hydrological Simulation Models. *Journal of Hydrologic Engineering* 20 (1). doi:artna401401010.1061/(asce)he.1943-5584.0000991.

BGS (2011). Edina Geology Digimap Service: Soil Parent Material Model [Shape Geospatial Data], Scale 1:50,000. British Geological Survey (BGS). URL: https://digimap.edina.ac.uk (Accessed: 5.3.2019).

BGS, E. A.
bibinitperiod (2017). Numerical Modelling of the Impact of Groundwater Abstraction on River Flows. (SC030233/SR1, OR/08/017).

Bhave, A. G., Conway, D., Dessai, S., and Stainforth, D. A. (2018). Water Resource Planning under Future Climate and Socioeconomic Uncertainty in the Cauvery River Basin in Karnataka, India. *Water resources research* 54 (2), pp. 708–728.

Bieger, K., Arnold, J., Rathjens, H., White, M., Bosch, D., and Allen, P. (2019). Representing the Connectivity of Upland Areas to Floodplains and Streams in Swat+. *Journal of the American Water Resources Association* 55 (3), pp. 578–590. doi:10.1111/1752-1688.12728.

Bieger, K., Arnold, J. G., Rathjens, H., White, M. J., Bosch, D. D., Allen, P. M., Volk, M., and Srinivasan, R. (2017). Introduction to Swat+, a Completely Restructured Version of the Soil and Water Assessment Tool. *JAWRA Journal of the American Water Resources Association* 53 (1), pp. 115–130. doi:10.1111/1752-1688.12482.

Bisselink, B., Bernhard, J., Gelati, E., Adamovic, M., Guenther, S., Mentaschi, L., and De Roo, A. (2018). Impact of a Changing Climate, Land Use, and Water Usage on Europe's Water Resources. In: vol. EUR 29130 EN. Publications Office of the European Union. Luxembourg.

Biswas, A. K. (2004). Integrated Water Resources Management: A Reassessment. *Water International* 29 (2), pp. 248–256. doi:10.1080/02508060408691775.

Bjerklie, D. M., Lawrence Dingman, S., Vorosmarty, C. J., Bolster, C. H., and Congalton, R. G. (2003). Evaluating the Potential for Measuring River Discharge from Space. *Journal of Hydrology* 278 (1), pp. 17–38. doi:https://doi.org/10.1016/s0022-1694(03)00129-x.

Blöschl, G., Hall, J., Parajka, J., Perdigão, R. A., Merz, B., Arheimer, B., Aronica, G. T., Bilibashi, A., et al. (2017). Changing Climate Shifts Timing of European Floods. *Science* 357 (6351), pp. 588–590.

Boardman, J., Burt, T., and Foster, I. (2020). Monitoring Soil Erosion on Agricultural Land: Results and Implications for the Rother Valley, West Sussex, UK. *Earth Surface Processes and Landforms* 45 (15), pp. 3931–3942. doi:10.1002/esp.5011.

Boddy, N. C., Fraley, K. M., Warburton, H. J., Jellyman, P. G., Booker, D. J., Kelly, D., and McIntosh, A. R. (2020). Big Impacts from Small Abstractions: The Effects of Surface Water Abstraction on Freshwater Fish Assemblages. *Aquatic Conservation: Marine and Freshwater Ecosystems* 30 (1), pp. 159–172.

Boé, J., Somot, S., Corre, L., and Nabat, P. (2020). Large Discrepancies in Summer Climate Change over Europe as Projected by Global and Regional Climate Models:

Causes and Consequences. *Climate Dynamics* 54 (5), pp. 2981–3002. doi:10.1007/s00382-020-05153-1.

Boeuf, B., Fritsch, O., and Martin-Ortega, J. (2016). Undermining European Environmental Policy Goals? The EU Water Framework Directive and the Politics of Exemptions. *Water* 8 (9). doi:10.3390/w8090388.

Boltz, F., LeRoy Poff, N., Folke, C., Kete, N., Brown, C. M., St. George Freeman, S., Matthews, J. H., Martinez, A., et al. (2019). Water Is a Master Variable: Solving for Resilience in the Modern Era. *Water Security* 8. doi:10.1016/j.wasec.2019.100048.

Bond, N. R. (2018). Hydrological Indices for Daily Time Series Data. *R-Package Hydrostats* (0.2.6).

Boretti, A. and Rosa, L. (2019). Reassessing the Projections of the World Water Development Report. *npj Clean Water* 2 (1), p. 15. doi:10.1038/s41545-019-0039-9.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V.-M., Kondo, Y., et al. (2013). Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 571–657.

Boulos, P. F., Jacobsen, L. B., Heath, J. E., and Kamojjala, S. (2014). Real-Time Modeling of Water Distribution Systems: A Case Study. *Journal AWWA* 106 (9), E391–E401. doi:https://doi.org/10.5942/jawwa.2014.106.0076.

Bower, D., Hannah, D. M., and McGregor, G. R. (2004). Techniques for Assessing the Climatic Sensitivity of River Flow Regimes. *Hydrological Processes* 18 (13), pp. 2515–2543. doi:10.1002/hyp.1479.

Bower, D. and Hannah, D. (2002). Spatial and Temporal Variability of UK River Flow Regimes. In: *Regional Hydrology: Bridging the Gap between Research and Practice Book Series*. Ed. by Friend. Vol. 274. IAHS Publication, pp. 457–464.

Bowles, F., Moir, H., Eardley, B., Phillips, J., Bond, W., and Parr, M. (2020). What Is the Stage Zero Approach to River Restoration? URL: https://www.therrc.co.uk/blog/what-stage-zero-approach-river-restoration (Accessed: 18.8.2020).

Box, G. E. P. and Cox, D. R. (1964). An Analysis of Transformations. *Journal of the Royal Statistical Society Series B-Statistical Methodology* 26 (2), pp. 211–252.

Bradford, R. B. and Marsh, T. J. (2003). Defining a Network of Benchmark Catchments for the UK. *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering* 156 (2), pp. 109–116. doi:doi10.1680/wame.2003.156.2.109.

Bradley, D., Streetly, M., Cadman, D., Dunscombe, M., Farren, E., and Banham, A. (2017). A Hydroecological Model to Assess the Relative Effects of Groundwater Abstraction and Fine Sediment Pressures on Riverine Macro-Invertebrates. *River Research and Applications* 33 (10). doi:10.1002/rra.3191.

Brand, B. M., Rausch, T. M., and Brandel, J. (2022). The Importance of Sustainability Aspects When Purchasing Online: Comparing Generation X and Generation Z. *Sustainability* 14 (9). doi:10.3390/su14095689.

Bresney, S. R., Forni, L., Mautner, M. R., Huber-Lee, A., Shrestha, M., Moncada, A. M., Ghosh, E., and Sopharith, T. (2020). Investigating Tradeoffs between Agricultural De-

velopment and Environmental Flows under Climate Change in the Stung Chinit Watershed, Cambodia. *Hydrology* 7 (4), p. 95.

British Geological Survey (2010). 1:625,000 Scale Hydrogeology (Shapefile). EDINA digimap. URL: https://www2.bgs.ac.uk/products/hydrogeology/maps.html (Accessed: 5.8.2018).

Brooks, A. J. and Haeusler, T. (2016). Invertebrate Responses to Flow: Trait-Velocity Relationships During Low and Moderate Flows. *Hydrobiologia* 773 (1), pp. 23–34. doi:10.1007/s10750-016-2676-z.

Brooks, B. W., Lazorchak, J. M., Howard, M. D., Johnson, M.-V. V., Morton, S. L., Perkins, D. A., Reavie, E. D., Scott, G. I., et al. (2016). Are Harmful Algal Blooms Becoming the Greatest Inland Water Quality Threat to Public Health and Aquatic Ecosystems? *Environmental toxicology and chemistry* 35 (1), pp. 6–13.

Brown, L. E., Aspray, K. L., Ledger, M. E., Mainstone, C., Palmer, S. M., Wilkes, M., and Holden, J. (2019). Sediment Deposition from Eroding Peatlands Alters Headwater Invertebrate Biodiversity. *Global Change Biology* 25 (2), pp. 602–619. doi:https://doi.org/10.1111/gcb.14516.

Bruckerhoff, L. A., Leasure, D. R., and Magoulick, D. D. (2019). Flow–Ecology Relationships Are Spatially Structured and Differ among Flow Regimes. *Journal of Applied Ecology* 56 (2), pp. 398–412. doi:https://doi.org/10.1111/1365-2664.13297.

Brunner, M. I. and Tallaksen, L. M. (2019). Proneness of European Catchments to Multiyear Streamflow Droughts. *Water Resources Research* 55 (11), pp. 8881–8894.

Brutsaert, W. and Nieber, J. L. (1977). Regionalized Drought Flow Hydrographs from a Mature Glaciated Plateau. *Water Resources Research* 13 (3), pp. 637–643.

Bunn, S. E. and Arthington, A. H. (2002). Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* 30 (4), pp. 492–507. doi:10.1007/s00267-002-2737-0.

Burt, T., Howden, N., Worrall, F., and Whelan, M. (2008). Importance of Long-Term Monitoring for Detecting Environmental Change: Lessons from a Lowland River in South East England. *Biogeosciences* 5 (6), pp. 1529–1535.

Buse, K. and Bayliss, K. (2022). England's Privatised Water: Profits over People and Planet. *BMJ* 378, o2076. doi:10.1136/bmj.o2076.

Bussi, G., Dadson, S. J., Prudhomme, C., and Whitehead, P. G. (2016). Modelling the Future Impacts of Climate and Land-Use Change on Suspended Sediment Transport in the River Thames (UK). *Journal of hydrology* 542, pp. 357–372.

Butturini, M. and Marcelis, L. F. M. (2020). Vertical Farming in Europe: Present Status and Outlook. In: *Plant Factory*. Ed. by T. Kozai, G. Niu, and M. Takagaki. 2nd ed. Academic Press. Chap. 4, pp. 77–91. ISBN: 978-0-12-816691-8. doi:https://doi.org/10.1016/b978-0-12-816691-8.00004-2.

CaBA (2021). Project Closure Report Idle and Torne Priority Catchment 2019 - March 2021. Catchment Based Approach. URL: https://catchmentbasedapproach.org/wp-content/uploads/2021/08/Project-Closure-Report-Idle-and-Torne.pdf (Accessed: 31.12.2021).

CaBA (2022a). CaBA Workflow. Catchment Based Approach. URL: https://catchmentbasedapproach.org/about/caba-workflow/ (Accessed: 10.11.2022).

CaBA (2022b). Monitoring and Evaluation 2020/2021. Catchment Based Approach. URL: https://catchmentbasedapproach.org/wp-content/uploads/2022/05/CaBA-Benefits-Report-2020-2021-CaBA-and-the-25YEPV0.2.pdf (Accessed: 8.11.2022).

Caldwell, P. V., Sun, G., McNulty, S. G., Cohen, E. C., and Moore Myers, J. A. (2012). Impacts of Impervious Cover, Water Withdrawals, and Climate Change on River Flows in the Conterminous Us. *Hydrology and Earth System Sciences* 16 (8), pp. 2839–2857. doi:10.5194/hess-16-2839-2012.

Canal & River Trust (2022). Using Technology to Manage Our Waterways. URL: https://canalrivertrust.org.uk/specialist-teams/managing-our-water/meica-scada-using-technology-to-manage-our-waterways (Accessed: 3.10.2022).

Capon, S. J., Leigh, C., Hadwen, W. L., George, A., McMahon, J. M., Linke, S., Reis, V., Gould, L., et al. (2018). Transforming Environmental Water Management to Adapt to a Changing Climate. *Frontiers in Environmental Science* 6. doi:10.3389/fenvs.2018.00080.

Capon, S. J., Stewart-Koster, B., and Bunn, S. E. (2021). Future of Freshwater Ecosystems in a 1.5℃ Warmer World. *Frontiers in Environmental Science* 9. doi:10.3389/fenvs.2021.784642.

Carbó, A., Alegbeyele, G., Anwar, H., Sebek, O., and Sharma, S. (n.d.). The Impact of Land Cover Change and Climate Change on Groundwater Recharge in Sherwood National Character Area. In: Cranfield University. Cranfield, United Kingdom.

Carpenter, S. R., Folke, C., Scheffer, M., and Westley, F. R. (2019). Dancing on the Volcano: Social Exploration in Times of Discontent. *Ecology and Society* 24 (1). doi:10.5751/es-10839-240123.

Carragher, B. J., Stewart, R. A., and Beal, C. D. (2012). Quantifying the Influence of Residential Water Appliance Efficiency on Average Day Diurnal Demand Patterns at an End Use Level: A Precursor to Optimised Water Service Infrastructure Planning. *Resources, Conservation and Recycling* 62, pp. 81–90. doi:https://doi.org/10.1016/j.resconrec.2012.02.008.

Cartwright, J., Caldwell, C., Nebiker, S., and Knight, R. (2017). Putting Flow–Ecology Relationships into Practice: A Decision-Support System to Assess Fish Community Response to Water-Management Scenarios. *Water* 9 (3), p. 196.

Carvalho, L., Mackay, E. B., Cardoso, A. C., Baattrup-Pedersen, A., Birk, S., Blackstock, K. L., Borics, G., Borja, A., et al. (2019). Protecting and Restoring Europe's Waters: An Analysis of the Future Development Needs of the Water Framework Directive. *Sci Total Environ* 658, pp. 1228–1238. doi:10.1016/j.scitotenv.2018.12.255.

Casanueva, A., Herrera, S., Iturbide, M., Lange, S., Jury, M., Dosio, A., Maraun, D., and Gutiérrez, J. M. (2020). Testing Bias Adjustment Methods for Regional Climate Change Applications under Observational Uncertainty and Resolution Mismatch. *Atmospheric Science Letters* 21 (7). doi:10.1002/asl.978.

CEH (2017). Land Cover Map 2015 Scale 1:250,000 [Tiff Geospatial Data]. CEH using EDINA Environment Digimap Service, Centre for Ecology and Hydrology (CEH), Wallingford, United Kingdom. URL: https://digimap.edina.ac.uks (Accessed: 14.11.2018).

CEH (2018). Land Cover Plus: Crops 2016, Crops 2017, Crops 2018, Scale: 1 : 2500. URL: https://www.ceh.ac.uk/crops2015 (Accessed: 1.8.2019).

CEH (2022). Floods and Droughts Research Infrastructure (Fdri). UK Centre for Ecology Hydrology (CEH). URL: https://www.ceh.ac.uk/our-science/projects/floods-and-droughts-research-infrastructure-fdri (Accessed: 1.2.2023).

Chaffin, B. C., Gosnell, H., and Cosens, B. A. (2014). A Decade of Adaptive Governance Scholarship: Synthesis and Future Directions. *Ecology and Society* 19 (3). doi:10.5751/es-06824-190356.

Chai, T. and Draxler, R. R. (2014). Root Mean Square Error (Rmse) or Mean Absolute Error (Mae)? - Arguments against Avoiding Rmse in the Literature. *Geoscientific Model Development* 7 (3), pp. 1247–1250. doi:10.5194/gmd-7-1247-2014.

Champathong, A., Hanasaki, N., Kiguchi, M., and Oki, T. (2020). Reconstructing the Pristine Flow of Highly Developed Rivers a Case Study on the Chao Phraya River. *Hydrological Research Letters* 14 (2), pp. 89–96.

Charlton, M. B., Bowes, M. J., Hutchins, M. G., Orr, H. G., Soley, R., and Davison, P. (2018). Mapping Eutrophication Risk from Climate Change: Future Phosphorus Concentrations in English Rivers. *Science of the Total Environment* 613, pp. 1510–1526. doi:10.1016/j.scitotenv.2017.07.218.

Charlton, M. B. and Arnell, N. W. (2011). Adapting to Climate Change Impacts on Water Resources in England—an Assessment of Draft Water Resources Management Plans. *Global Environmental Change* 21 (1), pp. 238–248. doi:10.1016/j.gloenvcha.2010.07.012.

Charlton, M. B. and Arnell, N. W. (2014). Assessing the Impacts of Climate Change on River Flows in England Using the UKCP09 Climate Change Projections. *Journal of Hydrology* 519, pp. 1723–1738. doi:10.1016/j.jhydrol.2014.09.008.

Chawla, Y., Kowalska-Pyzalska, A., and Oralhan, B. (2020). Attitudes and Opinions of Social Media Users Towards Smart Meters' Rollout in Turkey. *Energies* 13 (3), p. 732.

Chen, J., Brissette, F. P., Lucas-Picher, P., and Caya, D. (2017). Impacts of Weighting Climate Models for Hydro-Meteorological Climate Change Studies. *Journal of Hydrology* 549, pp. 534–546.

Chen, J., Brissette, F. P., Chaumont, D., and Braun, M. (2013). Finding Appropriate Bias Correction Methods in Downscaling Precipitation for Hydrologic Impact Studies over North America. *Water Resources Research* 49 (7), pp. 4187–4205. doi:10.1002/wrcr.20331.

Chen, J., Brissette, F. P., and Lucas-Picher, P. (2015). Assessing the Limits of Bias-Correcting Climate Model Outputs for Climate Change Impact Studies. *Journal of Geophysical Research: Atmospheres* 120 (3), pp. 1123–1136. doi:10.1002/2014jd022635.

Chen, J., St-Denis, B. G., Brissette, F. P., and Lucas-Picher, P. (2016). Using Natural Variability as a Baseline to Evaluate the Performance of Bias Correction Methods in

Hydrological Climate Change Impact Studies. *Journal of Hydrometeorology* 17 (8), pp. 2155–2174. doi:10.1175/jhm-d-15-0099.1.

Chen, W. and Olden, J. D. (2017). Evaluating Transferability of Flow-Ecology Relationships across Space, Time and Taxonomy. *Freshwater Biology*. doi:10.1111/fwb.13041.

Cheung, M. Y., Liang, S., and Lee, J. (2013). Toxin-Producing Cyanobacteria in Freshwater: A Review of the Problems, Impact on Drinking Water Safety, and Efforts for Protecting Public Health. *Journal of Microbiology* 51, pp. 1–10.

Chien, H., Yeh, P. J. F., and Knouft, J. H. (2013). Modeling the Potential Impacts of Climate Change on Streamflow in Agricultural Watersheds of the Midwestern United States. *Journal of Hydrology* 491, pp. 73–88. doi:10.1016/j.jhydrol.2013.03.026.

Chiew, F. H. S. (2006). Estimation of Rainfall Elasticity of Streamflow in Australia. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 51 (4), pp. 613–625. doi:doi10.1623/hysj.51.4.613.

Chithra, S. V., Nair, M. H., Amarnath, A., and Anjana, N. S. (2015). Impacts of Impervious Surfaces on the Environment. *International Journal of Engineering Science Invention* 4 (5), pp. 27–31.

Chiverton, A., Hannaford, J., Holman, I., Corstanje, R., Prudhomme, C., Bloomfield, J., and Hess, T. M. (2014). Which Catchment Characteristics Control the Temporal Dependence Structure of Daily River Flows? *Hydrological Processes* 29 (6), pp. 1353–1369. doi:10.1002/hyp.10252.

Chokkavarapu, N. and Mandla, V. R. (2019). Comparative Study of GCMs, RCMs, Downscaling and Hydrological Models: A Review toward Future Climate Change Impact Estimation. *SN Applied Sciences* 1 (12), pp. 1–15.

Christensen, J., Boberg, F., Christensen, O., and Lucas-Picher, P. (2008). On the Need for Bias Correction of Regional Climate Change Projections of Temperature and Precipitation. *Geophysical Research Letters* 35 (L20709). doi:10.1029/2008gl035694.

Christensen, J. H., Carter, T. R., Rummukainen, M., and Amanatidis, G. (2007). Evaluating the Performance and Utility of Regional Climate Models: The Prudence Project. *Climatic Change* 81 (1), pp. 1–6. doi:10.1007/s10584-006-9211-6.

Christensen, J. H., Kjellström, E., Giorgi, F., Lenderink, G., and Rummukainen, M. (2010). Weight Assignment in Regional Climate Models. *Climate Research* 44 (2-3), pp. 179–194.

Christensen, O. B. and Kjellström, E. (2020). Partitioning Uncertainty Components of Mean Climate and Climate Change in a Large Ensemble of European Regional Climate Model Projections. *Climate Dynamics* 54 (9), pp. 4293–4308.

Chung, M. G., Frank, K. A., Pokhrel, Y., Dietz, T., and Liu, J. (2021). Natural Infrastructure in Sustaining Global Urban Freshwater Ecosystem Services. *Nature Sustainability* 4 (12), pp. 1068–1075. doi:10.1038/s41893-021-00786-4.

CIWEM (2022). Schedule 3 of the Flood and Water Management Act 2010 - Open Letter to the Prime Minister. The Chartered Institution of Water and Environmental Management (CIWEM). URL: https://www.ciwem.org/assets/pdf/Policy/Letters/Rishi%20Sunak%20re%20Schedule%203%20Dec%202022.pdf (Accessed: 16.12.2022).

Clark, J. (2023). Households in England and Wales Face Biggest Water Bills Rise in Decades. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/money/2023/feb/02/households-in-england-and-wales-face-biggest-water-bills-rise-in-decades (Accessed: 3.2.2023).

Clausen, B. and Biggs, B. J. F. (2000). Flow Variables for Ecological Studies in Temperate Streams: Groupings Based on Covariance. *Journal of Hydrology* 237 (3-4), pp. 184–197. doi:doi10.1016/s0022-1694(00)00306-1.

Clausen, K. and Biggs, B. (1997). Relationships between Benthic Biota and Hydrological Indices in New Zealand Streams. *Freshwater Biology* 38, pp. 327–342.

Colley, T. (2022). Ofwat Challenged to Recover 'Misappropriated Funds' from Water Companies. The ENDS Report, Haymarket Media Group Ltd., London, United Kingdom. URL: https://www.endsreport.com/article/1791334/ofwat-challenged-recover-misappropriated-funds-water-companies (Accessed: 17.2.2023).

Collins, M., Booth, B. B. B., Bhaskaran, B., Harris, G. R., Murphy, J. M., Sexton, D. M. H., and Webb, M. J. (2010). Climate Model Errors, Feedbacks and Forcings: A Comparison of Perturbed Physics and Multi-Model Ensembles. *Climate Dynamics* 36 (9-10), pp. 1737–1766. doi:10.1007/s00382-010-0808-0.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., et al. (2013). Long-Term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013-the Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 1029–1136.

Collins, R., Johnson, D., Crilly, D., Rickard, A., Neal, L., Morse, A., Walker, M., Lear, R., et al. (2020). Collaborative Water Management across England–an Overview of the Catchment Based Approach. *Environmental Science Policy* 112, pp. 117–125.

Colloff, M. J., Doody, T. M., Overton, I. C., Dalton, J., and Welling, R. (2019). Re-Framing the Decision Context over Trade-Offs among Ecosystem Services and Wellbeing in a Major River Basin Where Water Resources Are Highly Contested. *Sustainability Science* 14 (3), pp. 713–731.

Colwell, R. K. (1974). Predictability, Constancy, and Contingency of Periodic Phenomena. *Ecology* 55 (5), pp. 1148–1153. doi:doi10.2307/1940366.

Committee of Public Accounts (2020). Water Supply and Demand Management. 9. (HC), Report to the Committee of the House of Commons. London, United Kingdom: House of Commons. URL: https://publications.parliament.uk/pa/cm5801/cmselect/cmpubacc/378/37802.htm.

Conner, J. and Smith, F. (2022). Most Britons Believe That Trains, Water and Energy Should Sit within the Public Sector. YouGov PLC. URL: https://yougov.co.uk/topics/politics/articles-reports/2022/10/19/most-britons-believe-trains-water-and-energy-shoul (Accessed: 25.2.2023).

Cook, B. R. and Spray, C. J. (2012). Ecosystem Services and Integrated Water Resource Management: Different Paths to the Same End? *J Environ Manage* 109, pp. 93–100. doi:10.1016/j.jenvman.2012.05.016.

Cooley, S. W., Ryan, J. C., and Smith, L. C. (2021). Human Alteration of Global Surface Water Storage Variability. *Nature* 591 (7848), pp. 78–81. doi:10.1038/s41586-021-03262-3.

Corbin, J. M. and Strauss, A. (1990). Grounded Theory Research: Procedures, Canons, and Evaluative Criteria. *Qualitative sociology* 13 (1), pp. 3–21.

Cosens, B., Gunderson, L., and Chaffin, B. (2014). The Adaptive Water Governance Project: Assessing Law, Resiliance and Governance in Regional Socio-Ecological Water Systems Facing a Changing Climate. *Idaho L. Rev.* 51, p. 1.

Cosens, B. A., Ruhl, J., Soininen, N., and Gunderson, L. (2020). Designing Law to Enable Adaptive Governance of Modern Wicked Problems. *Vand. L. Rev.* 73, p. 1687.

Cosgrove, W. J. and Loucks, D. P. (2015). Water Management: Current and Future Challenges and Research Directions. *Water Resources Research* 51 (6), pp. 4823–4839. doi:https://doi.org/10.1002/2014wr016869.

Cowx, I., Noble, R., Nunn, A., Harvey, J., Welcomme, R., and Halls, A. (2004). Flow and Level Criteria for Coarse Fish and Conservation Species. In: Environment Agency. Bristol, United Kingdom: Report, Science, p. 173. URL: http://www.environmentdata.org/archive/ealit:4617/OBJ/20022_ca_object_representations_media_308_original.pdf.

Coxon, G., Addor, N., Bloomfield, J. P., Freer, J., Fry, M., Hannaford, J., Howden, N. J. K., Lane, R., et al. (2020). Camels-Gb: Hydrometeorological Time Series and Landscape Attributes for 671 Catchments in Great Britain. *Earth System Science Data* 12 (4), pp. 2459–2483. doi:10.5194/essd-12-2459-2020.

CPES (2018). Our Pilot Sites - Rother River Catchment. Interreg Project. URL: https://www.cpes-interreg.eu/en/cpes-project/our-pilot-sites/rother-river-catchment (Accessed: 18.11.2019).

Craigen, I., Christopherson, E., Speakman, A., Cherry, J., Jones, A., and Wagstaff, S. (2021). Water Resource Benefits of Working with Natural Processes. Environment Agency. URL: https://consult.environment-agency.gov.uk/water-resources/water-resources-priority-catchments/supporting_documents/CETJBAXXXXRPZ0019A6C02WRB_WWNP_final%2010catch.PDF (Accessed: 3.1.2022).

Cranfield University (2014). Horizon Hydraulics Soil Series Horizon Hydraulics Data. School of Water, Energy and Environment, Cranfield University. URL: http://www.landis.org.uk/data/horhydraulics.cfm (Accessed: 9.7.2019).

Criss, R. E. and Winston, W. E. (2008). Do Nash Values Have Value? Discussion and Alternate Proposals. *Hydrological Processes* 22 (14), pp. 2723–2725. doi:10.1002/hyp.7072.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., and Sheikh, A. (2011). The Case Study Approach. *BMC Medical Research Methodology* 11 (1), p. 100. doi:10.1186/1471-2288-11-100.

Cubi-Molla, P., Buxton, M., and Devlin, N. (2021). Allocating Public Spending Efficiently: Is There a Need for a Better Mechanism to Inform Decisions in the UK and Elsewhere? *Appl Health Econ Health Policy* 19 (5), pp. 635–644. doi:10.1007/s40258-021-00648-2.

Cuceloglu, G. and Ozturk, I. (2019). Assessing the Impact of Cfsr and Local Climate Datasets on Hydrological Modeling Performance in the Mountainous Black Sea Catchment. *Water* 11 (11). doi:10.3390/w11112277.

Cukier, R. (1975). Study of the Sensitivity of Coupled Reaction Systems to Uncertainties in Rate Coefficients. Iii. Analysis of the Approximations. *The Journal of Chemical Physics* 63 (1140), pp. 1140–1149. doi:10.1063/1.431440.

Dalcin, A. P. and Fernandes Marques, G. (2020). Integrating Water Management Instruments to Reconcile a Hydro-Economic Water Allocation Strategy with Other Water Preferences. *Water Resources Research* 56 (5), e2019WR025558. doi:10.1029/2019wr025558.

Dallaire, C. O., Lehner, B., and Creed, I. (2019). Multidisciplinary Classification of Canadian River Reaches to Support the Sustainable Management of Freshwater Systems. *Canadian Journal of Fisheries and Aquatic Sciences* 77 (2).

Daniell, K. A. and Barreteau, O. (2014). Water Governance across Competing Scales: Coupling Land and Water Management. *Journal of hydrology* 519, pp. 2367–2380.

Davey, A. J. H., Bailey, L., Bewes, V., Mubaiwa, A., Hall, J., Burgess, C., Dunbar, M. J., Smith, P. D., et al. (2020). Water Quality Benefits from an Advice-Led Approach to Reducing Water Pollution from Agriculture in England. *Agriculture, Ecosystems Environment* 296. doi:10.1016/j.agee.2020.106925.

Davies, P., Naiman, R., Warfe, D., Pettit, N., Arthington, A., and Bunn, S. (2013). Flow–Ecology Relationships: Closing the Loop on Effective Environmental Flows. *Marine and Freshwater Research* 65 (2), pp. 133–141. doi:10.1071/mf13110.

DeCuir-Gunby, J. T., Marshall, P. L., and McCulloch, A. W. (2011). Developing and Using a Codebook for the Analysis of Interview Data: An Example from a Professional Development Research Project. *Field methods* 23 (2), pp. 136–155.

Defra (2013). Catchment Based Approach: Improving the Quality of Our Water Environment. 13934. Department for Environment, Food and Rural Affairs (Defra).

Defra (2016a). Changes to Water Abstraction Licensing Exemptions. London, United Kingdom: Department for Environment, Food and Rural Affairs (Defra). URL: https://consult.defra.gov.uk/water/water-abstraction-licensing-exemptions.

Defra (2016b). Water Abstraction Management Reform in England - What Would Reform Mean for Abstractors? Department for Environment, Food and Rural Affairs (Defra), London, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/492414/abstraction-reform-what-it-means-abstractors.pdf (Accessed: 3.2.2023).

Defra (2017). Explanatory Memorandum to the Water Abstraction (Transitional Provisions) Regulations 2017. Department of Environment, Food and Rural Affairs (Defra). URL: http://www.legislation.gov.uk/uksi/2017/1044/pdfs/uksiem_20171044_en.pdf (Accessed: 2.10.2018).

Defra (2018). A Green Future: Our 25 Year Plan to Improve the Environment. Department for Environment, Food and Rural Affairs (Defra), Policy Papers. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf (Accessed: 9.8.2022).

Defra (2019). British Survey of Fertiliser Practice - Fertiliser Use on Farm for the Crop Year 2018. In: Fertiliser Usage. National Statistics. London, United Kingdom: Department for Environment, Food and Rural Affairs. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872453/fertiliseruse-report2018-13mar20.pdf.

Defra (2020). Policy Paper: Water Abstraction Plan: Environment. Department of Environment, Food and Rural Affairs (Defra). URL: https://www.gov.uk/government/publications/water-abstraction-plan-2017/water-abstraction-plan-environment (Accessed: 21.8.2020).

Defra (2021a). River Basin Planning Guidance. Department for Environment, Food and Rural Affairs (Defra). URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1019774/River_basin_management_planning_ministerial_guidance.pdf (Accessed: 8.2.2021).

Defra (2021b). Water Abstraction Plan: Environment. Department of Environment, Food and Rural Affairs (Defra), Policy Papers. URL: https://www.gov.uk/government/publications/water-abstraction-plan-2017/water-abstraction-plan-environment (Accessed: 25.10.2022).

Defra (2022a). About Us. Department for Environment, Food and Rural Affairs (Defra). URL: https://www.gov.uk/government/organisations/department-for-environment-food-rural-affairs/about (Accessed: 31.10.2022).

Defra (2022b). Guidance - Sustainable Farming Incentive: Full Guidance. Department for Environment, Food and Rural Affairs (Defra) Rural Payments Agency (Accessed: 7.11.2022).

Defra (2022c). Statutory Guidance - Applying the Farming Rules for Water. Department for Environment, Food and Rural Affairs (Defra). URL: https://www.gov.uk/government/publications/applying-the-farming-rules-for-water/applying-the-farming-rules-for-water (Accessed: 19.8.2022).

Defra (2022d). Water Quality Archive. Department for Environment Food and Rural Affairs (Defra) and Environment Agency (EA). URL: https://environment.data.gov.uk/water-quality/view/landing (Accessed: 12.8.2022).

Defra (2023). Official Statistics Figure 3.2 Estimated Abstractions from Non-Tidal Surface Water and Groundwater in England by Purpose 2000 to 2018. Department for Environment, Food and Rural Affairs. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1125037/Fig_3.2_Est_abstractions_non-tidal_surface_water_and_groundwater_Eng_purpose_2000_2018_rev.csv/preview (Accessed: 25.2.2023).

DeFries, R. and Nagendra, H. (2017). Ecosystem Management as a Wicked Problem. *Science* 356 (6335), pp. 265–270. doi:10.1126/science.aal1950.

Demory, M. E., Berthou, S., Fernández, J., Sørland, S. L., Brogli, R., Roberts, M. J., Beyerle, U., Seddon, J., et al. (2020). European Daily Precipitation According to EURO-CORDEX Regional Climate Models (RCMs) and High-Resolution Global Climate Models (GCMs) from the High-Resolution Model Intercomparison Project (Highresmip). *Geosci. Model Dev.* 13 (11), pp. 5485–5506. doi:10.5194/gmd-13-5485-2020.

Déqué, M., Rowell, D. P., Lüthi, D., Giorgi, F., Christensen, J. H., Rockel, B., Jacob, D., Kjellström, E., et al. (2007). An Intercomparison of Regional Climate Simulations for Europe: Assessing Uncertainties in Model Projections. *Climatic Change* 81 (1), pp. 53–70. doi:10.1007/s10584-006-9228-x.

Derepasko, D., Guillaume, J. H. A., Horne, A. C., and Volk, M. (2021). Considering Scale within Optimization Procedures for Water Management Decisions: Balancing Environmental Flows and Human Needs. *Environmental Modelling Software* 139, p. 104991. doi:10.1016/j.envsoft.2021.104991.

Deser, C., Knutti, R., Solomon, S., and Phillips, A. S. (2012). Communication of the Role of Natural Variability in Future North American Climate. *Nature Climate Change* 2 (11), pp. 775–779. doi:10.1038/nclimate1562.

Dessai, S. and Hulme, M. (2007). Assessing the Robustness of Adaptation Decisions to Climate Change Uncertainties: A Case Study on Water Resources Management in the East of England. *Global Environmental Change-Human and Policy Dimensions* 17 (1), pp. 59–72. doi:10.1016/j.gloenvcha.2006.11.005.

Devia, G. K., Ganasri, B. P., and Dwarakish, G. S. (2015). A Review on Hydrological Models. *Aquatic Procedia* 4, pp. 1001–1007. doi:https://doi.org/10.1016/j.aqpro.2015.02.126.

Dewson, Z. S., James, A. B., and Death, R. G. (2007). A Review of the Consequences of Decreased Flow for Instream Habitat and Macroinvertebrates. *Journal of the North American Benthological Society* 26 (3), pp. 401–415.

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T. I. E., Garcia, M., Oel, P. R. van, et al. (2018). Water Shortages Worsened by Reservoir Effects. *Nature Sustainability* 1 (11), pp. 617–622. doi:10.1038/s41893-018-0159-0.

Diamantini, E., Lutz, S. R., Mallucci, S., Majone, B., Merz, R., and Bellin, A. (2018). Driver Detection of Water Quality Trends in Three Large European River Basins. *Science of The Total Environment* 612, pp. 49–62. doi:https://doi.org/10.1016/j.scitotenv.2017.08.172.

Dickinson, R. E., Errico, R. M., Giorgi, F., and Bates, G. T. (1989). A Regional Climate Model for the Western United States. *Climatic change* 15 (3), pp. 383–422.

Dierauer, J. R., Whitfield, P. H., and Allen, D. M. (2017). Assessing the Suitability of Hydrometric Data for Trend Analysis: The 'Flowscreen' Package for R. *Canadian Water Resources Journal* 42 (3), pp. 269–275. doi:10.1080/07011784.2017.1290553.

Dixon, H., Hannaford, J., and Fry, M. J. (2013). The Effective Management of National Hydrometric Data: Experiences from the United Kingdom. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* 58 (7), pp. 1383–1399. doi:10.1080/02626667.2013.787486.

Döll, P., Jiménez-Cisneros, B., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Jiang, T., Kundzewicz, Z. W., et al. (2014). Integrating Risks of Climate Change into Water Management. *Hydrological Sciences Journal* 60 (1), pp. 4–13. doi:10.1080/02626667.2014.967250.

Donegan, S., Murphy, C., Harrigan, S., Broderick, C., Foran Quinn, D., Golian, S., Knight, J., Matthews, T., et al. (2021). Conditioning Ensemble Streamflow Prediction with the North Atlantic Oscillation Improves Skill at Longer Lead Times. *Hydrol. Earth Syst. Sci.* 25 (7), pp. 4159–4183. doi:10.5194/hess-25-4159-2021.

Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., and Ludwig, F. (2017). Impacts of Climate Change on European Hydrology at 1.5, 2 and 3 Degrees Mean Global Warming above Preindustrial Level (Vol 143, Pg 13, 2017). *Climatic Change* 143 (3-4), pp. 535–535. doi:10.1007/s10584-017-2022-0.

Downing, A. S., Nes, E. H. van, Janse, J. H., Witte, F., Cornelissen, I. J. M., Scheffer, M., and Mooij, W. M. (2012). Collapse and Reorganization of a Food Web of Mwanza Gulf, Lake Victoria. *Ecological Applications* 22 (1), pp. 229–239. doi:doi10.1890/11-0941.1.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z., Knowler, D. J., Leveque, C., Naiman, R. J., Prieur-Richard, A. H., et al. (2006). Freshwater Biodiversity: Importance, Threats, Status and Conservation Challenges. *Biol Rev Camb Philos Soc* 81 (2), pp. 163–82. doi:10.1017/s1464793105006950.

Dudgeon, D. (2019). Multiple Threats Imperil Freshwater Biodiversity in the Anthropocene. *Current Biology* 29 (19), R960–R967. doi:https://doi.org/10.1016/j.cub.2019.08.002.

Dunbar, M. J., Pedersen, M. L., Cadman, D., Extence, C., Waddingham, J., Chadd, R., and Larsen, S. E. (2010). River Discharge and Local-Scale Physical Habitat Influence Macroinvertebrate Life Scores. *FRESHWATER BIOLOGY* 55 (1), pp. 226–242. doi:10.1111/j.1365-2427.2009.02306.x.

EA, Defra & (2021). Press Release - New Water Saving Measures to Safeguard Supplies. Department for Environment, Food and Rural Affairs (Defra) Environment Agency (EA). URL: https://www.gov.uk/government/news/new-water-saving-measures-to-safeguard-supplies (Accessed: 10.8.2022).

ECHR (2012). Grainger and Others Vs. The United Kingdom Decision. Application No. 34940/10. Strasbourg, France: European Court of Human Rights.

Eckhardt, K. (2005). How to Construct Recursive Digital Filters for Baseflow Separation. *Hydrological Processes* 19 (2), pp. 507–515. doi:10.1002/hyp.5675.

ECMWF (2021). European Hydrology and Climate Data Explorer. The Copernicus Climate Change Service (C3S), operated by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Union. URL: https://cds.climate.copernicus.eu/cdsapp#!/software/app-hydrology-climate-explorer?tab=overview (Accessed: 16.2.2023).

Eekhout, J. P. C., Hunink, J. E., Terink, W., and Vente, J. de (2018). Why Increased Extreme Precipitation under Climate Change Negatively Affects Water Security. *Hydrol. Earth Syst. Sci.* 22 (11), pp. 5935–5946. doi:10.5194/hess-22-5935-2018.

Eerd, M. C. J. van and Wiering, M. A. (2022). The Politics of Practical Implementation: Reloading of Information by Competing Coalitions in EU Water Governance. *International Journal of Water Resources Development* 38 (4), pp. 579–595. doi:10.1080/07900627.2021.1999218.

Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., and Liebert, J. (2012). "Should We Apply Bias Correction to Global and Regional Climate Model Data?" *Hydrology and Earth System Sciences* 16 (9), pp. 3391–3404. doi:10.5194/hess-16-3391-2012.

Ellison, J. C., Smethurst, P. J., Morrison, B. M., Keast, D., Almeida, A., Taylor, P., Bai, Q., Penton, D. J., et al. (2019). Real-Time River Monitoring Supports Community Management of Low-Flow Periods. *Journal of Hydrology* 572, pp. 839–850. doi:10.1016/j.jhydrol.2019.03.035.

England, M. H., Kajtar, J. B., and Maher, N. (2015). Robust Warming Projections Despite the Recent Hiatus. *Nature Climate Change* 5 (5), pp. 394–396. doi:10.1038/nclimate2575.

Environment Act (2021). C. 30. UK Public General Acts. URL: https://www.legislation.gov.uk/ukpga/2021/30/contents/enacted.

Environment Agency (2001). Managing Water Abstractions: The Catchment Abstraction Management Strategy Process. Bristol, United Kingdom: Environment Agency. URL: http://www.environmentdata.org/archive/ealit:2089.

Environment Agency (2009). Internal Memo: CAMS Natural Flow Sequences and the Period of Record. RF/assessment/09-10/04. Webb, T.

Environment Agency (2013a). Arun & Western Streams Abstraction Licensing Strategy. Bristol, United Kingdom: Environment Agency. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/793421/Arun_and_Western_Streams_Abstraction_Licensing_Strategy.pdf.

Environment Agency (2013b). Environmental Flow Indicator - What It Is and What It Does. URL: http://webarchive.nationalarchives.gov.uk/20140328104910/http://cdn.environment-agency.gov.uk/LIT_7935_811630.pdf (Accessed: 13.8.2018).

Environment Agency (2014a). Guidance Apply for a Water Abstraction or Impounding Licence. URL: https://www.gov.uk/guidance/water-management-apply-for-a-water-abstraction-or-impoundment-licence (Accessed: 9.11.2022).

Environment Agency (2014b). Water Supply and Resilience and Infrastructure - Environment Agency Advice to Defra. Bristol, United Kingdom: Environment Agency. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/504682/ea-analysis-water-sector.pdf.

Environment Agency (2015). Press Release: First Spawned Salmon Found in River Dearne for 150 Years. URL: https://www.gov.uk/government/news/first-spawned-salmon-found-in-river-dearne-for-150-years (Accessed: 2.12.2022).

Environment Agency (2016a). Final Water Resourcs Planning Guideline. Environment Agency Natural Resources Wales, Bristol, United Kingdom. URL: https://naturalresources.wales/media/678424/ea-nrw-and-defra-wg-ofwat-technical-water-resources-planning-guidelines.pdf (Accessed: 20.3.2019).

Environment Agency (2016b). Guidance: Flood Risk Assessments: Climate Change Allowances. Environment Agency, Bristol, United Kingdom. URL: https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances (Accessed: 9.11.2022).

Environment Agency (2017). Guidance - Algal Blooms: Advice for the Public and Landowners. URL: https://www.gov.uk/government/publications/algal-blooms-advice-for-the-

public-and-landowners/algal-blooms-advice-for-the-public-and-landowners (Accessed: 8.8.2022).

Environment Agency (2018a). Arun & Western Streams CAMS Ledger. In: ed. by B. Davies, S. Fewings, T. Byrne, J. Barker, R. Liu, K. Howard, R. Boutle, R. Smith, et al. Vol. version 4.8. (Collected: 05.09.2018).

Environment Agency (2018b). Environmental Flow Indicator - Application of the Efi for Water Resources Licensing - Position Statement. Bristol, United Kingdom: Environment Agency.

Environment Agency (2018c). Guidance: Water Companies: Water Treatment Works Discharge Limits for Environmental Permits. URL: https://www.gov.uk/government/publications/water-companies-water-treatment-works-discharge-limits-for-environmental-permits/water-companies-water-treatment-works-discharge-limits-for-environmental-permits (Accessed: 15.12.2022).

Environment Agency (2018d). Idle & Torne CAMS Ledger. In: ed. by R. Cooper, A. Barker, C. Anderson, M. Neal, S. Quinlan, J. Pereira, A. Chambers, L. Roberts, et al. Vol. version 4.8.3. (Collected: 30.05.2018).

Environment Agency (2018e). The State of the Environment: Water Resources. Department for Environment, Food & Rural Affairs (Defra). URL: https://www.gov.uk/government/publications/state-of-the-environment (Accessed: 16.2.2022).

Environment Agency (2019a). Abstraction Reform Report - Progress Made in Reforming the Arrangements for Managing Water Abstraction in England. Water Resources and Abstraction Team, Department for Environment, Food and Rural Affairs (Defra). URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/914427/abstraction-reform-report.pdf (Accessed: 6.1.2022).

Environment Agency (2019b). Escaping the Jaws of Death: Ensuring Enough Water in 2050, Speech by Sir James Bevan, Chief Executive of the Environment Agency. In: *Waterwise Conference*.

Environment Agency (2019c). Thames Abstraction Licensing Strategy - a Strategy to Manage Water Resources Sustainably. Environment Agency, Bristol, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/849612/Thames-Abstraction-Licensing-Strategy.pdf (Accessed: 31.1.2023).

Environment Agency (2020a). Broadland Rivers CAMS Ledger. In: ed. by M. Farmer, J. Thompson, N. Steel, P. Willett, P. Quinton, and G. Sharpin. Vol. version 4.8.2. (Collected: 12.03.2020).

Environment Agency (2020b). Don & Rother CAMS Ledger. In: ed. by C. Fyfe, J. Duke, J. Dracup, J. Credland, J. Briddock, B. Leigh, J. Senior, K. Wooster, et al. Vol. version 4.8.2. (Collected: 17.03.2020).

Environment Agency (2020c). Idle and Torne Abstraction Licensing Strategy (Accessed: 5.4.2022).

Environment Agency (2020d). Meeting Our Future Water Needs: A National Framework for Water Resources. Environment Agency, Bristol, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/

file/872759/National_Framework_for_water_resources_main_report.pdf (Accessed: 25.6.2020).

Environment Agency (2020e). Ribble CAMS Ledger. In: ed. by N. Walsh, J. Westgarth, L. Hesketh, D. Spiby, L. O'Neil, A. Murcott, S. Kansakar, S. Gebbett, et al. Vol. version 4.8.2. (Collected: 17.03.2020).

Environment Agency (2020f). Water Resources National Framework - Appendix 4: Longer Term Environmental Water Needs, Version 1. Environment Agency, Bristol, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872344/Appendix_4_Longer_term_environmental_water_needs.pdf (Accessed: 6.12.2022).

Environment Agency (2021a). Annual Report and Accounts for the Financial Year 2020 to 2021 (Accessed: 12.8.2022).

Environment Agency (2021b). Guidance - Water Resources Planning Guideline. Environment Agency, Natural Resources Wales, Office for Water Services. URL: https://www.gov.uk/government/publications/water-resources-planning-guideline/water-resources-planning-guideline (Accessed: 26.10.2022).

Environment Agency (2021c). Managing Water Abstraction. Environment Agency, Bristol, United Kingdom. URL: https://www.gov.uk/government/publications/managing-water-abstraction/managing-water-abstraction#catchment-abstraction-management-system-cams (Accessed: 13.2.2023).

Environment Agency (2021d). Updating the Determination of Water Stressed Areas in England - Consultation Response Document. Bristol, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/998931/Updating_the_determination_of_water_stressed_areas_in_England_-_consultation_response_document.pdf.

Environment Agency (2021e). Water Resources Priority Catchments. Environment Agency, Water Resources. URL: https://consult.environment-agency.gov.uk/water-resources/water-resources-priority-catchments/consult_view/ (Accessed: 13.12.2021).

Environment Agency (2022a). Consultation Outcome - Water Resources Charge Proposals from April 2022: Summary of Consultation Responses. URL: https://www.gov.uk/government/consultations/water-resources-charge-proposals-from-april-2022/public-feedback/water-resources-charge-proposals-from-april-2022-summary-of-consultation-responses (Accessed: 16.8.2022).

Environment Agency (2022b). Ecology and Fish Data Explorer. Department for Environment, Food & Rural Affairs (Defra). URL: https://environment.data.gov.uk/ecology/explorer/ (Accessed: 12.8.2022).

Environment Agency (2022c). Environmental Permitting and Abstraction Licensing)(England) Charging Scheme 2022, Version 1.1. Environment Agency, Bristol, United Kingdom. URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1098117/Environment_Agency_EPR_and_Abstraction_Licensing_Charging_Scheme_2022.pdf (Accessed: 16.8.2022).

Environment Agency (2022d). Flood Risk Management Plans 2021 to 2027: National Overview (Part a). URL: https://www.gov.uk/government/publications/flood-risk-

management-plans-2021-to-2027-national-overview-part-a/national-overview-part-a#fcerm-activities (Accessed: 11.1.2023).

Environment Agency (2022e). Guidance: Water Industry National Environment Programme (Winep) Methodology. Department for Environment Food & Rural Affairs (Defra), Environment Agency, Natural England. URL: https://www.gov.uk/government/publications/developing-the-environmental-resilience-and-flood-risk-actions-for-the-price-review-2024/water-industry-national-environment-programme-winep-methodology (Accessed: 26.10.2022).

Environment Agency (2022f). Policy Paper: Environment Agency Enforcement and Sanctions Policy. URL: https://www.gov.uk/government/publications/environment-agency-enforcement-and-sanctions-policy/environment-agency-enforcement-and-sanctions-policy (Accessed: 17.10.2022).

Environment Agency (2022g). Review of England's Emerging Regional Water Resources Plans. analysis, Research and. Bristol, United Kingdom: Environment Agency. URL: https://www.gov.uk/government/publications/review-of-englands-emerging-regional-water-resources-plans/review-of-englands-emerging-regional-water-resources-plans.

Environment Agency (2022h). Water and Sewerage Companies in England: Environmental Performance Report 2021. analysis, Research and. Bristol, United Kingdom: Environment Agency. URL: https://www.gov.uk/government/publications/water-and-sewerage-companies-in-england-environmental-performance-report-2021/water-and-sewerage-companies-in-england-environmental-performance-report-2021.

Environment Agency & Highways Agency (2009). Memorandum of Understanding between the Environment Agency and the Highways Agency: Annex 1 - Water Environment. M100263 Annex 1, Bedford Media Services, URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/341286/MoU_HA_and_EA_ANNEX_1_Water_latest_version_March_2011.pdf (Accessed: 9.11.2022).

Environment Agency and Ofwat (2011). The Case for Change - Reforming Water Abstraction Management in England. London, United Kingdom: Environment Agency.

Erfani, T., Binions, O., and Harou, J. J. (2015). Protecting Environmental Flows through Enhanced Water Licensing and Water Markets. *Hydrol. Earth Syst. Sci.* 19 (2), pp. 675–689. doi:10.5194/hess-19-675-2015.

EurEau (2020). The Governance of Water Services in Europe 2020 Edition. URL: https://www.eureau.org/resources/publications/eureau-publications/5219-the-governance-of-water-services-in-europe-2020-edition/file.

European Commission (2000). Directive 2000/60/EC. L 327/1. URL: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32000L0060.

European Commission (2007). Directive 2007/60/EC. OJ L 288. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32007L0060.

European Commission (2019). Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC)

and the Floods Directive (2007/60/EC). COM(2019) 95. Brussels, Belgium. URL: https://commission.europa.eu/system/files/2019-02/com_report_wfd_fd_2019_en_1.pdf.

Everitt, B. (1998). The Cambridge Dictionary of Statistics.

Evin, G., Somot, S., and Hingray, B. (2021). Balanced Estimate and Uncertainty Assessment of European Climate Change Using the Large Euro-Cordex Regional Climate Model Ensemble. *Earth Syst. Dynam.* 12 (4), pp. 1543–1569. doi:10.5194/esd-12-1543-2021.

Evin, G., Hingray, B., Blanchet, J., Eckert, N., Morin, S., and Verfaillie, D. (2019). Partitioning Uncertainty Components of an Incomplete Ensemble of Climate Projections Using Data Augmentation. *Journal of Climate* 32 (8), pp. 2423–2440.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (Cmip6) Experimental Design and Organization. *Geoscientific Model Development* 9 (5), pp. 1937–1958. doi:10.5194/gmd-9-1937-2016.

Falkenmark, M. (1995). Land-Water Linkages: A Synopsis. *FAO land and water bulletin* 1, pp. 15–17.

Falkenmark, M. and Rockström, J. (2010). Building Water Resilience in the Face of Global Change: From a Blue-Only to a Green-Blue Water Approach to Land-Water Management. *Journal of Water Resources Planning and Management (Asce)* 136 (6), pp. 606–610.

Falkenmark, M., Gottschalk, L., Lundqvist, J., and Wouters, P. (2004). Towards Integrated Catchment Management: Increasing the Dialogue between Scientists, Policy-Makers and Stakeholders. *International Journal of Water Resources Development* 20 (3), pp. 297–309.

Falkenmark, M., Wang-Erlandsson, L., and Rockström, J. (2019). Understanding of Water Resilience in the Anthropocene. *Journal of Hydrology X* 2, p. 100009. doi:https://doi.org/10.1016/j.hydroa.2018.100009.

Farren, E., Streetly, M., Black, A., and Daily, P. (2012). East Midlands Yorkshire Groundwater Model Technical Update 201. In: Environment Agency Report. Environment Agency. Midlands Region, United Kingdom.

Fatichi, S., Rimkus, S., Burlando, P., and Bordoy, R. (2014). Does Internal Climate Variability Overwhelm Climate Change Signals in Streamflow? The Upper Po and Rhone Basin Case Studies. *Science of The Total Environment* 493, pp. 1171–1182. doi:https://doi.org/10.1016/j.scitotenv.2013.12.014.

Feld, C. K., Fernandes, M. R., Ferreira, M. T., Hering, D., Ormerod, S. J., Venohr, M., and Gutiérrez-Cánovas, C. (2018). Evaluating Riparian Solutions to Multiple Stressor Problems in River Ecosystems—a Conceptual Study. *Water research* 139, pp. 381–394.

Fenemor, A., Phillips, C., Allen, W., Young, R., Harmsworth, G., Bowden, B., Basher, L., Gillespie, P., et al. (2011). Integrated Catchment Management—Interweaving Social Process and Science Knowledge. *New Zealand Journal of Marine and Freshwater Research* 45 (3), pp. 313–331.

Fernandes, J., Souza, A. de, and Tanaka, M. (2014). Can the Structure of a Riparian Forest Remnant Influence Stream Water Quality? A Tropical Case Study. *Hydrobiologia* 724 (1), pp. 175–185.

Fernández, J., Frías, M. D., Cabos, W. D., Cofiño, A. S., Domínguez, M., Fita, L., Gaertner, M. A., García-Díez, M., et al. (2019). Consistency of Climate Change Projections from Multiple Global and Regional Model Intercomparison Projects. *Climate Dynamics* 52 (1), pp. 1139–1156. doi:10.1007/s00382-018-4181-8.

Fernandez-Granja, J. A., Casanueva, A., Bedia, J., and Fernandez, J. (2021). Improved Atmospheric Circulation over Europe by the New Generation of Cmip6 Earth System Models. *Climate Dynamics* 56 (11), pp. 3527–3540. doi:10.1007/s00382-021-05652-9.

Ferré, M., Martin-Ortega, J., Di Gregorio, M., and Dallimer, M. (2022). How Do Information Flows Affect Impact from Environmental Research? - an Analysis of a Science-Policy Network. *Journal of Environmental Management* 321, p. 115828. doi:https://doi.org/10.1016/j.jenvman.2022.115828.

Finch, H. and Schneider, M. K. (2007). Classification Accuracy of Neural Networks Vs. Discriminant Analysis, Logistic Regression, and Classification and Regression Trees. *Methodology* 3 (2), pp. 47–57. doi:10.1027/1614-2241.3.2.47.

Finch, W. H., Bolin, J. H., and Kelley, K. (2014). Group Membership Prediction When Known Groups Consist of Unknown Subgroups: A Monte Carlo Comparison of Methods. *Front Psychol* 5, p. 337. doi:10.3389/fpsyg.2014.00337.

Finnessey, T., Hayes, M., Lukas, J., and Svoboda, M. (2016). Using Climate Information for Drought Planning. *Climate Research* 70 (2), pp. 251–263. doi:10.3354/cr01406.

Fitzpatrick, S., Bramley, G., Sosenko, F., Blenkinsopp, J., Johnsen, S., Littlewood, M., Netto, G., and Watts, B. (2016). Destitution in the UK. Joseph Rowntree Foundation York. ISBN: 1910783560.

Fleurbaey, M., Kartha, S., Bolwig, S., Chee, Y. L., Chen, Y., Corbera, E., Lecocq, F., Lutz, W., et al. (2014). Sustainable Development and Equity: Contribution of Working Group Iii to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: *Climate Change 2014: Mitigation of Climate Change*. Cambridge University Press.

Flood and Water Management Act (2010). C. 29 - Schedule 3. UK Public General Acts. URL: https://www.legislation.gov.uk/ukpga/2010/29/schedule/3.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., and Holling, C. S. (2004). Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. *Annual review of ecology, evolution, and systematics*, pp. 557–581.

Folke, C., Hahn, T., Olsson, P., and Norberg, J. (2005). Adaptive Governance of Social-Ecological Systems. *Annual Review of Environment and Resources* 30 (1), pp. 441–473. doi:10.1146/annurev.energy.30.050504.144511.

Font, R. A., Khamis, K., Milner, A. M., Smith, G. H. S., and Ledger, M. E. (2021). Low Flow and Heatwaves Alter Ecosystem Functioning in a Stream Mesocosm Experiment. *Science of the Total Environment* 777, p. 146067.

Forster, P. M., Maycock, A. C., McKenna, C. M., and Smith, C. J. (2020). Latest Climate Models Confirm Need for Urgent Mitigation. *Nature Climate Change* 10 (1), pp. 7–10.

Fowler, H. J. and Wilby, R. L. (2010). Detecting Changes in Seasonal Precipitation Extremes Using Regional Climate Model Projections: Implications for Managing Fluvial Flood Risk. *Water Resources Research* 46 (3). doi:10.1029/2008wr007636.

Fowler, H., Ekström, M., Kilsby, C., and P.D., J. (2005). New Estimates of Future Changes in Extreme Rainfall across the UK Using Regional Climate Model Integrations 1. Assessment of Control Climate. *Journal of Hydrology* 300, pp. 212–233.

Frankcombe, L. M., England, M. H., Mann, M. E., and Steinman, B. A. (2015). Separating Internal Variability from the Externally Forced Climate Response. *Journal of Climate* 28 (20), pp. 8184–8202. doi:10.1175/jcli-d-15-0069.1.

Freeman, D. M. (2000). Wicked Water Problems: Sociology and Local Water Organizations in Addressing Water Resources Policy. *JAWRA Journal of the American Water Resources Association* 36 (3), pp. 483–491.

Frigg, R., Bradley, S., Du, H., and Smith, L. A. (2014). Laplace's Demon and the Adventures of His Apprentices. *Philosophy of Science* 81 (1), pp. 31–59. doi:10.1086/674416.

Fritsch, O. (2019). Participatory Water Governance and Organisational Change: Implementing the Water Framework Directive in England and Wales. *Water* 11 (5). doi:10.3390/w11050996.

Fung, F. (2018). How to Bias Correct, UKCP18 Guidance, Met Office. URL: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---how-to-bias-correct.pdf (Accessed: 18.2.2020).

Gale, I., Neumann, I., Calow, R., and Moench, M. (2002). The Effectiveness of Artificial Recharge of Groundwater: A Review. *British Geological Survey Commissioned Report CR/02/108N*.

Gallant, A. J. E. and Gergis, J. (2011). An Experimental Streamflow Reconstruction for the River Murray, Australia, 1783-1988. *Water Resources Research* 47. doi:artnw00g0410.1029/2010wr009832.

Gao, J., Sheshukov, A. Y., Yen, H., Douglas-Mankin, K. R., White, M. J., and Arnold, J. G. (2019). Uncertainty of Hydrologic Processes Caused by Bias-Corrected Cmip5 Climate Change Projections with Alternative Historical Data Sources. *Journal of Hydrology* 568, pp. 551–561.

García de Jalón, S., González del Tánago, M., and García de Jalón, D. (2019). A New Approach for Assessing Natural Patterns of Flow Variability and Hydrological Alterations: The Case of the Spanish Rivers. *Journal of Environmental Management* 233, pp. 200–210. doi:https://doi.org/10.1016/j.jenvman.2018.12.049.

Garg, V., Nikam, B. R., Thakur, P. K., Aggarwal, S. P., Gupta, P. K., and Srivastav, S. K. (2019). Human-Induced Land Use Land Cover Change and Its Impact on Hydrology. *HydroResearch* 1, pp. 48–56. doi:10.1016/j.hydres.2019.06.001.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G. (2007). The Soil & Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the Asabe* 50 (4), pp. 1211–1250.

George, B., Malano, H., Davidson, B., Hellegers, P., Bharati, L., and Massuel, S. (2011). An Integrated Hydro-Economic Modelling Framework to Evaluate Water Allocation

Strategies Ii: Scenario Assessment. *Agricultural Water Management* 98 (5), pp. 747–758. doi:https://doi.org/10.1016/j.agwat.2010.12.005.

Gerten, D., Lucht, W., Ostberg, S., Heinke, J., Kowarsch, M., Kreft, H., Kundzewicz, Z. W., Rastgooy, J., et al. (2013). Asynchronous Exposure to Global Warming: Freshwater Resources and Terrestrial Ecosystems. *Environmental Research Letters* 8 (3).

Gerten, D., Rost, S., Bloh, W. von, and Lucht, W. (2008). Causes of Change in 20th Century Global River Discharge. *Geophysical Research Letters* 35 (20). doi:10.1029/2008gl035258.

Ghafouri-Azar, M. and Bae, D.-H. (2019). Analyzing the Variability in Low-Flow Projections under GCM Cmip5 Scenarios. *Water Resources Management* 33 (15), pp. 5035–5050. doi:10.1007/s11269-019-02396-4.

Gillett, N. P. (2015). Weighting Climate Model Projections Using Observational Constraints. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373 (2054), p. 20140425.

Giorgi, F. (2002). Dependence of the Surface Climate Interannual Variability on Spatial Scale. *Geophysical Research Letters* 29 (23), pp. 16-1-16–4. doi:https://doi.org/10.1029/2002gl016175.

Giorgi, F. (2019). Thirty Years of Regional Climate Modeling: Where Are We and Where Are We Going Next? *Journal of Geophysical Research: Atmospheres* 124 (11), pp. 5696–5723. doi:https://doi.org/10.1029/2018jd030094.

Giorgi, F. and Bates, G. T. (1989). The Climatological Skill of a Regional Model over Complex Terrain. *Monthly Weather Review* 117 (11), pp. 2325–2347.

Giorgi, F., Jones, C., and Asrar, G. R. (2009). Addressing Climate Information Needs at the Regional Level: The Cordex Framework. *World Meteorological Organization (WMO) Bulletin* 58 (3), p. 175.

Givati, A., Thirel, G., Rosenfeld, D., and Paz, D. (2019). Climate Change Impacts on Streamflow at the Upper Jordan River Based on an Ensemble of Regional Climate Models. *Journal of Hydrology: Regional Studies* 21, pp. 92–109.

Gleeson, T., Cuthbert, M., Ferguson, G., and Perrone, D. (2020). Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. *Annual review of earth and planetary sciences* 48, pp. 431–463.

Gong, J., He, L., Liu, X., and Wang, S. (2022). Optimizing the Allocation of Irrigation Water for Multiple Crops Based on the Crop Water Allocation Priority. *Irrigation Science*, pp. 1–20.

Goodin, R. E. (2013). Green Political Theory. Oxford, United Kingdom: John Wiley Sons. ISBN: 0745666701.

Goodman, D. H., Som, N., and Hetrick, N. (2018). Increasing the Availability and Spatial Variation of Spawning Habitats through Ascending Baseflows. *River Research and Applications* 34 (7), pp. 844–853.

Graaf, I. E. M. de, Beek, L. P. H. van, Wada, Y., and Bierkens, M. F. P. (2014). Dynamic Attribution of Global Water Demand to Surface Water and Groundwater Resources: Effects of Abstractions and Return Flows on River Discharges. *Advances in Water Resources* 64, pp. 21–33. doi:10.1016/j.advwatres.2013.12.002.

Gracia-de-Rentería, P. and Barberán, R. (2021). Economic Determinants of Industrial Water Demand: A Review of the Applied Research Literature. *Water* 13 (12). doi:10.3390/w13121684.

Grainger, S., Mao, F., and Buytaert, W. (2016). Environmental Data Visualisation for Non-Scientific Contexts: Literature Review and Design Framework. *Environmental Modelling Software* 85, pp. 299–318. doi:https://doi.org/10.1016/j.envsoft.2016.09.004.

Grams, P. E., Dean, D. J., Walker, A. E., Kasprak, A., and Schmidt, J. C. (2020). The Roles of Flood Magnitude and Duration in Controlling Channel Width and Complexity on the Green River in Canyonlands, Utah, USA. *Geomorphology* 371, p. 107438.

Grantham, T. E., Matthews, J. H., and Bledsoe, B. P. (2019). Shifting Currents: Managing Freshwater Systems for Ecological Resilience in a Changing Climate. *Water Security* 8, p. 100049. doi:https://doi.org/10.1016/j.wasec.2019.100049.

Grecksch, K. (2018). Scenarios for Resilient Drought and Water Scarcity Management in England and Wales. *International Journal of River Basin Management* 17 (2), pp. 219–227. doi:10.1080/15715124.2018.1461106.

Griffiths, J., Binley, A., Crook, N., Nutter, J., Young, A., and Fletcher, S. (2006). Streamflow Generation in the Pang and Lambourn Catchments, Berkshire, UK. *Journal of Hydrology* 330 (1-2), pp. 71–83.

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., et al. (2019). Mapping the World's Free-Flowing Rivers. *Nature* 569 (7755), pp. 215–221. doi:10.1038/s41586-019-1111-9.

Gu, P., Wu, Y., Liu, G., Chengcheng, X., Gaoxu, W., Xia, J., Chen, K., Huang, X., et al. (2020). Application of Meteorological Element Combination-Driven Swat Model Based on Meteorological Datasets in Alpine Catchment: A Case Study in the Yellow River Source Region (China). *Authorea Preprints*.

Gudmundsson, L., Bremnes, J. B., Haugen, J. E., and Engen-Skaugen, T. (2012). Technical Note: Downscaling RCM Precipitation to the Station Scale Using Statistical Transformations; a Comparison of Methods. *Hydrology and Earth System Sciences* 16 (9), pp. 3383–3390. doi:10.5194/hess-16-3383-2012.

Gunda, T., Hess, D., Hornberger, G. M., and Worland, S. (2019). Water Security in Practice: The Quantity-Quality-Society Nexus. *Water Security* 6, p. 100022. doi:https://doi.org/10.1016/j.wasec.2018.100022.

Gündüz, O. (2015). Water Quality Perspectives in a Changing World. *Water Quality, Exposure and Health* 7 (1), pp. 1–3. doi:10.1007/s12403-015-0161-y.

Guppy, L., Uyttendaele, P., Villholth, K. G., and Smakhtin, V. U. (2018). Groundwater and Sustainable Development Goals: Analysis of Interlinkages. In: vol. 4. UNU-INWEH Report Series. United Nations University, p. 26.

Gupta, H. and Razavi, S. (2017). Challenges and Future Outlook of Sensitivity Analysis. In: *Sensitivity Analysis in Earth Observation Modelling*. Ed. by G. P. Petropoulos and P. K. Srivastava. 1st ed. Elsevier. Chap. 20, pp. 397–415. ISBN: 978-0-12-803011-0. doi:10.1016/b978-0-12-803011-0.00020-3.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F. (2009). Decomposition of the Mean Squared Error and Nse Performance Criteria: Implications for Improving Hydrological Modelling. *Journal of Hydrology* 377 (1-2), pp. 80–91. doi:10.1016/j.jhydrol.2009.08.003.

Gustafsson, K. M. and Lidskog, R. (2018). Boundary Organizations and Environmental Governance: Performance, Institutional Design, and Conceptual Development. *Climate Risk Management* 19, pp. 1–11. doi:https://doi.org/10.1016/j.crm.2017.11.001.

Gustard, A., Bullock, A., and Dixon, J. (1992). Low Flow Estimation in the United Kingdom. In: vol. 108. Institute of Hydrology. Growmarsh Gifford, Wallingford, United Kingdom.

Gutjahr, O. and Heinemann, G. (2013). Comparing Precipitation Bias Correction Methods for High-Resolution Regional Climate Simulations Using Cosmo-Clm. *Theoretical and Applied Climatology* 114 (3-4), pp. 511–529. doi:10.1007/s00704-013-0834-z.

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Hanasaki, N., Heinke, J., et al. (2013). Climate Change Impact on Available Water Resources Obtained Using Multiple Global Climate and Hydrology Models. *Earth Syst. Dynam.* 4 (1), pp. 129–144. doi:10.5194/esd-4-129-2013.

Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D., and Piani, C. (2011). Impact of a Statistical Bias Correction on the Projected Hydrological Changes Obtained from Three GCMs and Two Hydrology Models. *Journal of Hydrometeorology* 12 (4), pp. 556–578. doi:10.1175/2011jhm1336.1.

Hair, J., Black, W., Babin, B., and Anderson, R. (2013). Multivariate Data Analysis. Pearson Education Limited. ISBN: 9781292021904.

Hakala, K., Addor, N., Teutschbein, C., Vis, M., Dakhlaoui, H., and Seibert, J. (2019). Hydrological Modeling of Climate Change Impacts. In: *Encyclopedia of Water: Science, Technology, and Society*. Ed. by P. Maurice. ISBN: 9781119300762. doi:10.1002/9781119300762.wsts0062.

Hakimian, R. (2022). The Challenge of Building More Reservoirs to Ensure Uk's Water Resilience, New Civil Engineer. EMAP Publishing Limited. URL: https://www.newcivilengineer.com/latest/the-challenge-of-building-more-reservoirs-to-ensure-uks-water-resilience-01-09-2022/ (Accessed: 1.9.2022).

Hall, A. (2014). Projecting Regional Change. *Science* 346 (6216), pp. 1461–1462.

Hall, D. (2019). Public Ownership, Benefits and Compensation I: Benefits of Nationalisation of UK Water and Energy Girds and Legal and Economic Issues in Determining Compensation. In: University of Greenwich CREW Public Services International Research Unit. Greenwich, London, United Kingdom. URL: https://gala.gre.ac.uk/id/eprint/26026/.

Hall, D. (2022). Water and Sewerage Company Finances 2021: Dividends and Investment and Company Attempts to Hide Dividends. In: Public Services International Research Unit (PSIRU), University of Greenwich. Greenwich, London, United Kingdom. URL: https://gala.gre.ac.uk/id/eprint/34274/14/34274%20HALL_Water_and_Sewerage_Company_Finances_%28Rev.2%29_2021.pdf.

Hall, D. and Lobina, E. (2019). The Birth, Growth and Decline of Multinational Water Companies. In: *Water Services Management and Governance - Lessons for a Sustainable Future*. Ed. by T. S. Katko, P. S. Juuti, and K. Schwartz. IWA Publishing. London, United Kingdom. Chap. 11, pp. 123–132. ISBN: 9781780400730.

Hall, J. (2008). The Development of Ram 4 Abstraction Sensitivity Bands. In: Internal Report. Environment Agency. Bristol, United Kingdom.

Hamilton, L. C., Hartter, J., and Bell, E. (2019). Generation Gaps in Us Public Opinion on Renewable Energy and Climate Change. *PloS one* 14 (7), e0217608.

Hanasaki, N., Yoshikawa, S., Pokhrel, Y., and Kanae, S. (2018). A Global Hydrological Simulation to Specify the Sources of Water Used by Humans. *Hydrology and Earth System Sciences* 22 (1), pp. 789–817. doi:10.5194/hess-22-789-2018.

Hannaford, J., Mastrantonas, N., Vesuviano, G., and Turner, S. (2021). An Updated National-Scale Assessment of Trends in UK Peak River Flow Data: How Robust Are Observed Increases in Flooding? *Hydrology Research* 52 (3), pp. 699–718.

Hannaford, J., Mackay, J., Ascott, M., Bell, V., Chitson, T., Cole, S., Counsell, C., Durant, M., et al. (2022). Eflag: Enhanced Future Flows and Groundwater. A National Dataset of Hydrological Projections Based on UKCP18. *Earth Syst. Sci. Data Discuss.* 2022, pp. 1–40. doi:10.5194/essd-2022-40.

Hannaford, J. and Marsh, T. (2006). An Assessment of Trends in UK Runoff and Low Flows Using a Network of Undisturbed Catchments. *International Journal of Climatology* 26 (9), pp. 1237–1253. doi:10.1002/joc.1303.

Hannaford, J. (2015). Climate-Driven Changes in UK River Flows. *Progress in Physical Geography* 39 (1), pp. 29–48. doi:10.1177/0309133314536755.

Hannaford, J., Folland, C. K., Kendon, M. C., and Bloomfield, J. P. (2014). Multi-Annual Droughts in the Water-Stressed English Lowlands: Long-Term Variability and Climate Drivers. *Hydrology in a Changing World: Environmental and Human Dimensions*, p. 23.

Hannaford, J. and Harvey, C. L. (2010). UK Seasonal River Flow Variability in near-Natural Catchments, Regional Outflows and Long Hydrometric Records.

Hannah, D. M., Demuth, S., Lanen, H. A. J. van, Looser, U., Prudhomme, C., Rees, G., Stahl, K., and Tallaksen, L. M. (2011). Large-Scale River Flow Archives: Importance, Current Status and Future Needs. *Hydrological Processes* 25 (7), pp. 1191–1200. doi:10.1002/hyp.7794.

Hare, D. K., Helton, A. M., Johnson, Z. C., Lane, J. W., and Briggs, M. A. (2021). Continental-Scale Analysis of Shallow and Deep Groundwater Contributions to Streams. *Nature communications* 12 (1), pp. 1–10.

Hargrove, W. L. and Heyman, J. M. (2020). A Comprehensive Process for Stakeholder Identification and Engagement in Addressing Wicked Water Resources Problems. *Land* 9 (4), p. 119. doi:10.3390/land9040119.

Harrigan, S., Hannaford, J., Muchan, K., and Marsh, T. J. (2018). Designation and Trend Analysis of the Updated UK Benchmark Network of River Flow Stations: The Ukbn2 Dataset. *Hydrology Research* 49 (2), pp. 552–567. doi:10.2166/nh.2017.058.

Harris, N. M., Gurnell, A. M., Hannah, D. M., and Petts, G. E. (2000). Classification of River Regimes: A Context for Hydroecology. *Hydrological Processes* 14 (16-17), pp. 2831–2848. doi:doi10.1002/1099-1085(200011/12)14:16/17<2831::aid-hyp122>3.3.co;2-f.

Harvey, F. (2022). England 'Failing to Invest in Water Networks to Avoid Future Droughts'. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2022/aug/15/england-failing-to-invest-in-water-networks-to-avoid-future-droughts (Accessed: 14.2.2023).

Harvey, F. (2023). England Needs New Reservoirs or Food Supplies Will Be at Risk, Warns Nfu Chief. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2023/feb/23/england-needs-new-reservoirs-food-supplies-nfu-chief-farming-water-shortages (Accessed: 25.2.2023).

Harwood, A. J., Tickner, D., Richter, B. D., Locke, A., Johnson, S., and Yu, X. (2018). Critical Factors for Water Policy to Enable Effective Environmental Flow Implementation. *Frontiers in Environmental Science* 6. doi:10.3389/fenvs.2018.00037.

Hatchwell, P. and Rose, E. (2020). Our Better Nature: Why Strong Environmental Protections Matter. unchecked uk. URL: https://unchecked.uk/wp-content/uploads/2020/12/Our-Better-Nature-why-strong-environmental-protections-matter.pdf (Accessed: 12.8.2022).

Hattermann, F. F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., Fekete, B., Flörke, F., et al. (2018). Sources of Uncertainty in Hydrological Climate Impact Assessment: A Cross-Scale Study. *Environmental Research Letters* 13 (1). doi:10.1088/1748-9326/aa9938.

Hausfather, Z. and Peters, G. P. (2020). Emissions–the 'Business as Usual'story Is Misleading. *Nature* 577, pp. 618–620. doi:10.1038/d41586-020-00177-3.

Hayes, R., Austin, H., Cadman, D., Bradley, D., and Milner, N. (2017). Literature Review of Short-Term Flow Reduction Ecological Impacts and Recovery. In: vol. R16115QQ. APEM, Scottish Environmental Protection Agency.

HC (1997). Adas, Vol. 295, 9 June 1997. House of Commons, London, United Kingdom. URL: https://hansard.parliament.uk/commons/1997-06-09/debates/b72da10e-fff5-4333-aedd-cd29ff7ed8bf/Adas (Accessed: 13.10.2022).

Heikkila, T. (2017). Evidence for Tackling the Complexities of Water Governance. *Public Administration Review* 77 (1), pp. 17–20. doi:https://doi.org/10.1111/puar.12679.

Hellwig, J., Stoelzle, M., and Stahl, K. (2021). Groundwater and Baseflow Drought Responses to Synthetic Recharge Stress Tests. *Hydrol. Earth Syst. Sci.* 25 (2), pp. 1053–1068. doi:10.5194/hess-25-1053-2021.

Helm, D. (2008). Tradeable Rabs and the Split Cost of Capitatl. Commentary. URL: http://www.dieterhelm.co.uk/assets/secure/documents/7.pdf (Accessed: 23.2.2023).

Helm, D. (2020). Thirty Years after Water Privatization—Is the English Model the Envy of the World? *Oxford review of economic policy* 36 (1), pp. 69–85.

Helmecke, M., Fries, E., and Schulte, C. (2020). Regulating Water Reuse for Agricultural Irrigation: Risks Related to Organic Micro-Contaminants. *Environmental Sciences Europe* 32 (1). doi:10.1186/s12302-019-0283-0.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., and Piontek, F. (2013). A Trend-Preserving Bias Correction - the Isi-Mip Approach. *Earth System Dynamics* 4 (2), pp. 219–236. doi:10.5194/esd-4-219-2013.

Henriksen, J., Heasley, J., Kennen, J., and Nieswand, S. (2006). Users' Manual for the Hydroecological Integrity Assessment Process Software (Including the New Jersey Assessment Tools). In: vol. 1093. Open-File Report. Survey, U.S. Geological, p. 72.

Her, Y., Yoo, S.-H., Cho, J., Hwang, S., Jeong, J., and Seong, C. (2019). Uncertainty in Hydrological Analysis of Climate Change: Multi-Parameter Vs. Multi-GCM Ensemble Predictions. *Scientific Reports* 9 (1), p. 4974. doi:10.1038/s41598-019-41334-7.

Hiers, J. K., Jackson, S. T., Hobbs, R. J., Bernhardt, E. S., and Valentine, L. E. (2016). The Precision Problem in Conservation and Restoration. *Trends in Ecology Evolution* 31 (11), pp. 820–830. doi:10.1016/j.tree.2016.08.001.

Highways Act (1980). C. 66. UK Public General Acts. URL: https://libguides.city.ac.uk/Harvardreferencinglawresources/legislation.

Higley, L. G. and Pedigo, L. P. (1996). Economic Thresholds for Integrated Pest Management. Vol. 9. U of Nebraska Press. ISBN: 0803223633.

Hingray, B. and Saïd, M. (2014). Partitioning Internal Variability and Model Uncertainty Components in a Multimember Multimodel Ensemble of Climate Projections. *Journal of Climate* 27 (17), pp. 6779–6798. doi:10.1175/jcli-d-13-00629.1.

Hinkelman, L. M., Lapo, K. E., Cristea, N. C., and Lundquist, J. D. (2015). Using Ceres Syn Surface Irradiance Data as Forcing for Snowmelt Simulation in Complex Terrain. *Journal of Hydrometeorology* 16 (5), pp. 2133–2152. doi:10.1175/jhm-d-14-0179.1.

Hobbs, R. J., Higgs, E., and Harris, J. A. (2009). Novel Ecosystems: Implications for Conservation and Restoration. *Trends Ecol Evol* 24 (11), pp. 599–605. doi:10.1016/j.tree.2009.05.012.

Hoekstra, A. Y. and Wiedmann, T. O. (2014). Humanity's Unsustainable Environmental Footprint. *Science* 344 (6188), pp. 1114–1117. doi:10.1126/science.1248365.

Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual review of ecology and systematics*, pp. 1–23.

Hollis, D., McCarthy, M., Kendon, M., Legg, T., and Simpson, I. (2019). HadUK-Grid-a New UK Dataset of Gridded Climate Observations. *Geoscience Data Journal*. doi:10.1002/gdj3.78.

Holmes, N. T. H., Boon, P. J., and Rowell, T. A. (1998). A Revised Classification System for British Rivers Based on Their Aquatic Plant Communities. *Aquatic Conservation-Marine and Freshwater Ecosystems* 8 (4), pp. 555–578. doi:doi10.1002/(sici)1099-0755(199807/08)8:4<555::aid-aqc296>3.0.co;2-y.

Horne, A., Webb, A., Stewardson, M., Richter, B., and Acreman, M. (2017). Water for the Environment: From Policy and Science to Implementation and Management. Academic Press. ISBN: 0128039450.

Horne, A. C., Nathan, R., Poff, N. L., Bond, N. R., Webb, J. A., Wang, J., and John, A. (2019). Modeling Flow-Ecology Responses in the Anthropocene: Challenges for Sustainable Riverine Management. *BioScience* 69 (10), pp. 789–799. doi:10.1093/biosci/biz087.

Horne, B. D., Rutherford, E. S., and Wehrly, K. E. (2004). Simulating Effects of Hydro-Dam Alteration on Thermal Regime and Wild Steelhead Recruitment in a Stable-Flow Lake Michigan Tributary. *River Research and Applications* 20 (2), pp. 185–203.

Horton, H. (2022). Calls to Cut Bonuses for UK Water Bosses until Reservoirs Built and Leaks Fixed. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2022/aug/15/uk-water-boss-bonuses-reservoirs-built-leaks-fixed (Accessed: 13.2.2023).

Howarth, C., Parsons, L., and Thew, H. (2020). Effectively Communicating Climate Science Beyond Academia: Harnessing the Heterogeneity of Climate Knowledge. *One Earth* 2 (4), pp. 320–324. doi:https://doi.org/10.1016/j.oneear.2020.04.001.

Hrachowitz, M. and Clark, M. P. (2017). Hess Opinions: The Complementary Merits of Competing Modelling Philosophies in Hydrology. *Hydrol. Earth Syst. Sci.* 21 (8), pp. 3953–3973. doi:10.5194/hess-21-3953-2017.

Hu, S., Niu, Z., Chen, Y., Li, L., and Zhang, H. (2017). Global Wetlands: Potential Distribution, Wetland Loss, and Status. *Science of the total environment* 586, pp. 319–327.

Huang, S., Krysanova, V., and Hattermann, F. F. (2012). Projection of Low Flow Conditions in Germany under Climate Change by Combining Three RCMs and a Regional Hydrological Model. *Acta Geophysica* 61 (1), pp. 151–193. doi:10.2478/s11600-012-0065-1.

Hubert, L. and Arabie, P. (1985). Comparing Partitions. *Journal of Classification* 2 (2-3), pp. 193–218. doi:doi10.1007/bf01908075.

Hughes, A., Mansour, M., Ward, R., Kieboom, N., Allen, S., Seccombe, D., Charlton, M., and Prudhomme, C. (2021). The Impact of Climate Change on Groundwater Recharge: National-Scale Assessment for the British Mainland. *Journal of Hydrology* 598, p. 126336.

Hughes, A. G., Vounaki, T., Peach, D. W., Ireson, A. M., Jackson, C. R., Butler, A. P., Bloomfield, J. P., Finch, J., et al. (2011). Flood Risk from Groundwater: Examples from a Chalk Catchment in Southern England. *Journal of Flood Risk Management* 4 (3), pp. 143–155. doi:10.1111/j.1753-318x.2011.01095.x.

Hughes, D., Desai, A., Birkhead, A., and Louw, D. (2014). A New Approach to Rapid, Desktop-Level, Environmental Flow Assessments for Rivers in South Africa. *Hydrological Sciences Journal* 59 (3-4), pp. 673–687.

Hulme, M. and Barrow, E. (1997). Climate of the British Isles - Past, Present and Future.

Hurk, B. van den, Oldenborgh, G. J. van, Lenderink, G., Hazeleger, W., Haarsma, R., and Vries, H. de (2014). Drivers of Mean Climate Change around the Netherlands Derived from Cmip5. *Climate Dynamics* 42 (5), pp. 1683–1697. doi:10.1007/s00382-013-1707-y.

Hurrell, J. W. and Deser, C. (2010). North Atlantic Climate Variability: The Role of the North Atlantic Oscillation. *Journal of Marine Systems* 79 (3), pp. 231–244. doi:https://doi.org/10.1016/j.jmarsys.2009.11.002.

Hutchins, M. G., Abesser, C., Prudhomme, C., Elliott, J. A., Bloomfield, J. P., Mansour, M. M., and Hitt, O. E. (2018). Combined Impacts of Future Land-Use and Climate

Stressors on Water Resources and Quality in Groundwater and Surface Waterbodies of the Upper Thames River Basin, UK. *Sci Total Environ* 631-632, pp. 962–986. doi:10.1016/j.scitotenv.2018.03.052.

Hutton, G. (2019). Water Meters: The Rights of Customers and Water Companies. In: vol. CBP 7342. House of Commons Library. London, United Kingdom. URL: https://researchbriefings.files.parliament.uk/documents/CBP-7342/CBP-7342.pdf.

Iacob, O., Rowan, J. S., Brown, I., and Ellis, C. (2014). Evaluating Wider Benefits of Natural Flood Management Strategies: An Ecosystem-Based Adaptation Perspective. *Hydrology Research* 45 (6), pp. 774–787. doi:10.2166/nh.2014.184.

International Water Management Institute (2009). Flexible Water Storage Options: For Adaptation to Climate Change. 31. (IWMI)., International Water Management Institute. Colombo, Sri Lanka.

IPCC (2013). Technical Summary. In: Climate Chnage 2013: The Physical Science Basis. Contribution of Working Group I to the Fifths Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, USA: Stocker, T.F. and D. Qin, G.-K. and Plattner, M. and Tignor, S.K. and J., Allen and Boschung, A. and Nauels, Y. and Xia, V. Bex and Midgley, P.M.

IPCC (2014a). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, Ii and Iii to the Fifths Assessment Report of the Intergovernmental Panel on Climate Change. In: Intergovernmental Panel on Climate Change. Geneva, Switzerland: Pachauri, R.K. and Meyer, L.A.

IPCC (2014b). Wg Ii Technical Summary. In: Climate Change 2014: The Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifths Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, USA, pp. 35–94.

IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group Ii to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama.

Irwin, R., Dickinson, W., and Lammers, W. (1975). Model for the Determination of the Natural Streamflow of-Venison Creek. *Canadian agricultural engineering*.

Ison, R. L., Collins, K. B., and Wallis, P. J. (2015). Institutionalising Social Learning: Towards Systemic and Adaptive Governance. *Environmental Science Policy* 53, pp. 105–117. doi:https://doi.org/10.1016/j.envsci.2014.11.002.

Iyengar, S. and Massey, D. S. (2019). Scientific Communication in a Post-Truth Society. *Proceedings of the National Academy of Sciences* 116 (16), pp. 7656–7661. doi:doi:10.1073/pnas.1805868115.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., Braun, A., Colette, A., et al. (2014). Euro-Cordex: New High-Resolution Climate Change

Projections for European Impact Research. *Regional Environmental Change* 14 (2), pp. 563–578. doi:10.1007/s10113-013-0499-2.

Jacobs, K., Lebel, L., Buizer, J., Addams, L., Matson, P., McCullough, E., Garden, P., Saliba, G., et al. (2016). Linking Knowledge with Action in the Pursuit of Sustainable Water-Resources Management. *Proceedings of the National Academy of Sciences* 113 (17), pp. 4591–4596. doi:doi:10.1073/pnas.0813125107.

Jägermeyr, J., Pastor, A., Biemans, H., and Gerten, D. (2017). Reconciling Irrigated Food Production with Environmental Flows for Sustainable Development Goals Implementation. *Nature Communications* 8. doi:10.1038/ncomms15900.

Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J.-D., and Ross, A. (2016). Integrated Groundwater Management. Springer Nature. ISBN: 9781584883173.

Jessop, J. and Shackleton, J. (2019). Renationalisation: Back to the Future? *Institute of Economic Affairs Current Controversies* (72).

Jeyrani, F., Morid, S., and Srinivasan, R. (2021). Assessing Basin Blue–Green Available Water Components under Different Management and Climate Scenarios Using Swat. *Agricultural Water Management* 256, p. 107074. doi:https://doi.org/10.1016/j.agwat.2021.107074.

Jiang, S., Jomaa, S., Büttner, O., Meon, G., and Rode, M. (2015). Multi-Site Identification of a Distributed Hydrological Nitrogen Model Using Bayesian Uncertainty Analysis. *Journal of Hydrology* 529, pp. 940–950.

Jin, Y., Liu, J., Lin, L., Wang, A., and Chen, X. (2017). Exploring Hydrologically Similar Catchments in Terms of the Physical Characteristics of Upstream Regions. *Hydrology Research* 49 (5), pp. 1467–1483. doi:10.2166/nh.2017.191.

JNCC (2016). Common Standards Monitoring Guidance for Rivers. In: Peterborough, United Kingdom: Joint Nature Conservation Committee (JNCC), Peterborough, UK.

JNCC (2021). Ukbi - B7. Surface Water Status. URL: https://jncc.gov.uk/our-work/ukbi-b7-surface-water-status/#key-results-figure-b7i-status-classification-of-uk-surface-water-bodies-under-the-water-framework-directive-2009-to-2020 (Accessed: 22.2.2023).

JNCC (2022). UK Biodiversity Indicators 2022. Indicator B7 – Surface Water Status 2021. Joint Nature Conservation Committee (JNCC), Peterborough, UK. URL: https://data.jncc.gov.uk/data/b6dbbc22-235a-4664-8192-3a178d32ffde/ukbi2022-ds-b7.xlsx (Accessed: 23.1.2023).

John, A., Horne, A., Nathan, R., Stewardson, M., Webb, J. A., Wang, J., and Poff, N. L. (2021). Climate Change and Freshwater Ecology: Hydrological and Ecological Methods of Comparable Complexity Are Needed to Predict Risk. *Wiley Interdisciplinary Reviews: Climate Change* 12 (2), e692.

Johnson, R. and Wichern, D. (2007). Applied Multivariate Statistical Analysis. Upper Saddle River, NJ, United States of America: Pearson Education Inc. ISBN: 0135143500.

Johnston, C. (1999). Development and Evaluation of Infilling Methods for Missing Hydrologic and Chemical Watershed Monitoring Data. Department of Civil and Environmental Engineering. Master of Science in Environmental Engineering. Falls Church, Virginia: Virginia Polytechnic Institute and State University.

Jones, R. N. (2001). An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments. *Natural Hazards* 23 (2-3), pp. 197–230. doi:doi10.1023/a:1011148019213.

Joseph, J., Ghosh, S., Pathak, A., and Sahai, A. (2018). Hydrologic Impacts of Climate Change: Comparisons between Hydrological Parameter Uncertainty and Climate Model Uncertainty. *Journal of Hydrology* 566, pp. 1–22.

Judd, A. and Lonsdale, J.-A. (2021). Applying Systems Thinking: The Ecosystem Approach and Natural Capital Approach – Convergent or Divergent Concepts in Marine Management? *Marine Policy* 129, p. 104517. doi:https://doi.org/10.1016/j.marpol.2021.104517.

Karim, I. and Ali, M. (2017). Artificial Recharge of Groundwater by Injection Wells (Case Study). *International Journal of Scientific Engineering and Technology Research* 6 (31), pp. 6193–6196.

Kaufmann, L. and Rousseeuw, P. (1990). Finding Groups in Data: An Introduction to Cluster Analysis. New York, NY, USA: John Wiley Sons, Inc. ISBN: 9780471878766. doi:10.1002/9780470316801.

Kaushal, N., Babu, S., Mishra, A., Ghosh, N., Tare, V., Kumar, R., Sinha, P. K., and Verma, R. U. (2019). Towards a Healthy Ganga—Improving River Flows through Understanding Trade Offs. *Frontiers in Environmental Science* 7, p. 83.

Kaushal, S. S., Gold, A. J., and Mayer, P. M. (2017). Land Use, Climate, and Water Resources—Global Stages of Interaction. *Water* 9 (10), p. 815.

Kay, A. L. and Jones, R. G. (2012). Comparison of the Use of Alternative UKCP09 Products for Modelling the Impacts of Climate Change on Flood Frequency. *Climatic Change* 114 (2), pp. 211–230. doi:10.1007/s10584-011-0395-z.

Kay, A., Watts, G., Wells, S. C., and Allen, S. (2019). The Impact of Climate Change on U. K. River Flows: A Preliminary Comparison of Two Generations of Probabilistic Climate Projections. *Hydrological Processes* 34 (4), pp. 1081–1088. doi:10.1002/hyp.13644.

Kay, A. L. (2021). Simulation of River Flow in Britain under Climate Change: Baseline Performance and Future Seasonal Changes. *Hydrological Processes* 35 (4). doi:10.1002/hyp.14137.

Kennard, M. J., Mackay, S. J., Pusey, B. J., Olden, J. D., and Marsh, N. (2010a). Quantifying Uncertainty in Estimation of Hydrologic Metrics for Ecohydrological Studies. *River Research and Applications* 26 (2), pp. 137–156. doi:10.1002/rra.1249.

Kennard, M. J., Pusey, B. J., Olden, J. D., MacKay, S. J., Stein, J. L., and Marsh, N. (2010b). Classification of Natural Flow Regimes in Australia to Support Environmental Flow Management. *Freshwater Biology* 55 (1), pp. 171–193. doi:10.1111/j.1365-2427.2009.02307.x.

Kennen, J. G., Stein, E. D., and Webb, J. A. (2018). Evaluating and Managing Environmental Water Regimes in a Water-Scarce and Uncertain Future. *Freshwater Biology*. doi:10.1111/fwb.13104.

Kent Wildlife Trust (2019). H2o:Source2sea. URL: https://www.kentwildlifetrust.org.uk/get-involved/our-projects/h2osource2sea (Accessed: 10.11.2022).

Kern, F. and Markard, J. (2016). Analysing Energy Transitions: Combining Insights from Transition Studies and International Political Economy. In: *The Palgrave Handbook of the International Political Economy of Energy*. Springer, pp. 291–318.

Kern, F., Rogge, K. S., and Howlett, M. (2019). Policy Mixes for Sustainability Transitions: New Approaches and Insights through Bridging Innovation and Policy Studies. *Research Policy* 48 (10), p. 103832. doi:https://doi.org/10.1016/j.respol.2019.103832.

Kiesel, J., Stanzel, P., Kling, H., Fohrer, N., Jähnig, S. C., and Pechlivanidis, I. (2020). Streamflow-Based Evaluation of Climate Model Sub-Selection Methods. *Climatic Change* 163 (3), pp. 1267–1285.

Kim, N. W., Chung, I. M., Won, Y. S., and Arnold, J. G. (2008). Development and Application of the Integrated Swat–Modflow Model. *Journal of hydrology* 356 (1-2), pp. 1–16.

Kim, T. J. and Wurbs, R. A. (2011). Development of Monthly Naturalized Flow Using Water Rights Analysis Package (Wrap)-Based Methods. *Ksce Journal of Civil Engineering* 15 (7), pp. 1299–1307. doi:10.1007/s12205-011-1184-y.

King, A. J., Gawne, B., Beesley, L., Koehn, J. D., Nielsen, D. L., and Price, A. (2015). Improving Ecological Response Monitoring of Environmental Flows. *Environmental Management* 55 (5), pp. 991–1005.

Kiprotich, P., Wei, X., Zhang, Z., Ngigi, T., Qiu, F., and Wang, L. (2021). Assessing the Impact of Land Use and Climate Change on Surface Runoff Response Using Gridded Observations and Swat+. *Hydrology* 8 (1). doi:10.3390/hydrology8010048.

Klaar, M. J., Carver, S., and Kay, P. (2020). Land Management in a Post-Brexit UK: An Opportunity for Integrated Catchment Management to Deliver Multiple Benefits? *WIREs Water* 7 (5), e1479. doi:https://doi.org/10.1002/wat2.1479.

Klaar, M. J., Dunbar, M. J., Warren, M., and Soley, R. (2014). Developing Hydroecological Models to Inform Environmental Flow Standards: A Case Study from England. *Wiley Interdisciplinary Reviews: Water* 1 (2), pp. 207–217. doi:10.1002/wat2.1012.

Knekta, E., Runyon, C., and Eddy, S. (2019). One Size Doesn't Fit All: Using Factor Analysis to Gather Validity Evidence When Using Surveys in Your Research. *CBE life sciences education* 18 (1), rm1–rm1. doi:10.1187/cbe.18-04-0064.

Knouft, J. H. and Ficklin, D. L. (2017). The Potential Impacts of Climate Change on Biodiversity in Flowing Freshwater Systems. *Annual Review of Ecology, Evolution, and Systematics* 48, pp. 111–133. doi:10.1146/annurev-ecolsys-110316-022803.

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., and Meehl, G. A. (2010). Challenges in Combining Projections from Multiple Climate Models. *Journal of Climate* 23 (10), pp. 2739–2758. doi:10.1175/2009jcli3361.1.

Knutti, R., Masson, D., and Gettelman, A. (2013). Climate Model Genealogy: Generation Cmip5 and How We Got There. *Geophysical Research Letters* 40 (6), pp. 1194–1199. doi:https://doi.org/10.1002/grl.50256.

Knutti, R. and Sedláček, J. (2013). Robustness and Uncertainties in the New Cmip5 Climate Model Projections. *Nature climate change* 3 (4), pp. 369–373.

Kopf, R. K., Finlayson, C. M., Humphries, P., Sims, N. C., and Hladyz, S. (2015). Anthropocene Baselines: Assessing Change and Managing Biodiversity in Human-Dominated Aquatic Ecosystems. *BioScience* 65 (8), pp. 798–811. doi:10.1093/biosci/biv092.

Kouchi, D. H., Esmaili, K., Faridhosseini, A., Sanaeinejad, S. H., Khalili, D., and Abbaspour, K. C. (2017). Sensitivity of Calibrated Parameters and Water Resource Estimates on Different Objective Functions and Optimization Algorithms. *Water* 9 (6), p. 384. doi:10.3390/w9060384.

Krause, F. and Strang, V. (2016). Thinking Relationships through Water. *Society Natural Resources* 29 (6), pp. 633–638. doi:10.1080/08941920.2016.1151714.

Krause, P., Boyle, D., and Bäse, F. (2005). Comparison of Different Efficiency Criteria for Hydrological Model Assessment. *Advances in Geosciences* 5 (89-97).

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., et al. (2017). Fossil-Fueled Development (Ssp5): An Energy and Resource Intensive Scenario for the 21st Century. *Global Environmental Change* 42, pp. 297–315. doi:https://doi.org/10.1016/j.gloenvcha.2016.05.015.

Kruskal, W. H. and Wallis, W. A. (1952). Use of Ranks in One-Criterion Variance Analysis. *Journal of the American Statistical Association* 47 (260), pp. 583–621. doi:10.1080/01621459.1952.10483441.

Krysanova, V. and Hattermann, F. F. (2017). Intercomparison of Climate Change Impacts in 12 Large River Basins: Overview of Methods and Summary of Results. *Climatic Change* 141 (3), pp. 363–379. doi:10.1007/s10584-017-1919-y.

Krysanova, V. and White, M. (2015). Advances in Water Resources Assessment with Swat—an Overview. *Hydrological Sciences Journal*, pp. 1–13. doi:10.1080/02626667.2015.1029482.

Kundzewicz, Z. W. and Krysanova, V. (2010). Climate Change and Stream Water Quality in the Multi-Factor Context. *Climatic Change* 103 (3-4), pp. 353–362. doi:10.1007/s10584.010.9822.9.

Kundzewicz, Z. W., Krysanova, V., Benestad, R. E., Hov, Ø., Piniewski, M., and Otto, I. M. (2018). Uncertainty in Climate Change Impacts on Water Resources. *Environmental Science & Policy* 79, pp. 1–8. doi:10.1016/j.envsci.2017.10.008.

Kuriqi, A., Pinheiro, A. N., Sordo-Ward, A., Bejarano, M. D., and Garrote, L. (2021). Ecological Impacts of Run-of-River Hydropower Plants—Current Status and Future Prospects on the Brink of Energy Transition. *Renewable and Sustainable Energy Reviews* 142, p. 110833.

Lafaysse, M., Hingray, B., Mezghani, A., Gailhard, J., and Terray, L. (2014). Internal Variability and Model Uncertainty Components in Future Hydrometeorological Projections: The Alpine Durance Basin. *Water resources research* 50 (4), pp. 3317–3341.

Laizé, C. L. R., Acreman, M. C., Schneider, C., Dunbar, M. J., Houghton-Carr, H. A., Flörke, M., and Hannah, D. M. (2014). Projected Flow Alteration and Ecological Risk for Pan-European Rivers. *River Research and Applications* 30 (3), pp. 299–314. doi:10.1002/rra.2645.

Laizé, C., Acreman, M., and Overton, I. (2017). Projected Novel Eco-Hydrological River Types for Europe. *Ecohydrology Hydrobiology* 17 (1), pp. 73–83. doi:10.1016/j.ecohyd.2016.12.006.

Landres, P. B., Morgan, P., and Swanson, F. J. (1999). Overview of the Use of Natural Variability Concepts in Managing Ecological Systems. *Ecological applications* 9 (4), pp. 1179–1188.

Lange, B., Bendall, B., and Williams, P. (2019). Managing Water Resources - Incorporating Drought and Water Scarctity - as Part of the Catchment Based Approach. In: Managing the Risks, Impacts and Uncertainties of drought and water Scarcity (MaRIUS). Centre for Socio-Legal Studies, University of Oxford. Oxford, United Kingdom. URL: www.mariusdroughtproject.org.

Lange, B. and Gouldson, A. (2010). Trust-Based Environmental Regulation. *Science of the total environment* 408 (22), pp. 5235–5243.

Larson, K. L. and Brumand, J. (2014). Paradoxes in Landscape Management and Water Conservation: Examining Neighborhood Norms and Institutional Forces. *Cities and the Environment (CATE)* 7 (1), p. 6.

Lathouri, M., England, J., Dunbar, M. J., Hannah, D. M., and Klaar, M. (2021). A River Classification Scheme to Assess Macroinvertebrate Sensitivity to Water Abstraction Pressures. *Water and Environment Journal* 35 (4), pp. 1226–1238. doi:10.1111/wej.12712.

Laville, S. (2022). England's Water Can Be Renationalised without Compensation, Activists Say. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2022/dec/02/water-renationalised-without-compensation-activists-shareholders-england (Accessed: 22.2.2023).

Lawson, C., Rothero, E., Gowing, D., Nisbet, T., N., B., Broadmeadow, S., and Skinner, A. (2018). The Natural Capital of Floodplains: Management, Protection and Restoration to Deliver Greater Benefits. In: vol. VNP09. Valuing Nature Natural Capital Synthesis Report. URL: https://valuing-nature.net/sites/default/files/documents/Synthesis_reports/VNP09-NatCapSynthesisReport-Floodplains-A4-16pp-144dpi.pdf.

Lawson, E., Farmani, R., Woodley, E., and Butler, D. (2020). A Resilient and Sustainable Water Sector: Barriers to the Operationalisation of Resilience. *Sustainability* 12 (5). doi:10.3390/su12051797.

Le Moine, N. (2008). Le Bassin Versant De Surface Vu Par Le Souterrain: Une Voie D'amélioration Des Performances Et Du Réalisme Des Modèles Pluie-Débit ? Doctor of Phylosophy. Paris, France: Université Pierre et Marie Curie.

Leach, A., Aguilar García, C., and Laville, S. (2022). Revealed: More Than 70% of English Water Industry Is in Foreign Ownership. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2022/nov/30/more-than-70-per-cent-english-water-industry-foreign-ownership (Accessed: 7.2.2023).

Lebart, L., Morineau, A., and Piron, M. (2000). Statistique Exploratoire Multidimensionelle. Paris, France: Dunod. ISBN: 2100053515.

Lee, M.-H. and Bae, D.-H. (2016). Uncertainty Assessment of Future High and Low Flow Projections According to Climate Downscaling and Hydrological Models. *Procedia Engineering* 154, pp. 617–623.

Lehner, F. and Coats, S. (2021). Does Regional Hydroclimate Change Scale Linearly with Global Warming? *Geophysical Research Letters* 48 (23), e2021GL095127. doi:https://doi.org/10.1029/2021gl095127.

Leigh, C. and Datry, T. (2017). Drying as a Primary Hydrological Determinant of Biodiversity in River Systems: A Broad-Scale Analysis. *Ecography* 40 (4), pp. 487–499.

Lemos, M. C. (2015). Usable Climate Knowledge for Adaptive and Co-Managed Water Governance. *Current Opinion in Environmental Sustainability* 12, pp. 48–52. doi:https://doi.org/10.1016/j.cosust.2014.09.005.

Lenderink, G., Buishand, A., and Deursen, W. van (2007). Estimates of Future Discharges of the River Rhine Using Two Scenario Methodologies: Direct Versus Delta Approach. *Hydrol. Earth Syst. Sci.* 11 (3), pp. 1145–1159. doi:10.5194/hess-11-1145-2007.

Letcher, R. A., Croke, B. F. W., and Jakeman, A. J. (2007). Integrated Assessment Modelling for Water Resource Allocation and Management: A Generalised Conceptual Framework. *Environmental Modelling Software* 22 (5), pp. 733–742. doi:https://doi.org/10.1016/j.envsoft.2005.12.014.

Levene, H. (1960). Robust Tests for Equality of Variances. In: *Contributions to Probability and Statistics Essays in Honor of Harold Hotelling*. Ed. by I. Olkin, S. G. Churye, W. Hoeffding, W. G. Madow, and H. B. Mann. Stanford Studies in Mathematics and Statistics. Stanford University Press, pp. 278–292.

Lewandowski, J., Meinikmann, K., and Krause, S. (2020). Groundwater–Surface Water Interactions: Recent Advances and Interdisciplinary Challenges. *Water* 12 (1), p. 296.

Liersch, S., Drews, M., Pilz, T., Salack, S., Sietz, D., Aich, V., A D Larsen, M., Gädeke, A., et al. (2020). One Simulation, Different Conclusions—the Baseline Period Makes the Difference! *Environmental Research Letters* 15 (10), p. 104014. doi:10.1088/1748-9326/aba3d7.

Lin, H.-E. and McDonough, E. F. (2014). Cognitive Frames, Learning Mechanisms, and Innovation Ambidexterity. *Journal of Product Innovation Management* 31, pp. 170–188.

Lobanova, A., Liersch, S., Nunes, J. P., Didovets, I., Stagl, J., Huang, S., Koch, H., Rivas López, M. d. R., et al. (2018). Hydrological Impacts of Moderate and High-End Climate Change across European River Basins. *Journal of Hydrology: Regional Studies* 18, pp. 15–30. doi:10.1016/j.ejrh.2018.05.003.

Lobina, E. (2019). UK: Strong and Weak Lock-in of Water Governance Outcomes in England. In: *Facing the Challenges of Water Governance*. Ed. by S. Porcher and S. Saussier. Palgrave Studies in Water Governance: Policy and Practice. Palgrave Macmillan. Basingstoke and New York, pp. 155–188. ISBN: 3319985140. doi:10.1007/978-3-319-98515-2_7.

Lobina, E. and Hall, D. (2008). The Illusions of Competition in the Water Sector: A Response to the Ofwat/Cave Consultations on Introducing Competition in the Water Sec-

tor in England and Wales. In: PSIRU Reports. Public Services International Research Unit (PSIRU), Business Faculty, University of Greenwich. Greenwich, London, United Kingdom.

Loftus, A. and March, H. (2019a). Integrating What and for Whom? Financialisation and the Thames Tideway Tunnel. *Urban Studies* 56 (11), pp. 2280–2296.

Loftus, A. and March, H. (2019b). Integrating What and for Whom? Financialisation and the Thames Tideway Tunnel. *Urban Studies* 56 (11), pp. 2280–2296.

Lowe, J. A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., et al. (2018). UKCP18 Science Overview Report. In: Met Office Hadley Centre. Exeter, United Kingdom.

Lowe, L., Szemis, J., and Webb, J. A. (2017). Uncertainty and Environmental Water. In: *Water for the Environment*. Ed. by A. C. Horne, J. A. Webb, M. J. Stewardson, B. Richter, and M. Acreman. Academic Press. Chap. 15, pp. 317–344. ISBN: 978-0-12-803907-6. doi:https://doi.org/10.1016/b978-0-12-803907-6.00015-2.

Lowndes, V., Pratchett, L., and Stoker, G. (2006). Diagnosing and Remedying the Failings of Official Participation Schemes: The Clear Framework. *Social Policy and Society* 5 (2), pp. 281–291. doi:10.1017/s1474746405002988.

Lubchenco, J., Barner, A. K., Cerny-Chipman, E. B., and Reimer, J. N. (2015). Sustainability Rooted in Science. *Nature Geoscience* 8 (10), pp. 741–745. doi:10.1038/ngeo2552.

Ludwig, F., Slobbe, E. van, and Cofino, W. (2014). Climate Change Adaptation and Integrated Water Resource Management in the Water Sector. *Journal of Hydrology* 518, pp. 235–242.

Lund, J. R. (2015). Integrating Social and Physical Sciences in Water Management. *Water Resources Research* 51 (8), pp. 5905–5918.

Lütkenhorst, W., Altenburg, T., Pegels, A., and Vidican, G. (2014). Green Industrial Policy: Managing Transformation under Uncertainty. *Deutsches Institut für Entwicklungspolitik Discussion Paper* 28.

Lytle, D. A., Merritt, D. M., Tonkin, J. D., Olden, J. D., and Reynolds, L. V. (2017). Linking River Flow Regimes to Riparian Plant Guilds: A Community-Wide Modeling Approach. *Ecological Applications* 27 (4), pp. 1338–1350. doi:10.1002/eap.1528.

Lytle, D. A. and Poff, N. L. (2004). Adaptation to Natural Flow Regimes. *Trends in ecology evolution* 19 (2), pp. 94–100.

Macnaughton, C. J., Senay, C., Dolinsek, I., Bourque, G., Maheu, A., Lanthier, G., Harvey-Lavoie, S., Asselin, J., et al. (2016). Using Fish Guilds to Assess Community Responses to Temperature and Flow Regimes in Unregulated and Regulated Canadian Rivers. *Freshwater Biology* 61 (10), pp. 1759–1772. doi:https://doi.org/10.1111/fwb.12815.

Malhotra, S. (2017). Horticultural Crops and Climate Change: A Review. *Indian Journal of Agricultural Sciences* 87 (1), pp. 12–22. doi:wos:000393015200002.

Mansour, M. M., Hughes, A. G., Robins, N. S., Ball, D., and Okoronkwo, C. (2012). The Role of Numerical Modelling in Understanding Groundwater Flow in Scottish Alluvial

Aquifers. *Geological Society, London, Special Publications* 364 (1), pp. 85–98. doi:doi:10.1144/sp364.7.

Maraun, D. (2016). Bias Correcting Climate Change Simulations - a Critical Review. *Current Climate Change Reports* 2 (4), pp. 211–220. doi:10.1007/s40641-016-0050-x.

Maraun, D. (2013). Bias Correction, Quantile Mapping, and Downscaling: Revisiting the Inflation Issue. *Journal of Climate* 26 (6), pp. 2137–2143. doi:10.1175/jcli-d-12-00821.1.

Maron, M., McAlpine, C. A., Watson, J. E. M., Maxwell, S., and Barnard, P. (2015). Climate-Induced Resource Bottlenecks Exacerbate Species Vulnerability: A Review. *Diversity and Distributions* 21 (7), pp. 731–743. doi:https://doi.org/10.1111/ddi.12339.

Marquardt, D. (1963). An Algorithm for Least-Squares Estimation of Nonlinear Parameters. *Journal of the Society for Industrial and Applied Mathematics* 11 (2), pp. 431–441. doi:10.1137/0111030.

Marsh, T. (2002). Capitalising on River Flow Data to Meet Changing National Needs - a UK Perspective. *Flow Measurement and Instrumentation* 13, pp. 291–298.

Marsh, T., Cole, G., and Wilby, R. (2007). Major Droughts in England and Wales, 1800-2006. *Weather* 62 (4), pp. 87–93.

Marsh, T., Parry, S., Kendon, M., and Hannaford, J. (2013). The 2010-12 Drought and Subsequent Extensive Flooding: A Remarkable Hydrological Transformation. NERC/-Centre for Ecology & Hydrology (CEH). ISBN: 1906698449.

Martin-Ortega, J., Mesa-Jurado, M. A., Pineda-Vazquez, M., and Novo, P. (2019). Nature Commodification: 'A Necessary Evil'? An Analysis of the Views of Environmental Professionals on Ecosystem Services-Based Approaches. *Ecosystem Services* 37. doi:10.1016/j.ecoser.2019.100926.

Martin-Ortega, J., Perni, A., Jackson-Blake, L., Balana, B. B., McKee, A., Dunn, S., Helliwell, R., Psaltopoulos, D., et al. (2015). A Transdisciplinary Approach to the Economic Analysis of the European Water Framework Directive. *Ecological Economics* 116, pp. 34–45. doi:10.1016/j.ecolecon.2015.03.026.

Maurer, E. P., Brekke, L. D., and Pruitt, T. (2010). Contrasting Lumped and Distributed Hydrology Models for Estimating Climate Change Impacts on California Watersheds 1. *JAWRA Journal of the American Water Resources Association* 46 (5), pp. 1024–1035.

McClain, M. E., Kashaigili, J. J., and Ndomba, P. (2013). Environmental Flow Assessment as a Tool for Achieving Environmental Objectives of African Water Policy, with Examples from East Africa. *International Journal of Water Resources Development* 29 (4), pp. 650–665.

McDonnell, R. A. (2008). Challenges for Integrated Water Resources Management: How Do We Provide the Knowledge to Support Truly Integrated Thinking? *International Journal of Water Resources Development* 24 (1), pp. 131–143. doi:10.1080/07900620701723240.

McFarlane, N. (2011). Parameterizations: Representing Key Processes in Climate Models without Resolving Them. *Wiley Interdisciplinary Reviews: Climate Change* 2 (4), pp. 482–497.

McGregor, G. R. (2019). Climate and Rivers. *River Research and Applications*. doi:10.1002/rra.3508.

McKay, M., Beckman, R., and Conover, W. (1979). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics* 21 (2), pp. 239–245. doi:10.2307/1268522.

McMillan, H. K., Westerberg, I. K., and Krueger, T. (2018). Hydrological Data Uncertainty and Its Implications. *Wiley Interdisciplinary Reviews: Water* 5 (6), e1319.

Mechoso, C. R. and Arakawa, A. (2003). General Circulation Models. In: *Encyclopedia of Atmospheric Sciences*. Ed. by J. R. Holton. Academic Press. Oxford, pp. 861–869. ISBN: 978-0-12-227090-1. doi:https://doi.org/10.1016/b0-12-227090-8/00157-3.

Medema, W., McIntosh, B. S., and Jeffrey, P. J. (2008). From Premise to Practice: A Critical Assessment of Integrated Water Resources Management and Adaptive Management Approaches in the Water Sector. *Ecology and Society* 13 (2).

Meehl, G. A., Senior, C. A., Eyring, V., Flato, G., Lamarque, J.-F., Stouffer, R. J., Taylor, K. E., and Schlund, M. (2020). Context for Interpreting Equilibrium Climate Sensitivity and Transient Climate Response from the Cmip6 Earth System Models. *Science Advances* 6 (26), eaba1981.

Mensah, J. K., Ofosu, E. A., Yidana, S. M., Akpoti, K., and Kabo-bah, A. T. (2022). Integrated Modeling of Hydrological Processes and Groundwater Recharge Based on Land Use Land Cover, and Climate Changes: A Systematic Review. *Environmental Advances* 8, p. 100224. doi:https://doi.org/10.1016/j.envadv.2022.100224.

Mercer, H. and Whitfield, D. (2018). Nationalising Special Purpose Vehicles to End Pfi: A Discussion of the Costs and Benefits. In: vol. 3. PSIRU Reports. Public Services International Research Unit (PSIRU), Business Faculty, University of Greenwich. Greenwich, London, United Kingdom.

Met Office (2018a). HadUK-Grid Gridded Climate Observations on a 1km Grid over the UK for 1862-2017. Centre for Environmental Data Analysis. URL: http://catalogue.ceda.ac.uk/uuid/2a62652a4fe6412693123dd6328f6dc8 (Accessed: 1.4.2019).

Met Office (2018b). UKCP18 Guidance: How to Use the UKCP18 Land Projections. Met Office. URL: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---how-to-use-the-land-projections.pdf (Accessed: 11.2.2023).

Met Office (2019). MIDAS Open: UK Hourly Weather Observation Data V201901. Centre for Environmental Data Analysis. URL: http://dx.doi.org/10.5285/c58c1af69b9745fda4cdf487a9547185 (Accessed: 1.3.2019).

Met Office (2021a). Charting the Uk's Changing Climate. Madge, G., Met Office, Exeter, United Kingdom. URL: https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/9120-new-climate-normal (Accessed: 30.1.2023).

Met Office (2021b). UKCP18 Guidance: Data Availability, Access and Formats. Met Office, Exeter, United Kingdom. URL: https://www.metoffice.gov.uk/binaries/content/

assets/metofficegovuk/pdf/research/ukcp/ukcp18_data_availability_jul-2021.pdf (Accessed: 10.6.2022).

Met Office (2023). Met Office: England Rainfall (mm) Areal Series, Starting from 1910. Met Office, Exeter, United Kingdom. URL: https://www.metoffice.gov.uk/pub/data/weather/uk/climate/datasets/Rainfall/date/England.txt (Accessed: 30.1.2023).

Metzenbaum, S. H. and Vasisht, G. (2015). What Makes a Regulator Excellent? Mission, Funding, Information, and Judgment. *Penn Program on Regulation's Best-in-Class Regulator Initiative*.

Michalak, A. M. (2016). Study Role of Climate Change in Extreme Threats to Water Quality. *Nature* 535 (7612), pp. 349–350. doi:10.1038/535349a.

Middleton, M. and Allen, D. (2017). Assessment of Hydraulic Connectivity Related to Groundwater Extraction on Selected Sensitive Steams: Stream Vulnerability Mapping. *Water Science Series, WSS2017-04. Prov. BC, Victoria BC*.

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., and Smith, L. C. (2008). Climatic and Anthropogenic Factors Affecting River Discharge to the Global Ocean, 1951-2000. *Global and Planetary Change* 62 (3-4), pp. 187–194. doi:10.1016/j.gloplacha.2008.03.001.

Milly P.C.D. Betancourt, J., Falkenmark, M., Hirsch, R., Kundzewicz, Z. W., Lettenmaier, D., and Stouffer, R. (2008). Stationarity Is Dead: Whither Water Management? *Science* 319 (5863), pp. 573–574.

Mizukami, N., Rakovec, O., Newman, A., Clark, M., Wood, A., Gupta, H., and Kumar, R. (2018). On the Choice of Calibration Metrics for "High-Flow" Estimation Using Hydrological Models. *Hydrology and Earth System Sciences* 23, pp. 2601–2614.

Molle, F. (2006). Planning and Managing Water Resources at the River-Basin Level: Emergence and Evolution of a Concept. Vol. 16. IWMI. ISBN: 9290906529.

Molnar, P., Burlando, P., and Ruf, W. (2002). Integrated Catchment Assessment of Riverine Landscape Dynamics. *Aquatic Sciences* 64 (2), pp. 129–140. doi:10.1007/s00027-002-8061-1.

Monk, W. A., Wood, P. J., Hannah, D. M., and Wilson, D. A. (2007). Selection of River Flow Indices for the Assessment of Hydroecological Change. *River Research and Applications* 23 (1), pp. 113–122. doi:10.1002/rra.964.

Monk, W. A., Wood, P. J., Hannah, D. M., Wilson, D. A., Extence, C. A., and Chadd, R. P. (2006). Flow Variability and Macroinvertebrate Community Response within Riverine Systems. *River Research and Applications* 22 (5), pp. 595–615. doi:10.1002/rra.933.

Moodys (2017). Gb Water and Regulated Energy Networks: Faq on Labour's Proposed Renationalisation. URL: https://app.researchpool.com/provider/moodys-investors-service/gb-water-and-regulated-energy-networks-faq-on-labours-proposed-renatio (Accessed: 25.2.2023).

Moore, R., Morris, D., and Flavin, R. (1994). Sub-Set of UK Digital 1:50,000 Scale River Centre-Line Network. URL: https://www.ceh.ac.uk/data/15000-watercourse-network (Accessed: 15.6.2019).

Morgan, J. and Nasir, M. A. (2021). Financialised Private Equity Finance and the Debt Gamble: The Case of Toys R Us. *New Political Economy* 26 (3), pp. 455–471. doi:10.1080/13563467.2020.1782366.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L. (2007). Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Transactions of the Asabe* 50 (3), pp. 885–900.

Mosley, L. M. (2015). Drought Impacts on the Water Quality of Freshwater Systems; Review and Integration. *Earth-Science Reviews* 140, pp. 203–214. doi:10.1016/j.earscirev.2014.11.010.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Vuuren, D. P. van, Carter, T. R., Emori, S., et al. (2010). The Next Generation of Scenarios for Climate Change Research and Assessment. *Nature* 463 (7282), pp. 747–56. doi:10.1038/nature08823.

Moss, R. H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J. A., Elgizouli, I., Emori, S., et al. (2008). Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. In: *Conference: IPCC Expert Meeting Report: Towards New Scenarios*. Ed. by P. N. N. L. (PNNL). Richland (WA), United States: IPCC.

Moulds, S., Slater, L., and Dunstone, N. (2022). Improving Decadal Flood Prediction in Northern Europe by Selecting Ensemble Members Based on North Atlantic Oscillation Skill. *EGU General Assembly, Vienna, Austria (23-27 May, 2022)*. doi:10.5194/egusphere-egu22-6158.

Moyle, P. B. and Mount, J. F. (2007). Homogenous Rivers, Homogenous Faunas. *Proceedings of the National Academy of Sciences* 104 (14), pp. 5711–5712.

Müller Schmied, H., Cáceres, D., Eisner, S., Flörke, M., Herbert, C., Niemann, C., Peiris, T. A., Popat, E., et al. (2021). The Global Water Resources and Use Model Watergap V2.2d: Model Description and Evaluation. *Geosci. Model Dev.* 14 (2), pp. 1037–1079. doi:10.5194/gmd-14-1037-2021.

Murphy, J. M., Booth, B. B. B., Collins, M., Harris, G. R., Sexton, D. M. H., and Webb, M. J. (2007). A Methodology for Probabilistic Predictions of Regional Climate Change from Perturbed Physics Ensembles. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* 365 (1857), pp. 1993–2028. doi:10.1098/rsta.2007.2077.

Murphy, J. M., Harris, G. R., Sexton, D. M. H., Kendon, E. J., P.E., B., Clark, R., Eagle, K., Fosser, G., et al. (2018). UKCP18 Land Projections: Science Report. In: Met Office Hadley Centre Climate Programme.

Murphy, J. M., Sexton, D. M., Barnett, D. N., Jones, G. S., Webb, M. J., Collins, M., and Stainforth, D. A. (2004). Quantification of Modelling Uncertainties in a Large Ensemble of Climate Change Simulations. *Nature* 430 (7001), pp. 768–772.

Muscutt, A., Harris, G., Bailey, S., and Davies, D. (1993). Buffer Zones to Improve Water Quality: A Review of Their Potential Use in UK Agriculture. *Agriculture, ecosystems environment* 45 (1-2), pp. 59–77.

Mysiak, J., Sullivan, C., Henrikson, H. J., Pahl-Wostl, C., and Bromley, J. (2010). The Adaptive Water Resource Management Handbook. Earthscan. ISBN: 1844077926.

Nakicenovic, N., Alcamo, J., Davis, G., Vries, B. d., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., et al. (2000). Special Report on Emissions Scenarios.

NAO (2020). Department for Environment, Food & Rural Affairs - Water Supply and Demand Management. In: vol. 03/20. Report by the Comptroller and Auditor General. National Audit Office, London, United Kingdom: Davis, R. and Gjertsen, J. and Smyth, R. and Hyde, J. and Davis, K. URL: https://www.nao.org.uk/wp-content/uploads/2020/03/Water-supply-and-demand-management-Summary.pdf.

Nash, J. and Sutcliffe, J. (1970). River Flow Forecasting through Conceptual Models Part I - a Discussion of Principles. *Journal of Hydrology* 10 (3), pp. 282–290. doi:10.1016/0022-1694(70)90255-6.

Nel, J. L., Roux, D. J., Maree, G., Kleynhans, C. J., Moolman, J., Reyers, B., Rouget, M., and Cowling, R. M. (2007). Rivers in Peril inside and Outside Protected Areas: A Systematic Approach to Conservation Assessment of River Ecosystems. *Diversity and Distributions* 13 (3), pp. 341–352. doi:10.1111/j.1472-4642.2006.00308.x.

Nelson, D. R., Adger, W. N., and Brown, K. (2007). Adaptation to Environmental Change: Contributions of a Resilience Framework. *Annual Review of Environment and Resources* 32 (1), pp. 395–419. doi:10.1146/annurev.energy.32.051807.090348.

Nilsson, C. and Renöfält, B. M. (2008). Linking Flow Regime and Water Quality in Rivers: A Challenge to Adaptive Catchment Management. *Ecology and Society* 13 (2).

Norfolk Rivers Trust (2018). River Ingol Wetland Creating - a Partnership to Benefit All. URL: https://catchmentbasedapproach.org/wp-content/uploads/2018/10/River-Ingol-Wetland-Brochure.pdf (Accessed: 12.11.2022).

NRFA (2017a). 28015 - Idle at Mattersey - Catchment Daily Rainfall Data. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/meanflow/28015 (Accessed: 9.11.2021).

NRFA (2017b). 41009 - Rother at Hardham - Catchment Daily Rainfall Data. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/meanflow/41009 (Accessed: 9.11.2021).

NRFA (2018). FEH Catchment Descriptors. Flood Estimation Handbook (FEH), National River Flow Archive. URL: https://nrfa.ceh.ac.uk/feh-catchment-descriptors (Accessed: 8.3.2019).

NRFA (2019a). 28015 - Idle at Mattersey - Catchment Info - Catchment Statistics. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/28015 (Accessed: 30.4.2018).

NRFA (2019b). 28015 - Idle at Mattersey - Daily Flow Data. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/meanflow/28015 (Accessed: 24.5.2018).

NRFA (2019c). 28015 - Idle at Mattersey - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/28015 (Accessed: 9.11.2021).

NRFA (2019d). 41009 - Rother at Hardham - Catchment Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/41009 (Accessed: 9.11.2021).

NRFA (2019e). 41009 - Rother at Hardham - Daily Flow Data. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/meanflow/41009 (Accessed: 18.2.2022).

NRFA (2019f). 41009 - Rother at Hardham - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/41009 (Accessed: 9.11.2021).

NRFA (2019g). 41011 - Rother at Iping Mill - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/41011 (Accessed: 1.12.2022).

NRFA (2022a). 27023 - Dearne at Barnsley Weir - Catchment Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/27023 (Accessed: 1.12.2022).

NRFA (2022b). 27023 - Dearne at Barnsley Weir - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/27023 (Accessed: 1.12.2022).

NRFA (2022c). 34001 - Yare at Colney - Catchment Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/34001 (Accessed: 1.12.2022).

NRFA (2022d). 34001 - Yare at Colney - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/34001 (Accessed: 1.12.2022).

NRFA (2022e). 41022 - Lod at Halfway Bridge - Catchment Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/41022 (Accessed: 11.2.2023).

NRFA (2022f). 71014 - Darwen at Blue Bridge - Catchment Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/spatial/71014 (Accessed: 1.12.2022).

NRFA (2022g). 71014 - Darwen at Blue Bridge - Station Info. National River Flow Archive. URL: https://nrfa.ceh.ac.uk/data/station/info/71014 (Accessed: 1.12.2022).

NSRI (2015). National Soil Map Soils Data (Natmap Vector). URL: http://www.landis.org.uk/data/nmvector.cfm (Accessed: 10.6.2019).

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., et al. (2016). The Scenario Model Intercomparison Project (Scenariomip) for Cmip6. *Geoscientific Model Development* 9 (9), pp. 3461–3482.

O'Brien, P., O'Neill, P., and Pike, A. (2019). Funding, Financing and Governing Urban Infrastructures. *Urban Studies* 56 (7), pp. 1291–1303.

O'Donnell, E. C., Lamond, J. E., and Thorne, C. R. (2017). Recognising Barriers to Implementation of Blue-Green Infrastructure: A Newcastle Case Study. *Urban Water Journal* 14 (9), pp. 964–971. doi:10.1080/1573062x.2017.1279190.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Ruijven, B. J. van, Vuuren, D. P. van, et al. (2017). The Roads Ahead: Narratives for Shared Socioeconomic Pathways Describing World Futures in the 21st Century. *Global environmental change* 42, pp. 169–180.

Oberdorff, T. (2022). Time for Decisive Actions to Protect Freshwater Ecosystems from Global Changes. *Knowledge Management of Aquatic Ecosystems* (423), p. 19.

OECD (2022). Financing a Water Secure Future. OECD Publishing, Paris, France. URL: https://www.oecd.org/environment/resources/policy-highlights-financing-a-water-secure-future.pdf (Accessed: 12.10.2022).

OEP (2022). Oep Launches Investigation into the Regulation of Combined Sewer Overflows (Csos). Office for Environmental Protection (OEP). URL: https://www.theoep.

org.uk/news/oep-launches-investigation-regulation-combined-sewer-overflows-csos (Accessed: 8.11.2022).

Ofwat (2012). Dataset: Water Put into Public Water Supply: 1990/1 to 2010/11. The Water Services Regulation Authority. URL: https://www.data.gov.uk/dataset/ef05ab87-04b7-4fbe-a02d-540c26dee36e/water-put-into-public-water-supply-1990-1-to-2010-11 (Accessed: 30.1.2023).

Ofwat (2017). Cathryn Ross Speaking Notes: Future of Utilities – Water 2017, 21 November 2017. The Water Services Regulation Authority, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2017/11/Cathryn-Ross-speaking-notes-Future-of-Utilities-Water-2017-21-November-2017-FINAL.pdf (Accessed: 21.2.2023).

Ofwat (2018). Pn 22/18: Thames Water's Failure to Tackle Leakage Results in £65m Package for Customers. The Water Services Regulation Authority (Accessed: 17.2.2023).

Ofwat (2019a). Pr19 Final Determinations - Aligning Risk and Return Technical Appendix. Birmingham, United Kingdom: The Water Services Regulation Authority. URL: https://www.ofwat.gov.uk/wp-content/uploads/2019/12/PR19-final-determinations-Aligning-risk-and-return-technical-appendix.pdf.

Ofwat (2019b). Service Delivery Report 2018-19. The Water Services Regulation Authority, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2019/10/Service-delivery-report-2019.pdf (Accessed: 10.8.2022).

Ofwat (2021). H2open - Open Data in the Water Industry: A Case for Change. Birmingham, United Kingdom: Water Services Regulation Authority for England and Wales.

Ofwat (2022a). About Us - Who We Are. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/about-us/who-we-are/ (Accessed: 20.9.2022).

Ofwat (2022b). Catchment Systems Thinking Cooperative (Castco). The Ofwat Innovation Fund, Water Services Regulation Authority for England and Wales. URL: https://waterinnovation.challenges.org/winners/castco/ (Accessed: 8.8.2022).

Ofwat (2022c). Cost of Living: Water Customers' Experiences. In: The Water Services Regulation Authority. Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2022/05/Cost-of-living-report-Final.pdf.

Ofwat (2022d). Creating Tomorrow, Together: Our Final Methodology for Pr24: Appendix 7 - Performance Commitments. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2022/12/PR24_final_methodology_Appendix_7_Performance_commitments.pdf (Accessed: 31.1.2023).

Ofwat (2022e). Innovation in Water Challenge Winners. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://waterinnovation.challenges.org/iwc/winners/ (Accessed: 9.11.2022).

Ofwat (2022f). Leakage in the Water Industry. Birmingham, United Kingdom: The Water Services Regulation Authority. URL: https://www.ofwat.gov.uk/leakage-in-the-water-industry/#leakage3.

Ofwat (2022g). Pn 13/22 Competition Act 1998 Investigation: Ofwat Confirms Changes to Thames Water's Smart Metering Policy for Business Customers. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/pn-13-22-competition-act-1998-investigation-ofwat-confirms-changes-to-thames-waters-smart-metering-policy-for-business-customers/ (Accessed: 11.11.2022).

Ofwat (2022h). Pn 27/22 Ofwat Raises Bar on Financial Resilience. The Water Services Regulation Authority. URL: https://www.ofwat.gov.uk/ofwat-raises-bar-on-financial-resilience/ (Accessed: 25.2.2023).

Ofwat (2022i). Pn 36/22 Thames Water and Southern Water to Return Almost £80m to Customers for under Performance. The Water Services Regulation Authority, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/in-period-2021-22-final-determinations-announced/ (Accessed: 17.2.2023).

Ofwat (2022j). Pr14 Review. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2022/01/PR14_Review_Paper_Jan_2022.pdf (Accessed: 6.2.2023).

Ofwat (2022k). Regulated Companies - Price Reviews. The Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/regulated-companies/price-review/ (Accessed: 20.9.2022).

Ofwat (2022l). Residential Customers - Your Water Bill. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/households/your-water-bill/ (Accessed: 10.8.2022).

Ofwat (2022m). Water Companies' Contact Details. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/households/your-water-company/contact-companies/ (Accessed: 31.10.2022).

Ofwat (2022n). Water Companies' Environmental Incentives to Support More Water Efficient New Homes. In: The Water Services Regulation Authority. Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/wp-content/uploads/2022/09/Environmental_incentives.pdf.

Ofwat (2022a). Corporate Releases - Ofwat Reveals Progress on Water Industry Leakage Performance. Water Services Regulation Authority for England and Wales, Birmingham, United Kingdom. URL: https://www.ofwat.gov.uk/ofwat-reveals-progress-on-water-industry-leakage-performance/ (Accessed: 10.8.2022).

Okumah, M., Chapman, P. J., Martin-Ortega, J., Novo, P., Ferre, M., Jones, S., Pearson, P., and Froggatt, T. (2021). Do Awareness-Focussed Approaches to Mitigating Diffuse Pollution Work? A Case Study Using Behavioural and Water Quality Evidence. *J Environ Manage* 287, p. 112242. doi:10.1016/j.jenvman.2021.112242.

Olden, J. D., Kennard, M. J., and Pusey, B. J. (2012). A Framework for Hydrologic Classification with a Review of Methodologies and Applications in Ecohydrology. *Ecohydrology* 5 (4), pp. 503–518. doi:10.1002/eco.251.

Olden, J. D., Messager, M. L., Tharme, R. E., Kashaigili, J. J., Munkyala, D., Zielinski, L., and Warner, A. (2021). Hydrologic Classification of Tanzanian Rivers to Support National Water Resource Policy. *Ecohydrology*. doi:10.1002/eco.2282.

Olden, J. D. and Poff, N. L. (2003). Redundancy and the Choice of Hydrologic Indices for Characterizing Streamflow Regimes. *River Research and Applications* 19 (2), pp. 101–121. doi:10.1002/rra.700.

Olsson, P., Folke, C., Galaz, V., Hahn, T., and Schultz, L. (2007). Enhancing the Fit through Adaptive Co-Management: Creating and Maintaining Bridging Functions for Matching Scales in the Kristianstads Vattenrike Biosphere Reserve, Sweden. *Ecology and society* 12 (1).

Olsson, T., Jakkila, J., Veijalainen, N., Backman, L., Kaurola, J., and Vehviläinen, B. (2015). Impacts of Climate Change on Temperature, Precipitation and Hydrology in Finland–Studies Using Bias Corrected Regional Climate Model Data. *Hydrology and Earth System Sciences* 19 (7), pp. 3217–3238.

Ong, A. and Cuttle, C. (2021). Outcome Based Environmental Regulation - Enabling the Water Sector to Make Its Contribution to the 25 Year Environment Plan. In: frontier economics. URL: https://www.ofwat.gov.uk/wp-content/uploads/2022/03/Wessex-Water-OBER-Final-Report-2021.pdf.

Ordnance Survey (2019). Os Terrain 5 - Asc Geospatial Data, Scale 1:10,000. Land and Height Data, Ordnance Survey. URL: https://digimap.edina.ac.uk/webhelp/os/data_information/os_products/os_terrain5_dtm.htm (Accessed: 31.5.2019).

Ornaghi, C. and Tonin, M. (2017). The Effect of Metering on Water Consumption—Policy Note. *University of Southampton*.

Overton, I. C., Smith, D. M., Dalton, J., Barchiesi, S., Acreman, M. C., Stromberg, J. C., and Kirby, J. M. (2014). Implementing Environmental Flows in Integrated Water Resources Management and the Ecosystem Approach. *Hydrological Sciences Journal* 59 (3-4), pp. 860–877. doi:10.1080/02626667.2014.897408.

Oxford Scientific Software (2008). Aquator: Water Resources Modelling Softwater by Hydro-Logic Services (International). URL: http://www.oxscisoft.com/index.aspx (Accessed: 9.8.2022).

Pacchetti, M. B., Dessai, S., Bradley, S., and Stainforth, D. A. (2021). Assessing the Quality of Regional Climate Information. *Bulletin of the American Meteorological Society* 102 (3), E476–E491.

Padrón, R. S., Gudmundsson, L., Decharme, B., Ducharne, A., Lawrence, D. M., Mao, J., Peano, D., Krinner, G., et al. (2020). Observed Changes in Dry-Season Water Availability Attributed to Human-Induced Climate Change. *Nature Geoscience* 13 (7), pp. 477–481. doi:10.1038/s41561-020-0594-1.

Pahl-Wostl, C. (2007). The Implications of Complexity for Integrated Resources Management. *Environmental Modelling Software* 22 (5), pp. 561–569. doi:10.1016/j.envsoft.2005.12.024.

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S. E., Hoff, H., Lebel, L., Nikitina, E., Palmer, M., et al. (2013). Environmental Flows and Water Governance: Managing Sustainable Water Uses. *Current Opinion in Environmental Sustainability* 5 (3-4), pp. 341–351. doi:10.1016/j.cosust.2013.06.009.

Pahl-Wostl, C., Holtz, G., Kastens, B., and Knieper, C. (2010). Analyzing Complex Water Governance Regimes: The Management and Transition Framework. *Environmental Science & Policy* 13 (7), pp. 571–581. doi:10.1016/j.envsci.2010.08.006.

Palmer, M. and Ruhi, A. (2019). Linkages between Flow Regime, Biota, and Ecosystem Processes: Implications for River Restoration. *Science* 365 (6459), eaaw2087.

Palmer, T. E., McSweeney, C. F., Booth, B. B. B., Priestley, M. D. K., Davini, P., Brunner, L., Borchert, L., and Menary, M. B. (2022). Performance Based Sub-Selection of Cmip6 Models for Impact Assessments in Europe. *Earth Syst. Dynam. Discuss.* 2022, pp. 1–45. doi:10.5194/esd-2022-31.

Pandya, A. B. and Sharma, P. (2021). Importance of Data in Mitigating Climate Change. In: *Hydrological Aspects of Climate Change*. Springer, pp. 123–137.

Papadimitriou, L. V., Koutroulis, A. G., Grillakis, M. G., and Tsanis, I. K. (2016). High-End Climate Change Impact on European Runoff and Low Flows; Exploring the Effects of Forcing Biases. *Hydrology and Earth System Sciences* 20 (5), pp. 1785–1808. doi:10.5194/hess-20-1785-2016.

Papageorgiou, G., Grant, S. W., Takkenberg, J. J. M., and Mokhles, M. M. (2018). Statistical Primer: How to Deal with Missing Data in Scientific Research? *Interactive Cardiovascular and Thoracic Surgery* 27 (2), pp. 153–158. doi:10.1093/icvts/ivy102.

Parker, W. S. (2010). Predicting Weather and Climate: Uncertainty, Ensembles and Probability. *Studies in history and philosophy of science part B: Studies in History and Philosophy of Modern Physics* 41 (3), pp. 263–272.

Parker, W. S. (2013). Ensemble Modeling, Uncertainty and Robust Predictions. *WIREs Climate Change* 4 (3), pp. 213–223. doi:https://doi.org/10.1002/wcc.220.

Partnership, West Cumbria Catchment (2022). Map Series. URL: https://wcrt.maps.arcgis.com/apps/MapSeries/index.html?appid=d4bc74ba52a2455695444559164d3eac (Accessed: 30.9.2022).

Pastén-Zapata, E., Jones, J. M., Moggridge, H., and Widmann, M. (2020). Evaluation of the Performance of Euro-Cordex Regional Climate Models for Assessing Hydrological Climate Change Impacts in Great Britain: A Comparison of Different Spatial Resolutions and Quantile Mapping Bias Correction Methods. *Journal of Hydrology* 584, p. 124653. doi:10.1016/j.jhydrol.2020.124653.

Pastor, A. V., Palazzo, A., Havlik, P., Biemans, H., Wada, Y., Obersteiner, M., Kabat, P., and Ludwig, F. (2019). The Global Nexus of Food–Trade–Water Sustaining Environmental Flows by 2050. *Nature Sustainability* 2 (6), pp. 499–507. doi:10.1038/s41893-019-0287-1.

Pathak, D., Hutchins, M., Brown, L., Loewenthal, M., Scarlett, P., Armstrong, L., Nicholls, D., Bowes, M., et al. (2021). Hourly Prediction of Phytoplankton Biomass and Its Environmental Controls in Lowland Rivers. *Water Resources Research* 57 (3), e2020WR028773. doi:https://doi.org/10.1029/2020wr028773.

Pedde, S., Harrison, P. A., Holman, I. P., Powney, G. D., Lofts, S., Schmucki, R., Gramberger, M., and Bullock, J. M. (2021). Enriching the Shared Socioeconomic Pathways to Co-Create Consistent Multi-Sector Scenarios for the UK. *Science of The Total Environment* 756, p. 143172. doi:https://doi.org/10.1016/j.scitotenv.2020.143172.

Perry, D. M. and Praskievicz, S. J. (2017). A New Era of Big Infrastructure?(Re) Developing Water Storage in the Us West in the Context of Climate Change and Environmental Regulation. *Water Alternatives* 10 (2).

Peters, J. H. (2020). Artificial Recharge of Groundwater. CRC Press. ISBN: 9781003078500.

Petersen-Øverleir, A. and Reitan, T. (2009). Accounting for Rating Curve Imprecision in Flood Frequency Analysis Using Likelihood-Based Methods. *Journal of Hydrology* 366 (1-4), pp. 89–100.

Peterson, R. A. (2000). A Meta-Analysis of Variance Accounted for and Factor Loadings in Exploratory Factor Analysis. *Marketing Letters* 11 (3), pp. 261–275. doi:10.1023/a:1008191211004.

Peyster, E. de (2016). Drought-Resistant Crops and Varieties. University of California - Agriculture and Natural Resources, Berkeley, United States. URL: https://ucanr.edu/sites/scmg/files/183771.pdf (Accessed: 20.10.2022).

Phung, Q. A., Thompson, A. L., Baffaut, C., Costello, C., and John Sadler, E. (2022). Assessing Future Water Allocation under Climate Variability and Land Management Change in an Agricultural Watershed. *JAWRA Journal of the American Water Resources Association*.

Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., and Wagener, T. (2016). Sensitivity Analysis of Environmental Models: A Systematic Review with Practical Workflow. *Environmental Modelling Software* 79, pp. 214–232. doi:10.1016/j.envsoft.2016.02.008.

Pielke, R. and Ritchie, J. (2021). Distorting the View of Our Climate Future: The Misuse and Abuse of Climate Pathways and Scenarios. *Energy Research Social Science* 72, p. 101890. doi:https://doi.org/10.1016/j.erss.2020.101890.

Piniewski, M. (2017). Classification of Natural Flow Regimes in Poland. *River Research and Applications* 33 (7), pp. 1205–1218. doi:10.1002/rra.3153.

Piniewski, M., Laize, C. L. R., Acreman, M. C., Okruszko, T., and Schneider, C. (2014). Effect of Climate Change on Environmental Flow Indicators in the Narew Basin, Poland. *Journal of Environmental Quality* 43 (1), pp. 155–167. doi:10.2134/jeq2011.0386.

Piniewski, M., Prudhomme, C., Acreman, M., Tylec, L., Oglęcki, P., and Okruszko, T. (2017). Responses of Fish and Invertebrates to Floods and Droughts in Europe. *Ecohydrology* 10 (1), e1793.

Pirret, Fung, Mitchell, and McInnes (2020). Soil Moisture and the Water Cycle in the UK Climate Projections. In: *EGU General Assembly*. Online.

Pltonykova, H., Koeppel, S., Bernardini, F., Tiefenauer-Linardon, S., and Strasser, L. de (2020). The United Nations World Water Development Report 2020: Water and Climate Change. UNESCO World Water Assessment Programme. URL: https://unesdoc.unesco.org/ark:/48223/pf0000372985?posInSet=1&queryId=8cae6745-4a76-4eb4-a032-094e94f17f45 (Accessed: 19.1.2023).

Poff, N. L. and Ward, J. V. (1989). Implications of Streamflow Variability and Predictability for Lotic Community Structure: A Regional Analysis of Streamflow Patterns. *Canadian journal of fisheries and aquatic sciences* 46 (10), pp. 1805–1818.

Poff, N. L. (2017). Beyond the Natural Flow Regime? Broadening the Hydro-Ecological Foundation to Meet Environmental Flows Challenges in a Non-Stationary World. *Freshwater Biology*. doi:10.1111/fwb.13038.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., and Stromberg, J. C. (1997). The Natural Flow Regime. *Bioscience* 47 (11), pp. 769–784. doi:doi10.2307/1313099.

Poff, N. L. and Schmidt, J. (2016). How Dams Can Go with the Flow. *Science* 353 (6304), pp. 1099–1100.

Poff, N. L. and Zimmerman, J. K. H. (2010). Ecological Responses to Altered Flow Regimes: A Literature Review to Inform the Science and Management of Environmental Flows. *Freshwater Biology* 55 (1), pp. 194–205. doi:10.1111/j.1365-2427.2009.02272.x.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., et al. (2010). The Ecological Limits of Hydrologic Alteration (Eloha): A New Framework for Developing Regional Environmental Flow Standards. *Freshwater Biology* 55 (1), pp. 147–170. doi:10.1111/j.1365-2427.2009.02204.x.

Pokorny, S., Stadnyk, T. A., Lilhare, R., Ali, G., Déry, S. J., and Koenig, K. (2020). Use of Ensemble-Based Gridded Precipitation Products for Assessing Input Data Uncertainty Prior to Hydrologic Modeling. *Water* 12 (10). doi:10.3390/w12102751.

Pollitt, C. (2000). Institutional Amnesia: A Paradox of The'information Age'? *Prometheus* 18 (1), pp. 5–16.

Posthuma, L., Zijp, M. C., De Zwart, D., Van de Meent, D., Globevnik, L., Koprivsek, M., Focks, A., Van Gils, J., et al. (2020). Chemical Pollution Imposes Limitations to the Ecological Status of European Surface Waters. *Sci Rep* 10 (1), p. 14825. doi:10.1038/s41598-020-71537-2.

Prein, A. F., Gobiet, A., Truhetz, H., Keuler, K., Goergen, K., Teichmann, C., Fox Maule, C., Meijgaard, E. van, et al. (2016). Precipitation in the Euro-Cordex 0.11° and 0.44° Simulations: High Resolution, High Benefits? *Climate Dynamics* 46 (1), pp. 383–412. doi:10.1007/s00382-015-2589-y.

Prudhomme, C., Crooks, S., Kay, A. L., and Reynard, N. (2013). Climate Change and River Flooding: Part 1 Classifying the Sensitivity of British Catchments. *Climatic Change* 119 (3-4), pp. 933–948. doi:10.1007/s10584-013-0748-x.

Pryke, M. and Allen, J. (2019). Financialising Urban Water Infrastructure: Extracting Local Value, Distributing Value Globally. *Urban Studies* 56 (7), pp. 1326–1346.

Puckridge, J. T., Walker, K. F., and Costelloe, J. F. (2000). Hydrological Persistence and the Ecology of Dryland Rivers. *Regulated Rivers-Research Management* 16 (5), pp. 385–402. doi:doi10.1002/1099-1646(200009/10)16:5<385::aid-rrr592>3.0.co;2-w.

Pushpalatha, R. (2013). Low-Flow Simulation and Forecasting on French River Basins: A Hydrological Modelling Approach. L'Institut des Sciences et Industries du Vivant et de l'Environnement. Doctor of Phylosophy. Paris, France: AgroParisTech.

PWC (2019). Funding Approaches for Leakage Reduction - Report for Ofwat. PricewaterhouseCoopers LLP. URL: https://www.ofwat.gov.uk/publication/pwc-funding-approaches-for-leakage-reduction/ (Accessed: 17.8.2022).

Qi, A., Holland, R. A., Taylor, G., and Richter, G. M. (2018). Grassland Futures in Great Britain–Productivity Assessment and Scenarios for Land Use Change Opportunities. *Science of the Total Environment* 634, pp. 1108–1118.

Quinn, P., Jonczyk, J., Rimmer, D., and Hewett, C. (2007). The Proactive Approach to Farm Integrated Runoff Management (Firm) Plans with Respect to Nutrients. School of Civil Engineering and Geosciences Report, Newcastle University, Newcastle, United Kingdom. URL: https://research.ncl.ac.uk/proactive/ms4w/Proactivenutrients.pdf (Accessed: 9.9.2022).

Raikes, J., Smith, T. F., Jacobson, C., and Baldwin, C. (2019). Pre-Disaster Planning and Preparedness for Floods and Droughts: A Systematic Review. *International Journal of Disaster Risk Reduction* 38, p. 101207. doi:https://doi.org/10.1016/j.ijdrr.2019.101207.

Raisanen, J. and Raty, O. (2013). Projections of Daily Mean Temperature Variability in the Future: Cross-Validation Tests with Ensembles Regional Climate Simulations. *Climate Dynamics* 41 (5-6), pp. 1553–1568. doi:10.1007/s00382-012-1515-9.

Rajczak, J. and Schär, C. (2017). Projections of Future Precipitation Extremes over Europe: A Multimodel Assessment of Climate Simulations. *Journal of Geophysical Research: Atmospheres* 122 (10), pp. 10, 773–10, 800. doi:https://doi.org/10.1002/2017jd027176.

Ramachandra Rao, A. and Srinivas, V. V. (2006). Regionalization of Watersheds by Hybrid-Cluster Analysis. *Journal of Hydrology* 318 (1-4), pp. 37–56. doi:10.1016/j.jhydrol.2005.06.003.

Rameshwaran, P., Bell, V. A., Brown, M. J., Davies, H. N., Kay, A. L., Rudd, A. C., and Sefton, C. (2021). Use of Abstraction and Discharge Data to Improve the Performance of a National-Scale Hydrological Model. *Water Resources Research* 58 (1). doi:10.1029/2021wr029787.

Refsgaard, J. C., Arnbjerg-Nielsen, K., Drews, M., Halsnæs, K., Jeppesen, E., Madsen, H., Markandya, A., Olesen, J. E., et al. (2012). The Role of Uncertainty in Climate Change Adaptation Strategies—a Danish Water Management Example. *Mitigation and Adaptation Strategies for Global Change* 18 (3), pp. 337–359. doi:10.1007/s11027-012-9366-6.

Renard, B., Kavetski, D., Kuczera, G., Thyer, M., and Franks, S. W. (2010). Understanding Predictive Uncertainty in Hydrologic Modeling: The Challenge of Identifying Input and Structural Errors. *Water Resources Research* 46 (5).

Rey, D., Pérez-Blanco, C. D., Escriva-Bou, A., Girard, C., and Veldkamp, T. I. E. (2019). Role of Economic Instruments in Water Allocation Reform: Lessons from Europe. *International Journal of Water Resources Development* 35 (2), pp. 206–239. doi:10.1080/07900627.2017.1422702.

Riahi, K., Vuuren, D. P. van, Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., et al. (2017). The Shared Socioeconomic Pathways and Their Energy,

Land Use, and Greenhouse Gas Emissions Implications: An Overview. *Global Environmental Change* 42, pp. 153–168. doi:https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Richardson, C. and Wright, D. (1984). Wgen: A Model for Generating Daily Weather Variables, Ars-8. In: United States Department of Agriculture (USDA)/Agriculture Research Service (ARS). Temple, U.S.A.

Richter, B. D., Baumgartner, J. V., Braun, D. P., and Powell, J. (1998). A Spatial Assessment of Hydrologic Alteration within a River Network. *Regulated Rivers-Research Management* 14 (4), pp. 329–340.

Richter, B. D., Baumgartner, J. V., Wigington, R., and Braun, D. P. (1997). How Much Water Does a River Need? *Freshwater Biology* 37 (1), pp. 231–249. doi:doi10.1046/j.1365-2427.1997.00153.x.

Richter, B. D., Baumgartner, J., Powell, J., and Braun, D. (1996). A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* 10 (4), pp. 1163–1174.

Richter, B. D., Brown, J. D., DiBenedetto, R., Gorsky, A., Keenan, E., Madray, C., Morris, M., Rowell, D., et al. (2017). Opportunities for Saving and Reallocating Agricultural Water to Alleviate Water Scarcity. *Water Policy* 19 (5), pp. 886–907.

Rising, J., Dietz, S., Dumas, M., Khurana, R., Kikstra, J., Lenton, T., Linsenmeier, M., Smith, C., et al. (2022). What Will Climate Change Cost the UK? Risks, Impacts and Mitigation for the Net-Zero Transition. In: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science. London, United Kingdom.

Ritchie, J. and Dowlatabadi, H. (2017). Why Do Climate Change Scenarios Return to Coal? *Energy* 140, pp. 1276–1291.

Rittel, H. W. and Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy sciences* 4 (2), pp. 155–169.

River Eden Catchment Partnership (2022). URL: https://edenriverstrust.maps.arcgis.com/apps/MapSeries/index.html?appid=df861e4b578146928156728872e1e9a2 (Accessed: 30.9.2022).

Rivers-Moore, N. A., Schulze, R. E., and Davis, N. S. (2020). A Regional Flow Type Classification for South African Perennial Rivers. *Water SA* 46 (3 July). doi:10.17159/wsa/2020.v46.i3.8648.

Robins, L., Burt, T. P., Bracken, L. J., Boardman, J., and Thompson, D. B. A. (2017). Making Water Policy Work in the United Kingdom: A Case Study of Practical Approaches to Strengthening Complex, Multi-Tiered Systems of Water Governance. *Environmental Science Policy* 71, pp. 41–55. doi:10.1016/j.envsci.2017.01.008.

Robins, L. and Kanowski, P. (2011). 'Crying for Our Country': Eight Ways in Which 'Caring for Our Country'has Undermined Australia's Regional Model for Natural Resource Management. *Australasian journal of environmental management* 18 (2), pp. 88–108.

Rocha, J., Duarte, A., Silva, M., Fabres, S., Vasques, J., Revilla-Romero, B., and Quintela, A. (2020). The Importance of High Resolution Digital Elevation Models for Im-

proved Hydrological Simulations of a Mediterranean Forested Catchment. *Remote Sensing* 12 (20), p. 3287. doi:10.3390/rs12203287.

Rockström, J., Falkenmark, M., Allan, T., Folke, C., Gordon, L., Jagerskog, A., Kummu, M., Lannerstad, M., et al. (2014). The Unfolding Water Drama in the Anthropocene: Towards a Resilience-Based Perspective on Water for Global Sustainability. *Ecohydrology* 7 (5), pp. 1249–1261. doi:10.1002/eco.1562.

Rodell, M., Beaudoing, H. K., L'Ecuyer, T. S., Olson, W. S., Famiglietti, J. S., Houser, P. R., Adler, R., Bosilovich, M. G., et al. (2015). The Observed State of the Water Cycle in the Early Twenty-First Century. *Journal of Climate* 28 (21), pp. 8289–8318. doi:10.1175/jcli-d-14-00555.1.

Rogge, K. S. and Reichardt, K. (2016). Policy Mixes for Sustainability Transitions: An Extended Concept and Framework for Analysis. *Research Policy* 45 (8), pp. 1620–1635. doi:https://doi.org/10.1016/j.respol.2016.04.004.

Rolls, R. J., Heino, J., Ryder, D. S., Chessman, B. C., Growns, I. O., Thompson, R. M., and Gido, K. B. (2018). Scaling Biodiversity Responses to Hydrological Regimes. *Biological Reviews* 93 (2), pp. 971–995.

Romaní, A. M., Chauvet, E., Febria, C., Mora-Gómez, J., Risse-Buhl, U., Timoner, X., Weitere, M., and Zeglin, L. (2017). The Biota of Intermittent Rivers and Ephemeral Streams: Prokaryotes, Fungi, and Protozoans. In: *Intermittent Rivers and Ephemeral Streams*. Ed. by T. Datry, N. Bonada, and A. Boulton. Academic Press. Chap. 4.1, pp. 161–188. ISBN: 978-0-12-803835-2. doi:https://doi.org/10.1016/b978-0-12-803835-2.00009-7.

Roo, A. de, Beck, H. E., and Dijk, A. I. J. M. van (2015). Global Maps of Streamflow Characteristics Based on Observations from Several Thousand Catchments. *Journal of Hydrometeorology* 16 (4), pp. 1478–1501. doi:10.1175/jhm-d-14-0155.1.

Rose, E. (2020). The Uk's Enforcement Gap 2020. unchecked UK. URL: https://www.unchecked.uk/wp-content/uploads/2020/11/The-UKs-Enforcement-Gap-2020.pdf (Accessed: 16.8.2022).

Rosenfeld, J. S. (2017). Developing Flow–Ecology Relationships: Implications of Nonlinear Biological Responses for Water Management. *Freshwater Biology* 62 (8), pp. 1305–1324. doi:https://doi.org/10.1111/fwb.12948.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., and Schaphoff, S. (2008). Agricultural Green and Blue Water Consumption and Its Influence on the Global Water System. *Water Resources Research* 44 (9). doi:artnw0940510.1029/2007wr006331.

Rostron, J. W., Sexton, D. M. H., McSweeney, C. F., Yamazaki, K., Andrews, T., Furtado, K., Ringer, M. A., and Tsushima, Y. (2020). The Impact of Performance Filtering on Climate Feedbacks in a Perturbed Parameter Ensemble. *Climate Dynamics* 55 (3-4), pp. 521–551. doi:10.1007/s00382-020-05281-8.

Rouillard, J. J. and Spray, C. J. (2016). Working across Scales in Integrated Catchment Management: Lessons Learned for Adaptive Water Governance from Regional Experiences. *Regional Environmental Change* 17 (7), pp. 1869–1880. doi:10.1007/s10113-016-0988-1.

Rousseeuw, P. J. and Van Driessen, K. (1999). A Fast Algorithm for the Minimum Covariance Determinant Estimator. *Technometrics* 41 (3), pp. 212–223. doi:doi10.2307/1270566.

RSPB (2021). Troubled Waters - Why Poor Water Quality Is Threatening Some of Our Best Places for Nature and How We Can Fix It. URL: https://www.rspb.org.uk/globalassets/downloads/our-work/troubled-waters-report (Accessed: 25.10.2022).

Rudd, A. C., Bell, V. A., and Kay, A. L. (2017). National-Scale Analysis of Simulated Hydrological Droughts (1891–2015). *Journal of Hydrology* 550, pp. 368–385. doi:10.1016/j.jhydrol.2017.05.018.

Rudd, A. C., Kay, A. L., and Bell, V. A. (2019). National-Scale Analysis of Future River Flow and Soil Moisture Droughts: Potential Changes in Drought Characteristics. *Climatic Change* 156 (3), pp. 323–340. doi:10.1007/s10584-019-02528-0.

Rummukainen, M. (2016). Added Value in Regional Climate Modelling. *WIREs Climate Change* 7, pp. 145–159. doi:10.1002/wcc.378.

Rycroft, D. W. and Smedema, L. K. (1983). Land Drainage: Planning and Design of Agricultural Drainage Systems. Batsford Academic & Educational London. ISBN: 0713435003.

Sadoff, C. W., Borgomeo, E., and Uhlenbrook, S. (2020). Rethinking Water for Sdg 6. *Nature Sustainability* 3 (5), pp. 346–347. doi:10.1038/s41893-020-0530-9.

Saha, G. C. and Quinn, M. (2020). Numerical Modelling of the Impacts of Water Abstraction for Hydraulic Fracturing on Groundwater–Surface Water Interaction: A Case Study from Northwestern Alberta, Canada. *Hydrological Sciences Journal* 65 (12), pp. 2142–2158.

Saintilan, N., Ling, J., and Wen, L. (2009). The Development of Interdisciplinary Flow-Ecology Models for the Wetlands of the Northern Murray-Darling Basin. *IAHS publication* 20, p. 86.

Salomons, E., Sela, L., and Housh, M. (2020). Hedging for Privacy in Smart Water Meters. *Water Resources Research* 56 (9), e2020WR027917.

Salvidge, R. (2022). Environment Agency Has 'No Idea' How Much Water Is Taken, Says Whistleblower. The Guardian, Guardian News and Media Limited. URL: https://www.theguardian.com/environment/2022/nov/11/environment-agency-has-no-idea-how-much-water-is-taken-says-whistleblower (Accessed: 1.2.2023).

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., and Jenkins, M. (2018). The Global Status and Trends of Payments for Ecosystem Services. *Nature Sustainability* 1 (3), pp. 136–144. doi:10.1038/s41893-018-0033-0.

Samaniego, L., Thober, S., Kumar, R., Wanders, N., Rakovec, O., Pan, M., Zink, M., Sheffield, J., et al. (2018). Anthropogenic Warming Exacerbates European Soil Moisture Droughts. *Nature Climate Change* 8 (5), pp. 421–426. doi:10.1038/s41558-018-0138-5.

Sandercock, H. (2023). Water Bill Increase 2023: How Much Are Average Water Bills Going up by in England and Wales - Rise Explained. National World Publishing Ltd. URL: https://www.nationalworld.com/news/uk/water-bill-increase-2023-how-much-average-water-bills-rise-4013473 (Accessed: 6.2.2023).

Sanz, MJ and De Vente, J and Chotte, Jean-Luc and Bernoux, Martial and Kust, G and Ruiz, I and Almagro, M and Alloza, JA and Vallejo, R and Castillo, V (2017). Sustainable Land Management Contribution to Successful Land-Based Climate Change Adaptation and Mitigation: A Report of the Science-Policy Interface. In: *Bonn, Germany: United Nations Convention to Combat Desertification (UNCCD)*.

Satoh, Y., Yoshimura, K., Pokhrel, Y., Kim, H., Shiogama, H., Yokohata, T., Hanasaki, N., Wada, Y., et al. (2022). The Timing of Unprecedented Hydrological Drought under Climate Change. *Nature Communications* 13 (1), p. 3287. doi:10.1038/s41467-022-30729-2.

Savenije, H. H. G. and Van der Zaag, P. (2008). Integrated Water Resources Management: Concepts and Issues. *Physics and Chemistry of the Earth, Parts A/B/C* 33 (5), pp. 290–297. doi:https://doi.org/10.1016/j.pce.2008.02.003.

Sayers, P., Horritt, M., Carr, S., Kay, A., Mauz, J., Lamb, R., and Penning-Rowsell, E. (2020). Third UK Climate Change Risk Assessment (CCRA3): Future Flood Risk. *Research undertaken by Sayers and Partners for the Committee on Climate Change. Published by Committee on Climate Change, London*.

Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., Eade, R., Fereday, D., et al. (2014). Skillful Long-Range Prediction of European and North American Winters. *Geophysical Research Letters* 41 (7), pp. 2514–2519. doi:https://doi.org/10.1002/2014gl059637.

Scanlon, B. R. and Smakhtin, V. (2016). Focus on Water Storage for Managing Climate Extremes and Change. *Environmental Research Letters* 11 (12).

Schaller, N., Kay, A. L., Lamb, R., Massey, N. R., Van Oldenborgh, G. J., Otto, F. E., Sparrow, S. N., Vautard, R., et al. (2016). Human Influence on Climate in the 2014 Southern England Winter Floods and Their Impacts. *Nature Climate Change* 6 (6), pp. 627–634.

Schaub, S., Vogeler, C., and Metz, F. (2022). Designing Policy Mixes for the Sustainable Management of Water Resources. *Journal of Environmental Policy Planning* 24 (5), pp. 463–471. doi:10.1080/1523908x.2022.2100751.

Schindler, D. E. and Hilborn, R. (2015). Prediction, Precaution, and Policy under Global Change. *Science* 347 (6225), pp. 953–954. doi:10.1126/science.1261824.

Schinegger, R., Trautwein, C., Melcher, A., and Schmutz, S. (2012). Multiple Human Pressures and Their Spatial Patterns in European Running Waters. *Water Environ J* 26 (2), pp. 261–273. doi:10.1111/j.1747-6593.2011.00285.x.

Seastedt, T. R., Hobbs, R. J., and Suding, K. N. (2008). Management of Novel Ecosystems: Are Novel Approaches Required? *Frontiers in Ecology and the Environment* 6 (10), pp. 547–553. doi:10.1890/070046.

Seitz, S., Goebes, P., Puerta, V. L., Pereira, E. I. P., Wittwer, R., Six, J., Heijden, M. G. A. van der, and Scholten, T. (2018). Conservation Tillage and Organic Farming Reduce Soil Erosion. *Agronomy for Sustainable Development* 39 (1), p. 4. doi:10.1007/s13593-018-0545-z.

SES Water (2022). Draft Water Resources Management Plan 2022 - Main Report Issue No. 3. Murphy, A. Kelly, T. URL: https://seswater.co.uk/-/media/files/seswater/your-environment/wrmp-2022/ses-water-draft-wrmp22.pdf (Accessed: 15.11.2022).

Shepherd, G. (2004). The Ecosystem Approach: Five Steps to Implementation. IUCN Gland. ISBN: 2831708400.

Shepherd, T. G. (2014). Atmospheric Circulation as a Source of Uncertainty in Climate Change Projections. *Nature Geoscience* 7 (10), pp. 703–708. doi:10.1038/ngeo2253.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., et al. (2018). Storylines: An Alternative Approach to Representing Uncertainty in Physical Aspects of Climate Change. *Climatic Change* 151 (3), pp. 555–571. doi:10.1007/s10584-018-2317-9.

Shepley, M. and Soley, R. (2009). East Midlands Yorkshire Sherwood Sandstone Groundwater Modelling Project – Task 3. In: vol. 1. Environment Agency Report. Environment Agency. UK.

Shepley, M. G., Whiteman, M., Hulme, P., and Grout, M. (2012). Introduction: Groundwater Resources Modelling: A Case Study from the UK. *Geological Society, London, Special Publications* 364 (1), pp. 1–6.

Shiklomanov, I. (1993). World Freshwater Resources. In: *Water in Crisis: A Guide to the World's Freshwater Resources*. Ed. by P. Gleick. Oxford University Press, pp. 13–24.

Shrestha, M., Acharya, S. C., and Shrestha, P. K. (2017a). Bias Correction of Climate Models for Hydrological Modelling - are Simple Methods Still Useful? *Meteorological Applications* 24 (3), pp. 531–539. doi:10.1002/met.1655.

Shrestha, N. K., Du, X., and Wang, J. (2017b). Assessing Climate Change Impacts on Fresh Water Resources of the Athabasca River Basin, Canada. *Science of The Total Environment* 601-602, pp. 425–440. doi:https://doi.org/10.1016/j.scitotenv.2017.05.013.

Shrivastava, P., Stafford Smith, M., O'Brien, K., and Zsolnai, L. (2020). Transforming Sustainability Science to Generate Positive Social and Environmental Change Globally. *One Earth* 2 (4), pp. 329–340. doi:10.1016/j.oneear.2020.04.010.

Shuttleworth, E. L., Evans, M. G., Pilkington, M., Spencer, T., Walker, J., Milledge, D., and Allott, T. E. H. (2019). Restoration of Blanket Peat Moorland Delays Stormflow from Hillslopes and Reduces Peak Discharge. *Journal of Hydrology X* 2, p. 100006. doi:https://doi.org/10.1016/j.hydroa.2018.100006.

Siebert, S. and Doll, P. (2010). Quantifying Blue and Green Virtual Water Contents in Global Crop Production as Well as Potential Production Losses without Irrigation. *Journal of Hydrology* 384 (3-4), pp. 198–217. doi:10.1016/j.jhydro1.2009.07.031.

Sikorska, A. E. and Renard, B. (2017). Calibrating a Hydrological Model in Stage Space to Account for Rating Curve Uncertainties: General Framework and Key Challenges. *Advances in water resources* 105, pp. 51–66.

Sillmann, J., Shepherd, T. G., Hurk, B. van den, Hazeleger, W., Martius, O., Slingo, J., and Zscheischler, J. (2021). Event-Based Storylines to Address Climate Risk. *Earth's Future* 9 (2), e2020EF001783. doi:https://doi.org/10.1029/2020ef001783.

Simberloff, D. and Dayan, T. (1991). The Guild Concept and the Structure of Ecological Communities. *Annual review of ecology and systematics* 22 (1), pp. 115–143.

Singh, N. K. and Basu, N. B. (2022). The Human Factor in Seasonal Streamflows across Natural and Managed Watersheds of North America. *Nature Sustainability* 5 (5), pp. 397–405. doi:10.1038/s41893-022-00848-1.

Skinner, D. and Langford, J. (2013). Legislating for Sustainable Basin Management: The Story of Australia's Water Act (2007). *Water Policy* 15 (6), pp. 871–894.

Smith, K. A., Barker, L. J., Tanguy, M., Parry, S., Harrigan, S., Legg, T. P., Prudhomme, C., and Hannaford, J. (2019). A Multi-Objective Ensemble Approach to Hydrological Modelling in the UK: An Application to Historic Drought Reconstruction. *Hydrology and Earth System Sciences* 23 (8), pp. 3247–3268. doi:10.5194/hess-23-3247-2019.

Smith, L., Porter, K., Benson, D., and Hiscock, K. (2015). 13 Conclusions and Future Challenges. *Catchment and River Basin Management: Integrating Science and Governance*, p. 262.

Smith, L. C., Isacks, B. L., Bloom, A. L., and Murray, A. B. (1996). Estimation of Discharge from Three Braided Rivers Using Synthetic Aperture Radar Satellite Imagery: Potential Application to Ungaged Basins. *Water Resources Research* 32 (7), pp. 2021–2034.

Smith, R. F. (1962). Integration of Biological and Chemical Control: Introduction and Principles. *Bulletin of the ESA* 8 (4), pp. 188–189.

Sokal, R. R. and Rohlf, F. (1969). Biometry - the Principles and Practice of Statistics in Biological Research. Vol. 4. New York City, United States of America: W.H. Freeman and Company. doi:10.2307/2343822.

Soley, R. W. N., Power, T., Mortimore, R. N., Shaw, P., Dottridge, J., Bryan, G., and Colley, I. (2012). Modelling the Hydrogeology and Managed Aquifer System of the Chalk across Southern England. *Geological Society, London, Special Publications* 364 (1), pp. 129–154. doi:10.1144/sp364.10.

Song, Y. H., Chung, E.-S., and Shiru, M. S. (2020). Uncertainty Analysis of Monthly Precipitation in GCMs Using Multiple Bias Correction Methods under Different Rcps. *Sustainability* 12 (18), p. 7508.

Southern Water (2022). Annual Report and Financial Statements for the Year Ended 31 March 2022. Southern Water. URL: https://www.southernwater.co.uk/media/7222/annual-report-and-financial-statements-2021-22.pdf (Accessed: 13.2.2023).

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., Vries, W. de, Vermeulen, S. J., et al. (2018). Options for Keeping the Food System within Environmental Limits. *Nature* 562 (7728), pp. 519–525. doi:10.1038/s41586-018-0594-0.

Srinivasan, V., Konar, M., and Sivapalan, M. (2017). A Dynamic Framework for Water Security. *Water Security* 1, pp. 12–20. doi:https://doi.org/10.1016/j.wasec.2017.03.001.

Stankey, G. H. (2005). Adaptive Management of Natural Resources: Theory, Concepts, and Management Institutions.

Stern, J. (2013). Water Rights and Water Trading in England and Wales. In: The Foundation for Law, Justice and Society (FLJ+S). Oxford, United Kingdom: Centre for Socio-Legal Studies and Wolfson College, University of Oxford. URL: https://ora.ox.ac.uk/objects/uuid:306f9adb-f92c-4b3b-a1a6-574bac30898c/download_file?file_format=pdf&safe_filename=Stern.pdf&type_of_work=General+item.

Stoate, C., Jones, S., Crotty, F., Morris, C., and Seymour, S. (2019). Participatory Research Approaches to Integrating Scientific and Farmer Knowledge of Soil to Meet Multiple Objectives in the English East Midlands. *Soil Use and Management* 35 (1), pp. 150–159. doi:https://doi.org/10.1111/sum.12488.

Stockhammer, E. (2010). Financialization and the Global Economy. *Political Economy Research Institute Working Paper* 242 (40), pp. 1–17.

Stoelzle, M., Stahl, K., Morhard, A., and Weiler, M. (2014). Streamflow Sensitivity to Drought Scenarios in Catchments with Different Geology. *Geophysical Research Letters* 41 (17), pp. 6174–6183. doi:10.1002/2014gl061344.

Storr, T., Simmons, R. W., and Hannam, J. A. (2019). A UK Survey of the Use and Management of Cover Crops. *Annals of Applied Biology* 174 (2), pp. 179–189. doi:https://doi.org/10.1111/aab.12488.

Strauss, A. and Corbin, J. (1998). Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory. 2nd ed. Thousand Oaks, California, USA: Sage Publications Inc. ISBN: 0-8039-5939-7.

Strayer, D. L. and Dudgeon, D. (2010). Freshwater Biodiversity Conservation: Recent Progress and Future Challenges. *Journal of the North American Benthological Society* 29 (1), pp. 344–358. doi:10.1899/08-171.1.

Suren, A. M. and Jowett, I. G. (2006). Effects of Floods Versus Low Flows on Invertebrates in a New Zealand Gravel-Bed River. *Freshwater Biology* 51 (12), pp. 2207–2227. doi:10.1111/j.1365-2427.2006.01646.x.

Tait, N. G., Lerner, D. N., Smith, J. W. N., and Leharne, S. A. (2004). Prioritisation of Abstraction Boreholes at Risk from Chlorinated Solvent Contamination on the UK Permo-Triassic Sandstone Aquifer Using a Gis. *Science of The Total Environment* 319 (1), pp. 77–98. doi:https://doi.org/10.1016/s0048-9697(03)00438-8.

Tamm, O., Maasikamäe, S., Padari, A., and Tamm, T. (2018). Modelling the Effects of Land Use and Climate Change on the Water Resources in the Eastern Baltic Sea Region Using the Swat Model. *Catena* 167, pp. 78–89. doi:10.1016/j.catena.2018.04.029.

Tashie, A., Pavelsky, T., and Kumar, M. (2022). A Calibration-Free Groundwater Module for Improving Predictions of Low Flows. *Water Resources Research* 58 (3).

Tavassoli, H. R., Tahershamsi, A., and Acreman, M. (2014). Classification of Natural Flow Regimes in Iran to Support Environmental Flow Management. *Hydrological sciences journal* 59 (3-4), pp. 517–529.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An Overview of Cmip5 and the Experiment Design. *Bulletin of the American Meteorological Society* 93 (4), pp. 485–498. doi:10.1175/bams-d-11-00094.1.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Beek, R. van, Wada, Y., Longuevergne, L., Leblanc, M., et al. (2013). Ground Water and Climate Change. *Nature Climate Change* 3 (4), pp. 322–329. doi:10.1038/nclimate1744.

Termeer, C. J. A. M. and Dewulf, A. (2018). A Small Wins Framework to Overcome the Evaluation Paradox of Governing Wicked Problems. *Policy and Society* 38 (2), pp. 298–314. doi:10.1080/14494035.2018.1497933.

Terrier, M., Perrin, C., Lavenne, A. de, Andréassian, V., Lerat, J., and Vaze, J. (2020). Streamflow Naturalization Methods: A Review. *Hydrological Sciences Journal* 66 (1), pp. 12–36. doi:10.1080/02626667.2020.1839080.

Teutschbein, C. and Seibert, J. (2012). Bias Correction of Regional Climate Model Simulations for Hydrological Climate-Change Impact Studies: Review and Evaluation of Different Methods. *Journal of Hydrology* 456-457, pp. 12–29. doi:10.1016/j.jhydrol.2012.05.052.

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., et al. (2019). Infrastructure for Sustainable Development. *Nature Sustainability* 2 (4), pp. 324–331. doi:10.1038/s41893-019-0256-8.

Thames Water (2021). Annual Performance Report 2020/2021. Thames Water Utilities Limited. URL: https://www.thameswater.co.uk/media-library/home/about-us/investors/our-results/current-reports/annual-performance-report-2021-2022.pdf (Accessed: 21.2.2023).

Thames Water (2022). Annual Performance Report 2021/2022. Thames Water Utilities Limited. URL: https://www.thameswater.co.uk/media-library/home/about-us/investors/our-results/current-reports/annual-performance-report-2021-2022.pdf (Accessed: 21.2.2023).

The Flood Risk Regulations (2009). No 3042. UK Statutory Instruments, URL: https://www.legislation.gov.uk/uksi/2009/3042/contents/made.

The Rivers Trust (2021). Catchment Monitoring Cooperative. Catchment Based Approach. URL: https://monitoring.catchmentbasedapproach.org/ (Accessed: 8.8.2022).

The South East Rivers Trust (2022a). Holistic Water for Horticulture. Leatherhead, United Kingdom. URL: https://www.southeastriverstrust.org/projects/holistic-water-for-horticulture/ (Accessed: 13.10.2022).

The South East Rivers Trust (2022b). Prowater: Managing Landscapes for Resilient Water Resources. URL: https://www.southeastriverstrust.org/projects/prowater-managing-landscapes-for-resilient-water-resources/ (Accessed: 19.10.2022).

The Water Environment (Water Framework Directive) (England and Wales) Regulations (2017). No. 407. UK Statutory Instruments. URL: https://www.legislation.gov.uk/uksi/2017/407/contents/made.

Thompson, R. M., King, A. J., Kingsford, R. M., Mac Nally, R., and Poff, N. L. (2018). Legacies, Lags and Long-Term Trends: Effective Flow Restoration in a Changed and Changing World. *Freshwater Biology* 63 (8), pp. 986–995. doi:10.1111/fwb.13029.

Tian, Y., Booij, M. J., and Xu, Y.-P. (2014). Uncertainty in High and Low Flows Due to Model Structure and Parameter Errors. *Stochastic environmental research and risk assessment* 28 (2), pp. 319–332.

Tijdeman, E., Hannaford, J., and Stahl, K. (2018). Human Influences on Streamflow Drought Characteristics in England and Wales. *Hydrology and Earth System Sciences* 22 (2), pp. 1051–1064. doi:10.5194/hess-22-1051-2018.

Todorov, V. and Pires, A. M. (2007). Comparative Performance of Several Robust Linear Discriminant Analysis Methods. *Revstat-Statistical Journal* 5 (1), pp. 63–83.

Tollison, R. D. and Wagner, R. E. (1991). The Logic of Natural Monopoly Regulation. *Eastern Economic Journal* 17 (4), pp. 483–490.

Tonkin, J. D., Poff, N. L., Bond, N. R., Horne, A., Merritt, D., Reynolds, L. V., Olden, J. D., Ruhi, A., et al. (2019). Prepare River Ecosystems for an Uncertain Future. *Nature* 570, pp. 301–303. doi:10.1038/d41586-019-01877-1.

Tonkin, J. D., Merritt, D. M., Olden, J. D., Reynolds, L. V., and Lytle, D. A. (2018). Flow Regime Alteration Degrades Ecological Networks in Riparian Ecosystems. *Nature Ecology Evolution* 2 (1), pp. 86–93. doi:10.1038/s41559-017-0379-0.

Torn, M. S. and Harte, J. (2006). Missing Feedbacks, Asymmetric Uncertainties, and the Underestimation of Future Warming. *Geophysical research letters* 33 (10).

Tortajada, C. (2020). Contributions of Recycled Wastewater to Clean Water and Sanitation Sustainable Development Goals. *npj Clean Water* 3 (1), p. 22. doi:10.1038/s41545-020-0069-3.

Townsend, T. J., Ramsden, S. J., and Wilson, P. (2016). How Do We Cultivate in England? Tillage Practices in Crop Production Systems. *Soil Use Manag* 32 (1), pp. 106–117. doi:10.1111/sum.12241.

Trenberth, K. E., Dai, A., Rasmussen, R. M., and Parsons, D. B. (2003). The Changing Character of Precipitation. *Bulletin of the American Meteorological Society* 84 (9), pp. 1205–1217. doi:10.1175/bams-84-9-1205.

Tress, G., Tress, B., and Fry, G. (2005). Clarifying Integrative Research Concepts in Landscape Ecology. *Landscape Ecology* 20 (4), pp. 479–493. doi:10.1007/s10980-004-3290-4.

Trolle, D., Nielsen, A., Andersen, H. E., Thodsen, H., Olesen, J. E., Børgesen, C. D., Refsgaard, J. C., Sonnenborg, T. O., et al. (2019). Effects of Changes in Land Use and Climate on Aquatic Ecosystems: Coupling of Models and Decomposition of Uncertainties. *Science of The Total Environment* 657, pp. 627–633. doi:https://doi.org/10.1016/j.scitotenv.2018.12.055.

Tukey, J. (1977). Exploratory Data Analysis. Series in Behavioral Science - Quantitative Methods. Reading, Massachusetts, United States of America: Addison-Wesley Publishing Company. ISBN: 978-0-201-07616-5.

Tyson, A., Kennedy, B., and Funk, C. (2021). Gen Z, Millennials Stand out for Climate Change Activism, Social Media Engagement with Issue. Pew Research Center. URL: https://www.pewresearch.org/science/wp-content/uploads/sites/16/2021/05/PS_2021.05.26_climate-and-generations_REPORT.pdf (Accessed: 1.2.2023).

UK Government (2010). The Building Regulations. URL: https://www.labc.co.uk/sites/default/files/EXT.Approved-Document-G-Hygiene-%26-Water-Supply-ENG-2013.JMCN_.v1.200417.pdf (Accessed: 11.8.2022).

UK Government (2020). Catchment Sensitive Farming. URL: https://www.gov.uk/guidance/catchment-sensitive-farming-reduce-agricultural-water-pollution (Accessed: 19.8.2022).

UK Parliament (2022). Environmental Land Management Schemes. Public Accounts Committee. URL: https://committees.parliament.uk/work/1472/environmental-land-management-scheme/ (Accessed: 16.8.2022).

UK Water (2022). A Leakage Routemap to 2050. URL: https://www.water.org.uk/wp-content/uploads/2022/03/Water_UK_A-LEAKAGE-ROUTEMAP-TO-2050_Low-Res_V3.pdf (Accessed: 29.9.2022).

UKCORDEX (2022). Ukcordex - Enabling the Use and Producing Improved Understanding of Eurocordex Data over the UK. URL: https://www.ucl.ac.uk/statistics/research/ukcordex (Accessed: 6.9.2022).

UKRI (2022). British Geological Survey (BGS) Groundwater Research: Groundwater Resources in the UK. URL: https://www.bgs.ac.uk/geology-projects/groundwater-research/groundwater-resources-in-the-uk/ (Accessed: 2.9.2022).

UKTAG (2008). UK Environmental Standards and Conditions (Phase 1), Sr1 - 2006. UK Technical Advisory Group on the Water Framework Directive. URL: https://southeastaquatics.net/resources/pdfs/UK_enviro_stds_conditns%20Phase%201.pdf (Accessed: 11.2.2023).

UKTAG (2013). Updated Recommendations on Environmental Standards - River Basin Management (2015-21) Final Interim Report (Sr3 -2012). UK Technical Advisory Group on the Water Framework Directive, URL: https://gat04-live-1517c8a4486c41609369c68f30c8-aa81074.divio-media.org/M4-Newport/C%20-%20Core%20Documents/12.%20Geology%20and%20Soils/12.4.5%20-%20UK%20TAG%20on%20the%20WFD%20Updated%20Recommendations%20on%20Environmental%20Standards%20River%20Basin%20Management%20(2015-21)%20(Minor%20amendments%20201.pdf (Accessed: 11.2.2023).

UN (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. In: Tech. Rep. A/70/L1. New York City, New York, United States of America: Nations, United.

UN (2019). World Population Prospects 2019 Highlights. In: United Nations, Department of Economic and Social Affairs, Population Division. New York City, New York, United States of America.

UN Water (2018). Sustainable Development Goal 6 - Synthesis Report on Water and Sanitation. New York City, New York, United States of America: United Nations (UN).

USDA-ARS & Texas A&M AgriLife Research (2020). Swat+ Input Data, Revision 60.5. The Texas AM University System, Temple, Texas, United States of America. URL: https://swatplus.gitbook.io/docs/user/io (Accessed: 26.4.2022).

Van Delden, S., SharathKumar, M., Butturini, M., Graamans, L., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R., et al. (2021). Current Status and Future Challenges in Implementing and Upscaling Vertical Farming Systems. *Nature Food* 2 (12), pp. 944–956.

Vanham, D., Alfieri, L., and Feyen, L. (2022). National Water Shortage for Low to High Environmental Flow Protection. *Scientific reports* 12 (1), pp. 1–9.

Vautard, R., Christidis, N., Ciavarella, A., Alvarez-Castro, C., Bellprat, O., Christiansen, B., Colfescu, I., Cowan, T., et al. (2019). Evaluation of the Hadgem3-a Simulations in View of Detection and Attribution of Human Influence on Extreme Events in Europe. *Climate Dynamics* 52 (1), pp. 1187–1210. doi:10.1007/s00382-018-4183-6.

Velázquez, J. A., Schmid, J., Ricard, S., Muerth, M. J., Gauvin St-Denis, B., Minville, M., Chaumont, D., Caya, D., et al. (2013). An Ensemble Approach to Assess Hydrological Models' Contribution to Uncertainties in the Analysis of Climate Change Impact on Water Resources. *Hydrol. Earth Syst. Sci.* 17 (2), pp. 565–578. doi:10.5194/hess-17-565-2013.

Verdonschot, R. C. M., Oosten-Siedlecka, A. M. van, Braak, C. J. F. ter, and Verdonschot, P. F. M. (2015). Macroinvertebrate Survival During Cessation of Flow and Streambed Drying in a Lowland Stream. *Freshwater Biology* 60 (2), pp. 282–296. doi:https://doi.org/10.1111/fwb.12479.

Vetter, T., Huang, S., Aich, V., Yang, T., Wang, X., Krysanova, V., and Hattermann, F. (2015). Multi-Model Climate Impact Assessment and Intercomparison for Three Large-Scale River Basins on Three Continents. *Earth System Dynamics* 6 (1), pp. 17–43. doi:10.5194/esd-6-17-2015.

Vetter, T., Reinhardt, J., Flörke, M., Griensven, A. van, Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I. G., et al. (2016). Evaluation of Sources of Uncertainty in Projected Hydrological Changes under Climate Change in 12 Large-Scale River Basins. *Climatic Change* 141 (3), pp. 419–433. doi:10.1007/s10584-016-1794-y.

Vial, J., Dufresne, J.-L., and Bony, S. (2013). On the Interpretation of Inter-Model Spread in Cmip5 Climate Sensitivity Estimates. *Climate Dynamics* 41 (11), pp. 3339–3362. doi:10.1007/s00382-013-1725-9.

Victor, J. N., Montgomery, A. H., and Lubell, M. (2017). The Oxford Handbook of Political Networks. Oxford University Press. ISBN: 0190228733.

Vilcan, T. and Potter, K. (2020). Delivering Sustainable Drainage Systems through the English Planning System: A Proposed Case of Institutional Void. *Journal of Flood Risk Management* 13 (1). doi:10.1111/jfr3.12591.

Vitolo, C., Fry, M., and Buytaert, W. (2016). Rnrfa: An R Package to Retrieve, Filter and Visualize Data from the UK National River Flow Archive. *R Journal* 8 (2), pp. 102–116.

Vlach, V., Ledvinka, O., and Matouskova, M. (2020). Changing Low Flow and Streamflow Drought Seasonality in Central European Headwaters. *Water* 12 (12), p. 3575.

Vlček, O. and Huth, R. (2009). Is Daily Precipitation Gamma-Distributed? *Atmospheric Research* 93 (4), pp. 759–766. doi:10.1016/j.atmosres.2009.03.005.

Vliet, M. T. H. van, Beek, L. P. H. van, Eisner, S., Flörke, M., Wada, Y., and Bierkens, M. F. P. (2016). Multi-Model Assessment of Global Hydropower and Cooling Water Discharge Potential under Climate Change. *Global Environmental Change* 40, pp. 156–170. doi:https://doi.org/10.1016/j.gloenvcha.2016.07.007.

Vliet, M. T. H. van, Ludwig, F., and Kabat, P. (2013). Global Streamflow and Thermal Habitats of Freshwater Fishes under Climate Change. *Climatic Change* 121 (4), pp. 739–754. doi:10.1007/s10584-013-0976-0.

Vliet, M. T. H. van, Jones, E. R., Flörke, M., Franssen, W. H. P., Hanasaki, N., Wada, Y., and Yearsley, J. R. (2021). Global Water Scarcity Including Surface Water Quality and Expansions of Clean Water Technologies. *Environmental Research Letters* 16 (2), p. 024020. doi:10.1088/1748-9326/abbfc3.

Vollstedt, M. and Rezat, S. (2019). An Introduction to Grounded Theory with a Special Focus on Axial Coding and the Coding Paradigm. *Compendium for early career researchers in mathematics education* 13, pp. 81–100.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., et al. (2010). Global Threats to Human Water Security and River Biodiversity. *Nature* 467 (7315), pp. 555–561. doi:10.1038/nature09440.

Vu, T. T., Kiesel, J., Guse, B., and Fohrer, N. (2019). Analysis of the Occurrence, Robustness and Characteristics of Abrupt Changes in Streamflow Time Series under Future Climate Change. *Climate Risk Management* 26, p. 100198. doi:https://doi.org/10.1016/j.crm.2019.100198.

Vuuren, D. P. van, Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., et al. (2011). The Representative Concentration Pathways: An Overview. *Climatic Change* 109 (1-2), pp. 5–31. doi:10.1007/s10584-011-0148-z.

Vuuren, D. P. van, Kok, M. T. J., Girod, B., Lucas, P. L., and Vries, B. de (2012). Scenarios in Global Environmental Assessments: Key Characteristics and Lessons for Future Use. *Global Environmental Change* 22 (4), pp. 884–895. doi:https://doi.org/10.1016/j.gloenvcha.2012.06.001.

Walker, G. R., Horne, A. C., Wang, Q. J., and Rendell, R. (2021). Assessing the Impact of Irrigation Efficiency Projects on Return Flows in the South-Eastern Murray–Darling Basin, Australia. *Water* 13 (10), p. 1366.

Walker, W. E., Harremoës, P., Rotmans, J., Sluijs, J. P. van der, Asselt, M. B. A. van, Janssen, P., and Krayer von Krauss, M. P. (2003). Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. *Integrated Assessment* 4 (1), pp. 5–17. doi:10.1076/iaij.4.1.5.16466.

Wang, H.-M., Chen, J., Xu, C.-Y., Chen, H., Guo, S., Xie, P., and Li, X. (2019). Does the Weighting of Climate Simulations Result in a Better Quantification of Hydrological Impacts? *Hydrology and Earth System Sciences* 23 (10), pp. 4033–4050.

Wang, H.-M., Chen, J., Xu, C.-Y., Zhang, J., and Chen, H. (2020). A Framework to Quantify the Uncertainty Contribution of GCMs over Multiple Sources in Hydrological Impacts of Climate Change. *Earth's Future* 8 (8), e2020EF001602. doi:https://doi.org/10.1029/2020ef001602.

Wang, R., Kalin, L., Kuang, W., and Tian, H. (2014). Individual and Combined Effects of Land Use/Cover and Climate Change on Wolf Bay Watershed Streamflow in Southern Alabama. *Hydrological Processes* 28 (22), pp. 5530–5546. doi:10.1002/hyp.10057.

Wang, Y., Leung, L. R., McGREGOR, J. L., Lee, D.-K., Wang, W.-C., Ding, Y., and Kimura, F. (2004). Regional Climate Modeling: Progress, Challenges, and Prospects. *Journal of the Meteorological Society of Japan. Ser. II* 82 (6), pp. 1599–1628.

Ward, J. H. (1963). Hierarchical Grouping to Optimize an Objective Function. *Journal of the American Statistical Association* 58 (301), 236–. doi:doi10.2307/2282967.

Warner, B. P., Schattman, R. E., and Hatch, C. E. (2017). Farming the Floodplain: Ecological and Agricultural Tradeoffs and Opportunities in River and Stream Governance in New England's Changing Climate. *Case Studies in the Environment* 1 (1), p. 1.18.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., and Schewe, J. (2014). The Inter-Sectoral Impact Model Intercomparison Project (Isi-Mip): Project Framework. *Proc Natl Acad Sci U S A* 111 (9), pp. 3228–32. doi:10.1073/pnas.1312330110.

Water Act (2014). C. 21. UK Public General Acts. URL: https://www.legislation.gov.uk/ukpga/2014/21/contents/enacted.

Water Industry Act (1999). C. 9. UK Public General Acts. URL: https://www.legislation.gov.uk/ukpga/1999/9/contents.

Watterson, I. G., Bathols, J., and Heady, C. (2014). What Influences the Skill of Climate Models over the Continents? *Bulletin of the American Meteorological Society* 95 (5), pp. 689–700. doi:10.1175/bams-d-12-00136.1.

Watts, G., Battarbee, R. W., Bloomfield, J. P., Crossman, J., Daccache, A., Durance, I., Elliott, J. A., Garner, G., et al. (2015). Climate Change and Water in the UK – Past Changes and Future Prospects. *Progress in Physical Geography* 39 (1), pp. 6–28. doi:10.1177/0309133314542957.

WCL (2020). Blueprint for Water. Wildlife and Countryside Link, London, United Kingdom. URL: https://www.wcl.org.uk/blueprintforwater.asp (Accessed: 13.10.2022).

Weatherhead, E., Knox, J., Daccache, A., Morris, J., Groves, S., Hulin, A., and Kay, M. (2014). Water for Agriculture: Collaborative Approaches and on-Farm Storage. *Cranfield University, Cranfield, United Kingdom* (FFG1112).

Weaver, C. P., Lempert, R. J., Brown, C., Hall, J. A., Revell, D., and Sarewitz, D. (2013). Improving the Contribution of Climate Model Information to Decision Making: The Value and Demands of Robust Decision Frameworks. *Wiley Interdisciplinary Reviews: Climate Change* 4 (1), pp. 39–60.

Wen, Y., Schoups, G., and Giesen, N. van de (2017). Organic Pollution of Rivers: Combined Threats of Urbanization, Livestock Farming and Global Climate Change. *Scientific Reports* 7 (1), p. 43289. doi:10.1038/srep43289.

Werndl, C. (2016). On Defining Climate and Climate Change. *The British Journal for the Philosophy of Science* 67 (2), pp. 337–364. doi:10.1093/bjps/axu048.

Wesselink, A., Warner, J., Syed, M. A., Chan, F., Tran, D. D., Huq, H., Huthoff, F., Le Thuy, N., et al. (2015). Trends in Flood Risk Management in Deltas around the World: Are We Going 'Soft'? *International Journal of Water Governance* 3 (4), pp. 25–46.

Wheeler, D. and Mayes, J. (1997). Regional Climates of the British Isles. London, United Kingdom: Routledge, p. 368. ISBN: 9780415139311.

Wheeler, K., Wenger, S. J., and Freeman, M. C. (2018). States and Rates: Complementary Approaches to Developing Flow-Ecology Relationships. *Freshwater Biology* 63 (8), pp. 906–916.

Wheeler, S., Garrick, D., Loch, A., and Bjornlund, H. (2013). Evaluating Water Market Products to Acquire Water for the Environment in Australia. *Land use policy* 30 (1), pp. 427–436.

Wieland, A., Durach, C. F., Kembro, J., and Treiblmaier, H. (2017). Statistical and Judgmental Criteria for Scale Purification. *Supply Chain Management-an International Journal* 22 (4), pp. 321–328. doi:10.1108/scm-07-2016-0230.

Wilby, R. L. (2006). When and Where Might Climate Change Be Detectable in UK River Flows? *Geophysical Research Letters* 33 (19). doi:artnl1940710.1029/2006gl027552.

Wilby, R. L. and Dessai, S. (2010). Robust Adaptation to Climate Change. *Weather* 65 (7), pp. 180–185. doi:10.1002/wea.543.

Wilby, R. L., Fenn, C. R., Wood, P. J., Timlett, R., and LeQuesne, T. (2011). Smart Licensing and Environmental Flows: Modeling Framework and Sensitivity Testing. *Water Resources Research* 47 (12). doi:10.1029/2011wr011194.

Wilby, R. and Wigley, T. (1997). Downscaling General Circulation Model Output: A Review of Methods and Limitations. *Progress in Physical Geography* 21 (4), pp. 530–548.

Wilcoxon, F. (1945). Individual Comparisons by Ranking Methods. *Biometrics Bulletin* 1 (6), pp. 80–83. doi:10.2307/3001968.

Wild, M. (2018). Things Can Only Get Beta - an Opportunity to Get Financing Costs Right for Consumers. In: Citizens Advice. URL: https://www.citizensadvice.org.uk/Global/CitizensAdvice/Energy/Things%20can%20only%20get%20beta.pdf.

Wilhite, D. A., Sivakumar, M. V., and Pulwarty, R. (2014). Managing Drought Risk in a Changing Climate: The Role of National Drought Policy. *Weather and climate extremes* 3, pp. 4–13.

Williams, B. K. (2011). Adaptive Management of Natural Resources–Framework and Issues. *Journal of Environmental Management* 92 (5), pp. 1346–53. doi:10.1016/j.jenvman.2010.10.041.

Williams, D. (2020). The Influence of Statutory Land Use Planning on Water Sensitive Urban Design Practices. *Australasian Journal of Water Resources* 24 (1), pp. 60–72.

Williams, K. D., Copsey, D., Blockley, E. W., Bodas-Salcedo, A., Calvert, D., Comer, R., Davis, P., Graham, T., et al. (2018). The Met Office Global Coupled Model 3.0 and 3.1 (Gc3.0 and Gc3.1) Configurations. *Journal of Advances in Modeling Earth Systems* 10 (2), pp. 357–380. doi:10.1002/2017ms001115.

Willis, R. M., Stewart, R. A., Giurco, D. P., Talebpour, M. R., and Mousavinejad, A. (2013). End Use Water Consumption in Households: Impact of Socio-Demographic Factors and Efficient Devices. *Journal of Cleaner Production* 60, pp. 107–115. doi:https://doi.org/10.1016/j.jclepro.2011.08.006.

Wilson, W. and Barton, C. (2022). Research Briefing - Tackling the under-Supply of Housing. URL: https://researchbriefings.files.parliament.uk/documents/CBP-7671/CBP-7671.pdf (Accessed: 12.8.2022).

Wolsink, M. (2010). Contested Environmental Policy Infrastructure: Socio-Political Acceptance of Renewable Energy, Water, and Waste Facilities. *Environmental Impact Assessment Review* 30 (5), pp. 302–311.

Woodhill, J. and Röling, N. (1998). The Second Wing of the Eagle: The Human Dimension in Learning Our Way to More Sustainable Futures. In: *Facilitating Sustainable Agriculture: Participatory Learning and Adaptive Management in Times of Environmental Uncertainty*. Ed. by N. Röling and M. Wagemakers. Cambridge University Press. Cambridge, United Kingdom, p. 348. ISBN: 0-521-58174-5.

WRSE (2020). Method Statement: Environmental Ambition, Consulation Version 2020. Water Resources South East. URL: https://www.wrse.org.uk/media/zijbfld1/wrse_file_1333_wrse-ms-environmental-ambition-v2.pdf (Accessed: 14.12.2022).

WSBF (2020). Bricks & Water: Building Resilience for England's Homes. Westminster Sustainable Business Forum (WSBF). URL: https://www.policyconnect.org.uk/research/bricks-water-building-resilience-englands-homes (Accessed: 11.8.2022).

Wu, K. and Johnston, C. A. (2007). Hydrologic Response to Climatic Variability in a Great Lakes Watershed: A Case Study with the Swat Model. *Journal of hydrology* 337 (1-2), pp. 187–199.

Wurbs, R. A. (2006). Methods for Developing Naturalized Monthly Flows at Gaged and Ungaged Sites. *Journal of Hydrologic Engineering* 11 (1), pp. 55–64.

WWAP (2015). United Nations World Water Assessment Programme; World Water Development Report 2015: Water for a Sustainable World. The United Nations, Paris, France. URL: https://en.unesco.org/themes/water-security/wwap/wwdr/series (Accessed: 4.2.2023).

WWF (2022). Living Planet Report 2022 - Building a Nature-Positive Society. Almond, R.E.A., Grooten, M., Juffe Bignoli, D. and Petersen, T., Gland, Switzerland. URL: https://wwflpr.awsassets.panda.org/downloads/lpr_2022_full_report_1.pdf (Accessed: 16.1.2023).

Xu, C.-y., Widén, E., and Halldin, S. (2005). Modelling Hydrological Consequences of Climate Change—Progress and Challenges. *Advances in Atmospheric Sciences* 22 (6), pp. 789–797.

Xu, Z., Han, Y., Tam, C.-Y., Yang, Z.-L., and Fu, C. (2021). Bias-Corrected Cmip6 Global Dataset for Dynamical Downscaling of the Historical and Future Climate (1979–2100). *Scientific Data* 8 (1), p. 293. doi:10.1038/s41597-021-01079-3.

Yamazaki, K., Sexton, D. M. H., Rostron, J. W., McSweeney, C. F., Murphy, J. M., and Harris, G. R. (2021). A Perturbed Parameter Ensemble of Hadgem3-Gc3.05 Coupled Model Projections: Part 2: Global Performance and Future Changes. *Climate Dynamics* 56 (11-12), pp. 3437–3471. doi:10.1007/s00382-020-05608-5.

Yang, J. H., Cheng, C. H., and Chan, C. P. (2017). A Time-Series Water Level Forecasting Model Based on Imputation and Variable Selection Method. *Comput Intell Neurosci* 2017, p. 8734214. doi:10.1155/2017/8734214.

Yang, T., Wang, X., Zhongbo, Y., Krysanova, V., Chen, X., and Schwartz, F. (2014). Climate Change and Probabilistic Scenario of Streamflow Extremes in an Alpine

Region. *Journal of Geophysical Research: Atmospheres* 119 (14), pp. 8535–8551. doi:10.1002/2014jd021824.

Yang, W., Andréasson, J., Phil Graham, L., Olsson, J., Rosberg, J., and Wetterhall, F. (2010). Distribution-Based Scaling to Improve Usability of Regional Climate Model Projections for Hydrological Climate Change Impacts Studies. *Hydrology Research* 41 (3-4), pp. 211–229. doi:10.2166/nh.2010.004.

Yearwood, K. (2018). The Privatised Water Industry in the UK. An ATM for Investors. In: vol. 5. PSIRU Reports. Public Services International Research Unit (PSIRU), Business Faculty, University of Greenwich. Greenwich, London, United Kingdom.

Yuan, Y. and Koropeckyj-Cox, L. (2022). Swat Model Application for Evaluating Agricultural Conservation Practice Effectiveness in Reducing Phosphorous Loss from the Western Lake Erie Basin. *Journal of Environmental Management* 302, p. 114000. doi:https://doi.org/10.1016/j.jenvman.2021.114000.

Zare, M., Azam, S., and Sauchyn, D. (2022). Evaluation of Soil Water Content Using Swat for Southern Saskatchewan, Canada. *Water* 14 (2). doi:10.3390/w14020249.

Zelinka, M. D., Randall, D. A., Webb, M. J., and Klein, S. A. (2017). Clearing Clouds of Uncertainty. *Nature Climate Change* 7 (10), pp. 674–678. doi:10.1038/nclimate3402.

Zhang, H. and Hiscock, K. (2010). Modelling the Impact of Forest Cover on Groundwater Resources: A Case Study of the Sherwood Sandstone Aquifer in the East Midlands, UK. *Journal of Hydrology* 392 (3-4), pp. 136–149.

Zhang, H., Wang, B., Liu, D. L., Zhang, M., Leslie, L. M., and Yu, Q. (2020). Using an Improved Swat Model to Simulate Hydrological Responses to Land Use Change: A Case Study of a Catchment in Tropical Australia. *Journal of Hydrology* 585, p. 124822. doi:10.1016/j.jhydrol.2020.124822.

Zhang, H., Huang, G. H., Wang, D., and Zhang, X. (2011). Multi-Period Calibration of a Semi-Distributed Hydrological Model Based on Hydroclimatic Clustering. *Advances in Water Resources* 34 (10), pp. 1292–1303. doi:10.1016/j.advwatres.2011.06.005.

Zhang, S., Chen, J., and Gu, L. (2022). Overall Uncertainty of Climate Change Impacts on Watershed Hydrology in China. *International Journal of Climatology* 42 (1), pp. 507–520.

Zhang, Y., Arthington, A. H., Bunn, S. E., Mackay, S., Xia, J., and Kennard, M. (2012). Classification of Flow Regimes for Environmental Flow Assessment in Regulated Rivers: The Huai River Basin, China. *River Research and Applications* 28 (7), pp. 989–1005. doi:10.1002/rra.1483.

Zhang, Y., Collins, A. L., Murdoch, N., Lee, D., and Naden, P. S. (2014). Cross Sector Contributions to River Pollution in England and Wales: Updating Waterbody Scale Information to Support Policy Delivery for the Water Framework Directive. *Environmental Science & Policy* 42, pp. 16–32. doi:https://doi.org/10.1016/j.envsci.2014.04.010.

Zhou, S., Wang, Y., Li, Z., Chang, J., and Guo, A. (2021). Quantifying the Uncertainty Interaction between the Model Input and Structure on Hydrological Processes. *Water Resources Management* 35 (12), pp. 3915–3935. doi:10.1007/s11269-021-02883-7.

Zhu, K., Xie, Z., Zhao, Y., Lu, F., Song, X., Li, L., and Song, X. (2018). The Assessment of Green Water Based on the Swat Model: A Case Study in the Hai River Basin, China. *Water* 10 (6). doi:10.3390/w10060798.

Zwan, N. van der (2014). Making Sense of Financialization. *Socio-Economic Review* 12 (1), pp. 99–129. doi:10.1093/ser/mwt020.

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Appendix A - Chapter 2

A.1 The UKBN catchments

The most recent update of the UKBN, version 2, contains 80 catchments that are defined as benchmark across the full flow regime. However, these don't provide an adequate spatial coverage of the whole country as central, southern and eastern areas are under-represented. Of the additional 62 gauges that do provide a satisfactory coverage, 20 should be treated with caution during low flow, 23 during high flow and 5 in the medium flow ranges (Harrigan et al., 2018). The reason for not achieving the highest score for all flow ranges often relates to too few gaugings or the impossibility of ruling out abstraction effects. Most of the sites included in this study received an overall score of 5 or 6 out of a top score of 6 (Figure A.1 and Table A.1) which represents the highest quality data for all flow ranges according to the evaluation by Harrigan et al. (2018).

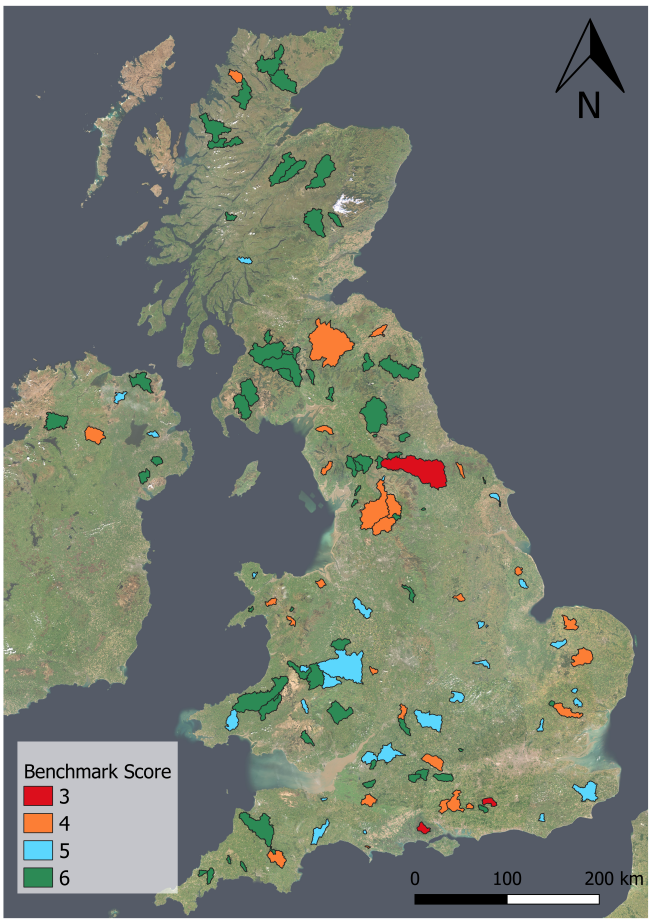


Figure A.1: Location of the 126 benchmark catchments considered in this study, scores of flow range suitability index by Harrigan et al. (2018) (6 – full range, 5 – minor uncertainties in one flow range, 4 – uncertainties in one or two flow ranges, 3 – caution required)

Table A.1: Details on the UK Benchmark Network (UKBN) stations included in this classification, score according to Harrigan et al. (2018)

NRFA Station Number	River	Area	Median Altitude	Score	Group
2002	Brora	434.40	240.50	6	group4
3003	Oykel	330.70	273.80	6	group3
4005	Meig	120.50	462.70	6	group3
7001	Findhorn	415.60	559.70	6	group5
8004	Avon	542.80	493.00	6	group5
8009	Dulnain	272.20	448.70	6	group5
13004	Prosen Water	104.00	413.30	6	group3
15025	Ericht	432.00	423.60	6	group4
21006	Tweed	1500.00	341.50	4	group1
21023	Leet Water	113.00	74.70	4	group2
21024	Jed Water	139.00	240.80	6	group2
22001	Coquet	569.80	192.80	6	group4
23004	South Tyne	751.10	331.70	6	group4
24004	Bedburn Beck	74.90	322.20	6	group2
25003	Trout Beck	11.40	649.00	6	group3
25006	Greta	86.10	409.10	6	group3
26003	Foston Beck	57.20	77.10	5	group5
27035	Aire	282.30	200.70	4	group4
27042	Dove	59.20	202.20	4	group2
27047	Snaizeholme Beck	10.20	431.30	5	group3
27051	Crimple	8.10	171.10	6	group2
27071	Swale	1363.00	104.10	3	group1
27073	Brompton Beck	12.90	63.90	6	group3
27084	Eastburn Beck	43.35	269.50	6	group3
28046	Dove	83.00	315.70	6	group2
28072	Greet	46.20	63.60	4	group5
29003	Lud	55.20	88.90	4	group5
30004	Lymn	61.60	60.80	5	group5

Table A.1 Continued: Details on the UK Benchmark Network (UKBN) stations included in this classification, score according to Harrigan et al. (2018)

30015	Cringle Brook	50.50	131.50	5	group5
31023	West Glen	4.40	110.50	5	group2
32003	Harpers Brook	74.30	90.40	5	group5
33018	Tove	138.10	133.60	5	group5
33019	Thet	316.00	38.60	4	group1
33029	Stringside	98.80	20.00	5	group4
34011	Wensum	161.90	62.70	4	group4
36003	Box	53.90	62.40	5	group5
36009	Brett	25.70	88.70	5	group5
36010	Bumpstead Brook	28.30	98.10	6	group5
37005	Colne	238.20	68.00	4	group1
38026	Pincey Brook	54.60	81.00	5	group5
39019	Lambourn	234.10	165.70	4	group4
39020	Coln	106.70	194.20	6	group5
39025	Enborne	147.60	113.50	6	group5
39028	Dun	101.30	156.20	6	group4
39034	Evenlode	430.00	135.70	5	group1
39065	Ewelme Brook	13.40	135.10	6	group2
40011	Great Stour	345.00	75.50	5	group1
41022	Lod	52.00	70.40	6	group3
41025	Loxwood Stream	91.60	60.10	3	group5
41027	Rother	37.20	98.70	4	group3
41029	Bull	40.80	57.40	5	group3
42003	Lymington	98.90	41.80	3	group5
42008	Cheriton Stream	75.10	115.50	5	group5
42010	Itchen	360.00	106.00	4	group5
42016	Itchen	236.80	119.80	4	group5
43014	East Avon	85.78	139.80	6	group5
44006	Sydling Water	12.40	192.40	5	group3
44009	Wey	7.00	104.10	4	group3
45005	Otter	202.50	131.80	5	group2

Table A.1 Continued: Details on the UK Benchmark Network (UKBN) stations included in this classification, score according to Harrigan et al. (2018)

46003	Dart	247.60	348.10	4	group3
46005	East Dart	21.50	462.30	6	group3
47009	Tiddy	37.20	108.30	6	group3
48003	Fal	87.00	125.20	6	group3
48004	Warleggan	25.30	232.70	6	group3
49004	Gannel	41.00	78.20	6	group2
50002	Torridge	663.00	146.20	6	group4
52010	Brue	135.20	105.60	4	group2
52016	Currypool Stream	15.70	172.40	5	group3
53006	Frome (Bristol)	148.90	66.20	5	group2
53008	Avon	303.00	114.80	5	group5
53009	Wellow Brook	72.60	136.00	6	group2
53017	Boyd	47.90	105.90	6	group3
54008	Teme	1134.40	214.40	5	group1
54018	Rea Brook	178.00	145.80	6	group2
54025	Dulas	52.70	337.00	5	group2
54034	Dowles Brook	40.80	128.90	4	group2
54036	Isbourne	90.70	98.90	4	group5
55014	Lugg	203.30	287.40	5	group2
55016	Ithon	358.00	319.00	6	group4
55026	Wye	174.00	385.70	6	group3
55029	Monnow	354.00	184.00	6	group4
56013	Yscir	62.80	361.90	5	group3
57004	Cynon	106.00	266.70	6	group3
60002	Cothi	297.80	230.00	6	group3
60003	Taf	217.30	122.40	5	group3
60012	Twrch	20.70	309.40	6	group3
62001	Teifi	893.60	196.00	6	group4
65001	Glaslyn	68.60	327.70	4	group3
65005	Erch	18.10	143.90	6	group3
66004	Wheeler	62.90	199.70	4	group2

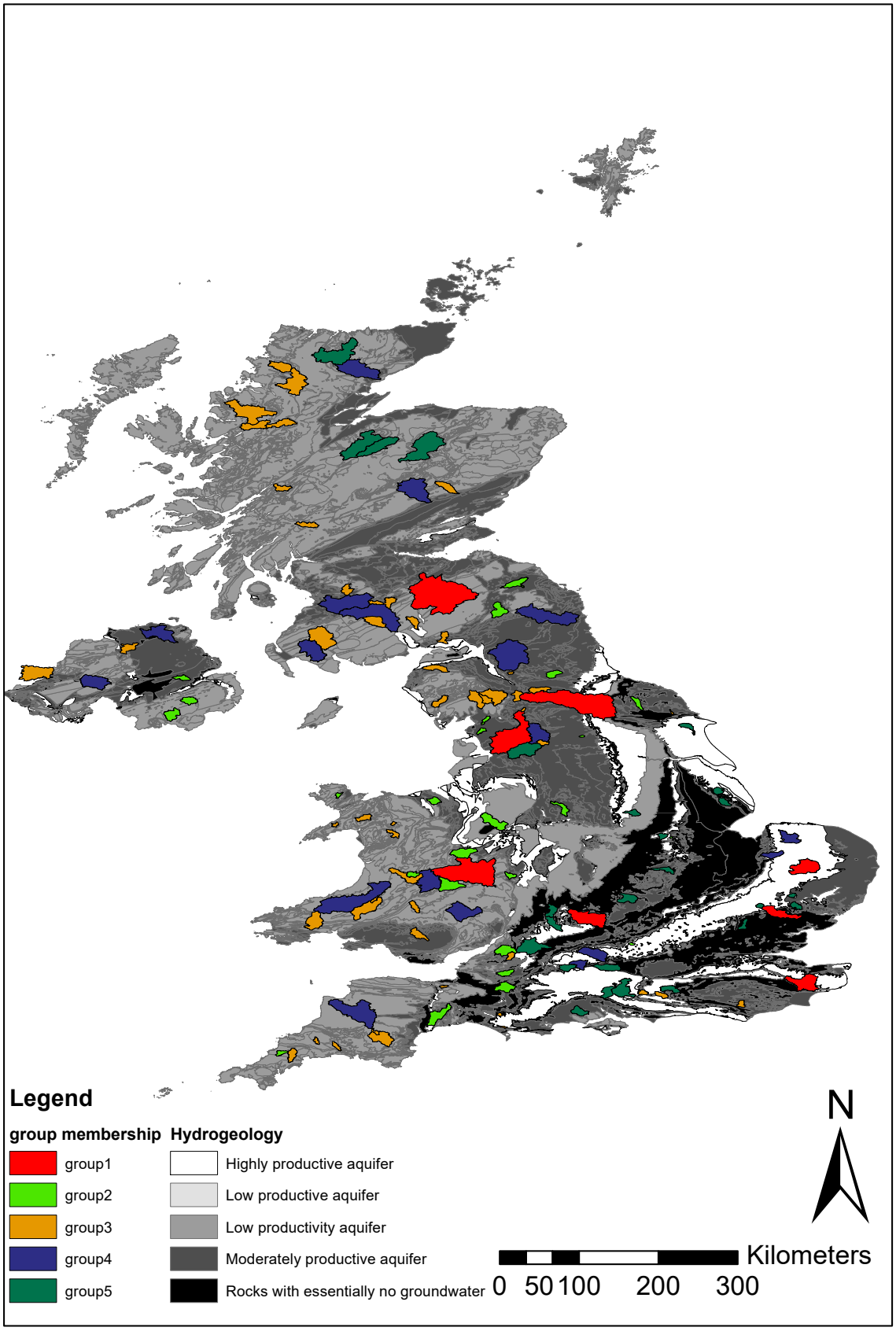
Table A.1 Continued: Details on the UK Benchmark Network (UKBN) stations included in this classification, score according to Harrigan et al. (2018)

67010	Gelyn	13.10	413.40	6	group3
67018	Dee	53.90	397.80	4	group3
68005	Weaver	207.00	86.20	5	group2
71001	Ribble	1145.00	197.20	4	group1
71004	Calder	316.00	209.80	4	group5
72005	Lune	219.00	294.30	6	group3
72014	Conder	28.50	105.10	6	group2
73005	Kent	209.00	205.80	6	group3
73011	Mint	65.80	210.90	6	group3
73015	Keer	48.00	92.90	6	group2
74001	Duddon	85.66	296.10	4	group3
75017	Ellen	96.00	157.20	4	group3
76014	Eden	69.40	377.00	6	group3
77004	Kirtle Water	72.00	124.10	6	group3
78004	Kinnel Water	76.10	236.40	6	group3
79002	Nith	799.00	288.90	6	group4
79004	Scar Water	142.00	319.70	6	group3
81002	Cree	368.00	212.60	6	group3
81004	Bladnoch	334.00	94.10	6	group4
83006	Ayr	574.00	212.10	6	group4
83010	Irvine	72.80	240.60	6	group3
84022	Duneaton	110.30	334.50	6	group3
85003	Falloch	80.30	447.40	5	group3
90003	Nevis	69.20	521.00	6	group3
93001	Carron	137.80	344.40	6	group3
94001	Ewe	441.10	310.50	6	group3
95001	Inver	137.50	269.70	4	group3
96002	Naver	477.00	187.70	6	group5
102001	Cefni	21.70	67.80	5	group2
201005	Camowen	276.60	151.30	4	group4
201008	Derg	335.40	172.10	6	group3

Table A.1 Continued: Details on the UK Benchmark Network (UKBN) stations included in this classification, score according to Harrigan et al. (2018)

203028	Agivey	100.50	161.50	5	group3
203042	Crumlin	55.30	127.40	5	group2
204001	Bush	299.20	90.10	6	group4
205008	Lagan	84.60	156.40	6	group2
206001	Clanrye	120.30	89.80	6	group2

A.2 Location of Benchmark Groups in main Aquifers (British Geological Survey, 2010)]



A.3 Description of the applied Metrics

Table A.2: Hydrological Metrics, climatic and physical parameters included in this assessment (A- annual, d – daily, m- monthly)

Abbreviation	Metric	Metric Definition	Unit	Temporal resolution	Sources/ Applications	R-Package
	Magnitude of flow events – average conditions					
jan, apr, jul, oct	mean monthly flow	mean daily flow in four months	$mmday^{-1}$	m	Laizé et al. (2017), Monk et al. (2006)	hydrostats
med	median daily flow	median daily flow	m^3s^{-1}	d		
skew	skewness of daily flow	mean daily flow divided by median daily flow	dimensionless	d	Olden and Poff (2003), Sokal and Rohlf (1969), Clausen and Biggs (1997) Clausen and Biggs (2000)	
arcm	mean annual runoff	mean annual flow divided by catchment area	$mmday^{-1}$	A		FlowScreen
arcn	median annual runoff	median annual flow divided by catchment area	$mmday^{-1}$	A		FlowScreen

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

medan10	median annual Q_{10}	median of the annual flow exceeded 10 percent of time	m^3s^{-1}	A	Piniewski (2017)	
medan90	median annual Q_{90}	median of the annual flow exceeded 90 percent of time	m^3s^{-1}	A	Piniewski (2017)	
sdlog	standard deviation daily flows	standard deviation of log daily flows	m^3s^{-1}	d	Piniewski (2017)	
skew2	skewness in annual flow	mean annual flow divided by median annual flow	dimensionless	A	Sokal and Rohlf (1969), Puckridge et al. (2000)	
	magnitude of flow events – low flow conditions					
bf	baseflow index (BFI)	proportion of river runoff that derives from stored sources, mean annual baseflow index	percentage		Eckhardt (2005)	FlowScreen
Q_{90}	average Q_{90}	Flow exceeded 90% of the time	$mmday^{-1}$			FlowScreen
Q_{95}	average Q_{95}	Flow exceeded 95% of the time	$mmday^{-1}$			FlowScreen

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

lfd	low flow discharge	flow exceeded 90% of the time divided by Q_{50}	dimensionless		Clausen and Biggs (2000)	
bfcv	CV in BFI	the ratio between the standard deviation and mean of baseflow index	dimensionless			
	magnitude of flow events – high flow conditions					
hfd1	high flow discharge	Flow exceeded 10% of the time divided by Q_{50}	dimensionless		Clausen and Biggs (2000)	
Q_{10}	average Q_{10}	Flow exceeded 10% of the time	$mmday^{-1}$			
Q_5	average Q_5	Flow exceeded 5% of the time	$mmday^{-1}$			
anmax	median annual maximum flow	the median of the annual maximum flow series of the year	m^3s^{-1}			FlowScreen
	Frequency of flow events – low flow conditions					
lfs1	low flow event count 1	mean number of annual occurrences during which the magnitude of flow is below Q_{99}	days	A	Kennard et al. (2010a)	hydrostats

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

lfs2	low flow event count 2	CV in number of annual occurrences during which the magnitude of flow is below Q_{75}	days	A	Richter et al. (1998, 1997, 1996)	hydrostats
	Frequency of flow events – high flow conditions					
hfs1	high flow event count	mean number of annual occurrences during which the flow is above Q_{10}	days	A	Clausen and Biggs (2000) Clausen and Biggs (1997), Olden and Poff (2003), Kennard et al. (2010a)	FlowScreen
hfs2	CV high flow event count	CV in number of annual occurrences during which the flow is above Q_{25} (*100)	dimensionless	A	Clausen and Biggs (2000) Clausen and Biggs (1997), Kennard et al. (2010a)	EflowStats
	Duration of flow events					
dlf	low flow/drought duration	CV in duration of occurrences during which the magnitude of flow remains below Q_{80}	dimensionless	d		FlowScreen
amin7	annual minima of 7 days	magnitude of mean annual minimum flows of 7 days	$mmday^{-1}$	d	Kennard et al. (2010a)	FlowScreen
aminf30	annual minima of 30 days	Magnitude of mean annual minimum flows of 30 days	$mmday^{-1}$	m	Kennard et al. (2010a)	FlowScreen

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

amax7	annual maxima of 7 days	magnitude of mean annual maximum flows of 7 days	$mmday^{-1}$	d	Kennard et al. (2010a)	EflowStats
amax30	annual maxima of 30 days	magnitude of mean annual maximum flows of 30 days	$mmday^{-1}$	m	Kennard et al. (2010a)	EflowStats
anmin	median annual minimum flow	median of the 7 day annual minimum flow series	$mmday^{-1}$	d		FlowScreen
dur	duration between 25% and 75% of flow	mean duration between the day when 50% of annual flow volume and the day when 75% of annual flow volume have passed	days	A		FlowScreen

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

	Timing of flow events – average flow conditions					
seas	seasonality of mean daily flows	contingency of mean daily flows divided by predictability	dimensionless	d	Colwell (1974)	hydrostats
pred	predictability of mean daily flow	predictability of flow, composed of two components: constancy + contingency				
mmtd	timing between annual high and low flow	average number of months between the highest and lowest monthly runoff	months	m		hydrostats
consts	constancy of mean daily flow	the temporal invariance of daily flow	dimensionless		Colwell (1974)	hydrostats
	Timing of flow events – low flow conditions					
jdmi	date of annual minimum	julian date of annual minimum flow, given as day of the year	dimensionless	d	Kennard et al. (2010a)	EflowStats
cvjdmi	CV date of annual minimum	CV julian date of annual minimum flow, given as day of the year	dimensionless	d		EflowStats

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

predmi	predictability of min daily flow	predictability of minimum daily flow	dimensionless	d	Colwell (1974)	hydrostats
	Timing of flow events – high flow conditions					
jdma	date of annual maximum	julian date of annual maximum flow, given as day of the year	dimensionless	d	Kennard et al. (2010a), Richter et al. (1998, 1997)	EflowStats
cvjdma	CV date of annual maximum	dimensionless	d			
predma	predictability of max daily flow	predictability of maximum daily flow	dimensionless	d	Colwell (1974)	hydrostats
	Rate of change in flow events					
nr	number of reversals	average number of negative and positive changes in flow from one day to the next	A	year1	Kennard et al. (2010a)	EflowStats
mrr	CV rate of rise	CV in rate of positive changes in flow from one day to the next	d	dimensionless	Kennard et al. (2010a)	EflowStats

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

mrf	CV rate of fall	CV in rate of negative changes in flow from one day to the next	d	dimensionless	Kennard et al. (2010a)	EflowStats
	Climatic parameters					
shost	percentage of rainfall that becomes runoff	percentage of rainfall that contributes to increase of runoff				FEH NRFA[1]
saar	Standard Average Annual Rainfall	average annual rainfall in average millimetres per month from 1997 to 2017	mm	m	Acreman et al. (2008)	available through the NRFA API[2]
	Physical Parameters					
area	catchment area	drainage area of the gauge	km^2			available through the NRFA API
alt	altitude	altitude of the gauging station	meter			available through the NRFA API

Table A.2 Continued: Hydrological Metrics, climatic and physical parameters included in this assessment (A – annual, d – daily, m – monthly)

slope	mean slope	mean drainage path slope, it is calculated as the mean of all inter-nodal slopes (derived from a digital terrain model) for the catchment	m/km			FEH[1]
prop	proportion of time catchment soils are wet	proportion of the time soils are wet (defined as a soil moisture deficit of less than 6 mm)	percentage			FEH[1]
bfih	catchment responsive-ness	BFIHOST, a measure of catchment responsiveness based on the hydrology of soil types classification	percentage		Acreman et al. (2008)	FEH/NRFA[1]
(urb)	percentage of urban areas	percentage of areas classed as urban within the catchment	percentage			FEH[1,3]

[1]Flood Estimation Handbook (FEH) provides the metrics slope, prop, urb, bfih, saar and shost. The latter called “spr” in the FEH. They were partly derived through the Integrated Hydrological Digital Terrain Model further explained by (NRFA, 2018)

[2]Note that for six stations the NRFA server doesn’t dispose of the SAAR data, for four of those stations SAAR was hence retrieved from the FEH for the standard period of 1961-1990 and for further two data was retrieved for the nearest station where data was available. For station 33040 (Rhee at Ashwell) this was 33033 (Hiz at Arlesey) and for 206002 (Jerretspass at Jerretspass) this was 206001 (Clanrye at Mountmill Bridge).

[3]This descriptor was run for control reasons as it should not have an effect on natural flow regimes

A.4 Supplementary Results

A.4.1 Clustering and Distribution of Metrics across the Natural Classification

The figures Figure A.2 and Figure A.3 show the distribution of the remaining metrics across the natural regime classes. Unlike the 16 metrics in Figure 2.11 these metrics were not considered in the clustering algorithm.

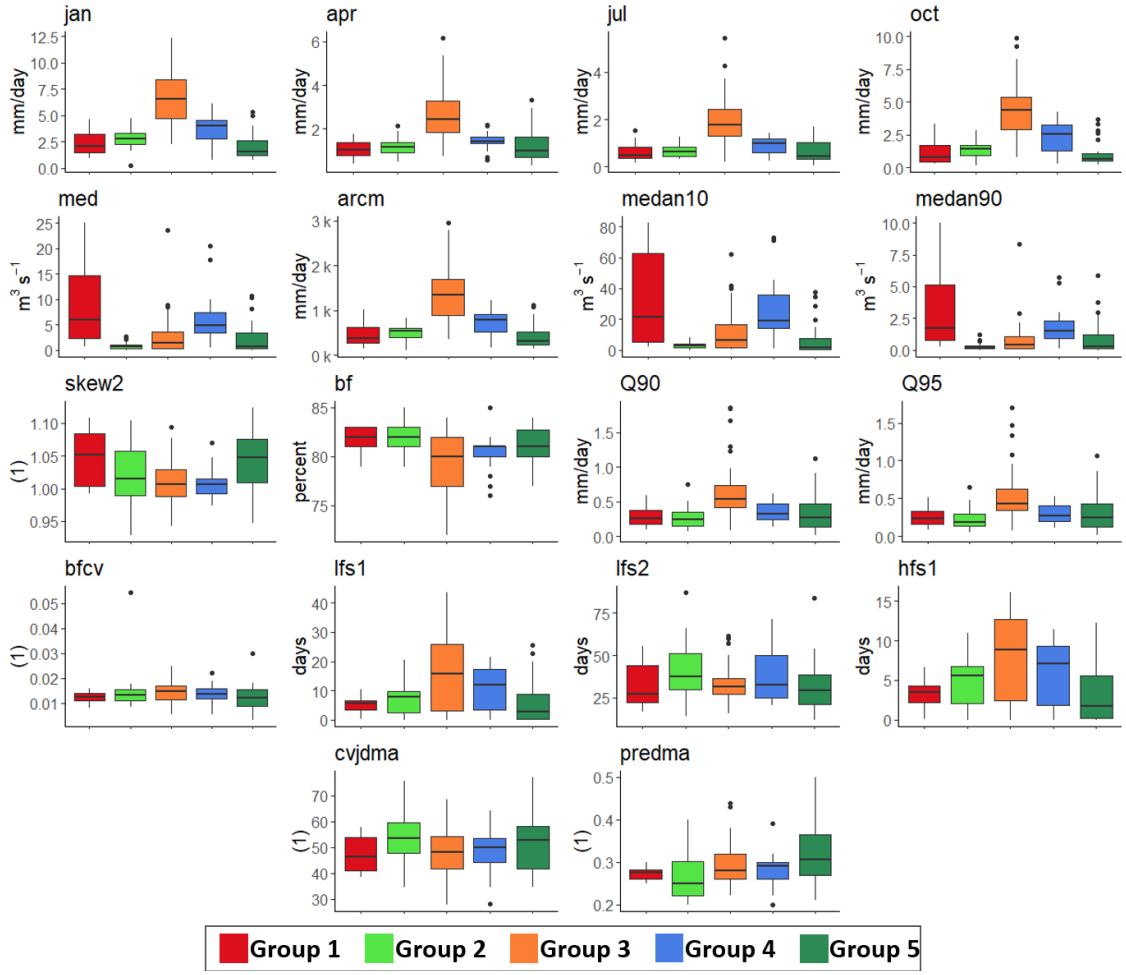


Figure A.2: Distribution of the magnitude of flow events during average conditions (jan, apr, jul, oct, med, arcm, medan10, medan90, skew2), low flow magnitude (bf, Q_{90}, Q_{95}, bfcv), frequency of low flow (lfs1, lfs2) and frequency (hfs2) and timing of high flow events (cvjdma, predma) in the natural flow regime classification, (n=126). For acronyms see Table A.2.

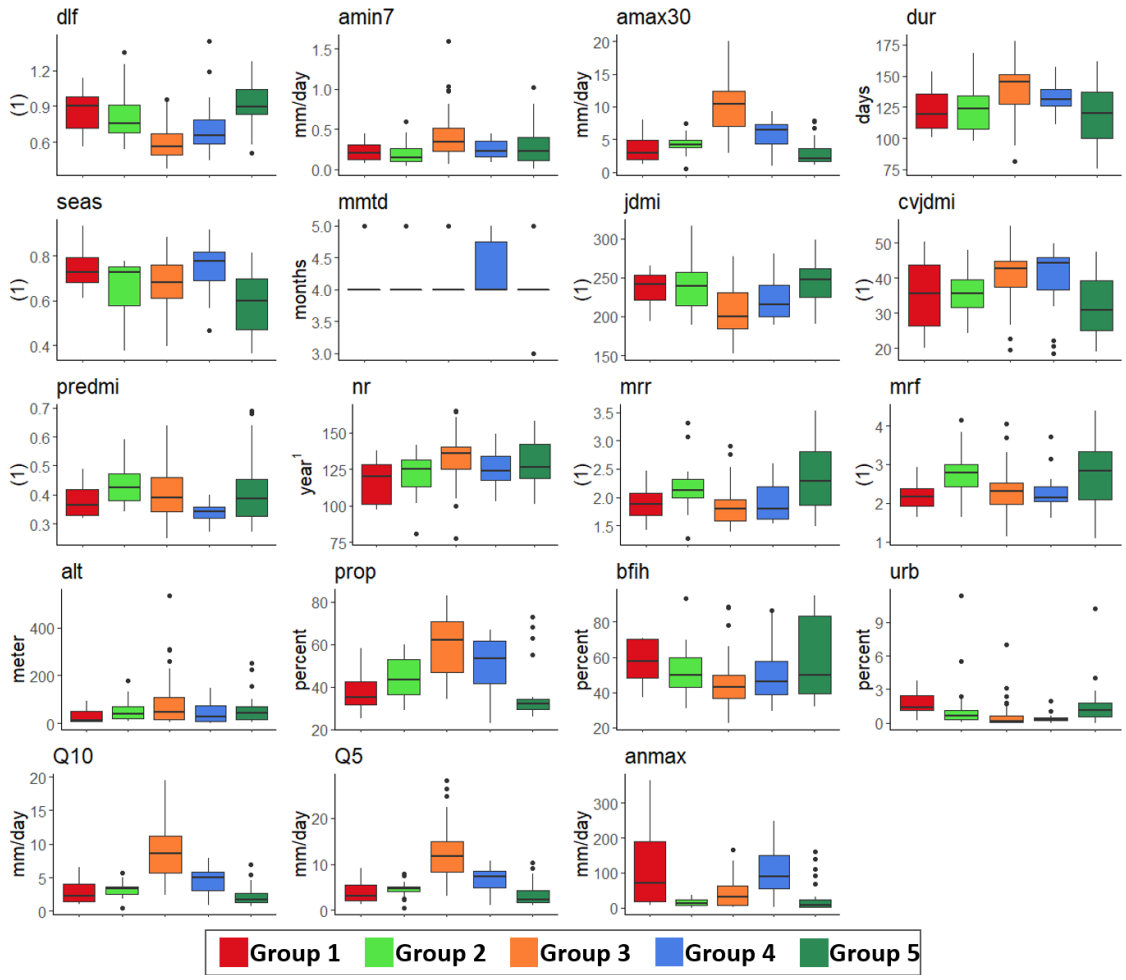


Figure A.3: Distribution of the duration of flow events (dlf, amin7, amax30, dur), timing of high flow (seas, mmtd) and low flow events (jdmi, cvjdmi, predmi), rate of change (nr, mrr, mrf), physical (alt, prop, bfih) catchment descriptors and high flow magnitude (Q_{10}, Q_5, anmax) in the natural flow regime classification, (n=126). For acronyms see Table A.2.

A.4.2 Post Analysis

While the non-parametric test developed by Kruskal and Wallis (1952) only tests if the variables in the groups have different means, the Wilcoxon signed-rank test Wilcoxon (1945) analyses which groups have statistically significant different means. Table A.3 contains the details underlying figures Figure 2.15, Figure A.4 and Figure A.5.

Table A.3: Kruskall-Wallis test (df=4) and non-significant group differences according to Wilcoxon (1945) (95%)

Flow category	Metric	Chi-squared	Sig.	Non sig. pairings Wilcox(.95)
Magnitude of flow events – average conditions	jan	508.00	< 0.005	2-1
	apr	445.00	< 0.005	2-1
	jul	432.00	< 0.005	2-1
	oct	471.00	< 0.005	2-1
	med*	394.00	< 0.005	4-1, 5-2
	skew*	71.00	< 0.005	2-1, 4-2, 5-3, 5-4
	arcn	502.00	< 0.005	2-1
	arcm	503.00	< 0.005	2-1
	medan10	378.00	< 0.005	4-1, 5-2
	medan90	367.00	< 0.005	5-2
	sdlog*	59.00	< 0.005	2-1, 4-2, 5-2, 5-4
	skew2	151.00	< 0.005	2-1, 4-3
Magnitude of flow events – low flow conditions	Q_{90}	328.00	< 0.005	2-1
	Q_{95}	293.00	< 0.005	2-1
	bf	70.00	< 0.005	2-1, 5-1, 5-2
	bfcv	36.00	< 0.005	2-1, 4-1, 4-2, 5-2, 5-4
	lfd	64.00	< 0.005	2-1, 5-1, 4-2, 5-2
Magnitude of flow events – high flow conditions	hfd1	75.00	< 0.005	2-1, 5-4
	Q_{10}	503.00	< 0.005	2-1
	Q_5	485.00	< 0.005	2-1
	anmax	305.00	< 0.005	4-1
Frequency of flow events low flow conditions	lfs1	161.00	< 0.005	2-1, 5-1
	lfs2	19.00	< 0.005	3-1, 4-1, 5-1, 3-2, 5-2, 5-3, 5-4
Frequency of flow events high flow conditions	hfs1	156.00	< 0.005	5-1
	hfs2	92.00	< 0.005	2-1, 5-1, 5-2, 4-3
Duration of flow events	dlf*	311.00	< 0.005	2-1, 5-1, 5-2
	amin7*	250.00	< 0.005	2-1
	aminf30	342.00	< 0.005	2-1
	amax7*	463.00	< 0.005	2-1, 5-1

Table A.3 Continued: Kruskall-Wallis test (df=4) and non-significant group differences according to Wilcoxon (1945) (95%)

	amax30	495.00	< 0.005	2-1
	anmin*	237.00	< 0.005	2-1
	dur	117.00	< 0.005	2-1
Timing of flow events average flow conditions	seas*	236.00	< 0.005	3-1, 4-1, 5-2
	pred*	177.00	< 0.005	3-1, 4-1, 5-2, 4-3
	mmtd	33.00	< 0.005	3-1, 4-1, 5-1, 5-2, 4-3, 5-3
	consts*	252.00	< 0.005	3-1, 4-1, 5-2, 4-3
Timing of flow events low flow conditions	jdmi*	199.00	< 0.005	2-1, 5-1, 5-2
	cvjdmi*	129.00	< 0.005	2-1, 5-1, 5-2, 4-3
	predmi*	100.00	< 0.005	4-1, 5-2
Timing of flow events high flow conditions	jdma*	62.00	< 0.005	2-1, 3-1, 5-1, 3-2,4-2, 4-3
	cvjdma*	80.00	< 0.005	3-1, 4-1, 5-2, 4-3
	predma*	22.00	< 0.005	3-2, 4-2, 5-2, 4-3, 5-3, 5-4
Rate of Change	nr	21.00	< 0.005	2-1, 4-1, 3-2, 4-2, 5-2, 5-3, 5-4
	mrr*	191.00	< 0.005	3-1, 4-1, 4-3
	mrf*	130.00	< 0.005	4-3
Climatic Metrics	saar	583.00	< 0.005	2-1
	shost	176.00	< 0.005	2-1, 5-4
Physical Descriptors	slope	379.00	< 0.005	2-1
	area	472.00	< 0.005	3-2
	alt	69.00	< 0.005	3-2, 4-2, 5-2, 5-4
	prop	465.00	< 0.005	-
	bfih	109.00	< 0.005	2-1, 5-4

* variables with daily resolution

The two following figures Figure A.4 and Figure A.5 display the distribution of the metrics and results of the Wilcoxon (1945) test across the final catchment classification. These metrics were not specifically discussed in section 2.4.4. As illustrated in Table A.3, the flow categories these metrics describe are less suitable to distinguish the catchment classes than the magnitude of flow during average conditions and high flow conditions, the duration of flow events and the timing of low flow conditions. This is due to a higher number of non-significant group pairings and more metrics describing events on a daily scale where the effects of abstraction cannot be ruled out.

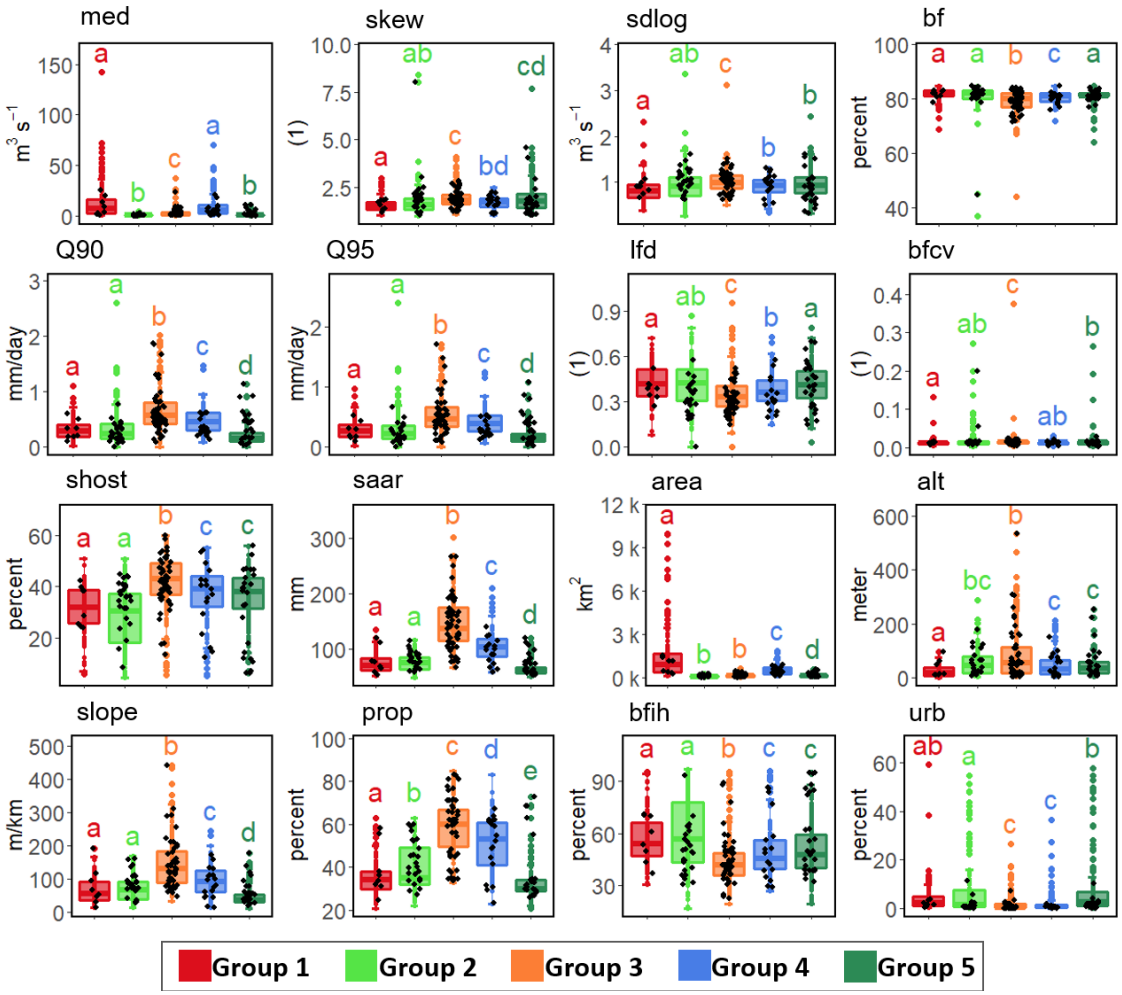


Figure A.4: Distribution of the metrics describing magnitude of average flow on daily scale (med, skew, sdlog), magnitude of low flow (bf, Q_{90}, Q_{95}, lfd, bfcv), climatic characteristics (shost, saar) and physical characteristics (area, alt, slope, prop, bfih, (urb)) across the final catchment classification. Benchmark catchments are given in black. Groups sharing the same letter are not significantly different according to the Wilcoxon signed-rank test by Wilcoxon (1945) (n=875). For acronyms see Table A.2.

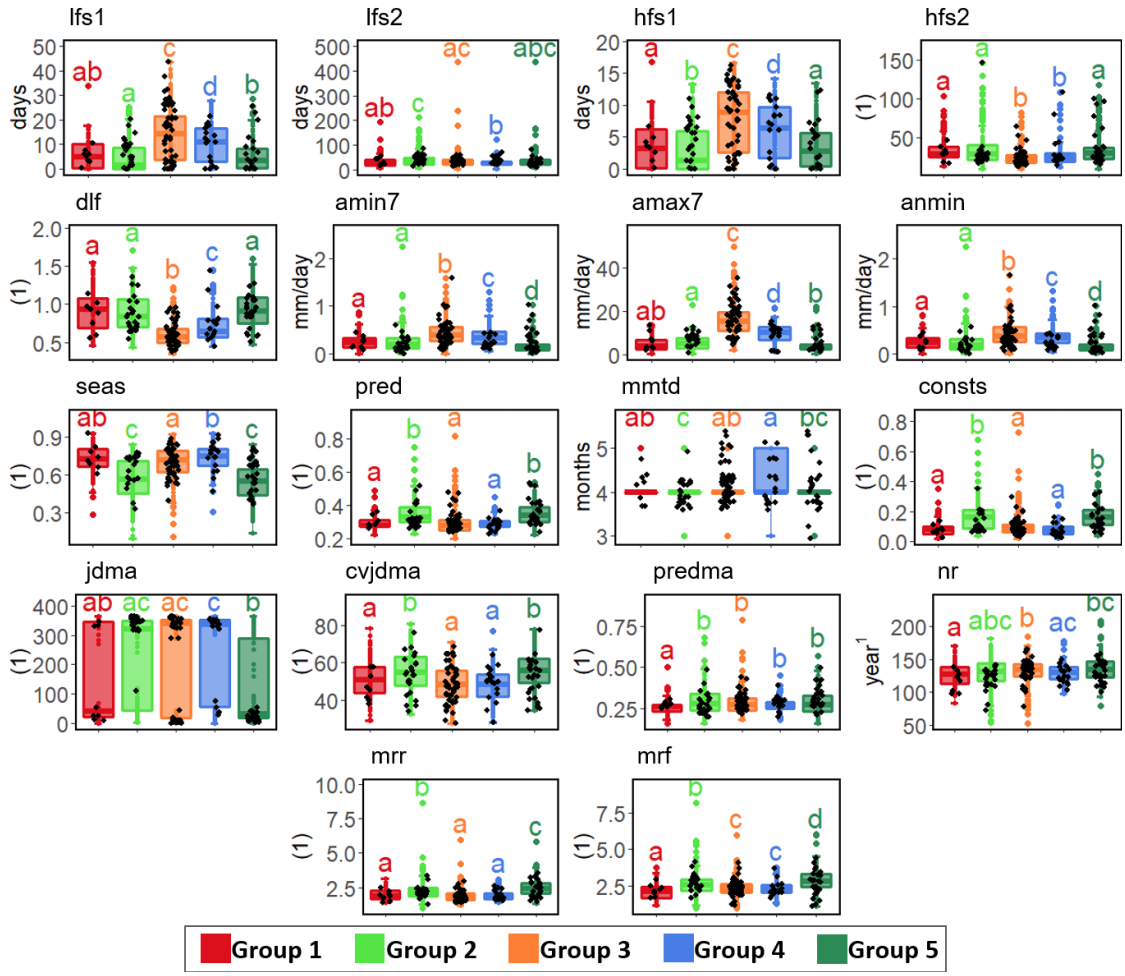


Figure A.5: Distribution of the hydrological metrics describing the frequency of low flow (lfs1, lfs2) and high flow events (hfs1, hfs2), the duration of flow events on daily scale (dlf, amin7, amax7, anmin), the timing of flow events (seas, pred, mmtd, consts, jdma, cvjdma, predma) and the rate of change (nr, mrr, mrf) across the final catchment classification. Benchmark catchments are given in black. Groups sharing the same letter are not significantly different according to the Wilcoxon signed-rank test by Wilcoxon (1945) (n=875). For acronyms see Table A.2.

Appendix B - Chapter 3

B.1 The UKCP18 Regional Projections

Table B.1: The members of the UKCP18's Regional Climate Model (RCM)-Perturbed Physics Ensemble (PPE) and identifier used in this study (adapted from Met Office (2021b))

GCM	RCM	Identifier
HadGEM3-GC3.05	HadREM3-GA705	member 1
		member 4
		member 5
		member 6
		member 7
		member 8
		member 9
		member 10
		member 11
		member 12
		member 13
		member 15

B.2 Supplementary Results

Table B.2 lists all parameters considered in the calibration of SWAT+, Table B.3 provides the projected mean monthly changes in streamflow for each of the 12 UKCP18 ensemble members by the far future and Table B.4 & Table B.5 provide the same for each of the eCX ensemble members.

The variability introduced by different SWAT+ parameter sets (internal variability) and by different GCM-RCM combinations/ensemble members discussed in section 3.3.5 is provided in Figure B.1 followed by Figure B.2 which shows a bar plot of the SWAT+ parameter values across the 20% driest and 20% wettest SWAT+ projections.

Table B.2: SWAT+ parameters included in the sensitivity analysis and in the calibration and validation.

Parameter	Description	Unit	Change type* and Parameter range used in sensitivity analysis	sensitive efficiency parameter	used in calibration & validation
Surface response					
biomix	redistribution of soil constituents due to biota activity	-	abschg / -1 | 1		
canmx	maximum canopy storage	mm H_2O	pctchg / -60 | 60		
cn2	curve number condition 2	-	abschg / -15 | 10	NSE$_{inv}$	Idle, Rother
cn3_swf	pothole evaporation coefficient	-	absval / 0 | 1		
dis_stream	average distance to stream	m	absval/ 0 | 6000		
epco	plant uptake compensation factor	-	abschg / -1 | 1	KGE	Idle, Rother
esco	soil evaporation compensation factor	-	abschg / -1 | 1	KGE, pbias	Idle, Rother
lat_len	slope length for subsurface flow	m	pctchg / -50 | 50		
lat_ttime	lateral flow travel time	days	absval / 0 | 180		
ovn	overland Manning roughness	-	absval / 0.01 | 30		
perco	percolation coefficient for soil moisture adjustment	fraction	absval / 0 | 1	bR^2, KGE, pbias, VE	Idle, Rother
slope	catchment steepness	m/m	pctchg / -50 | 50		
slope_len	average slope length	m	relchg / -0.6 | 0.6		

Tabel B.2 Continued: SWAT+ parameters included in the sensitivity analysis and in the calibration and validation.

Subsurface response					
alpha	baseflow alpha factor	days	abschg / -1 | 1	bR^2, pbias, VE, KGE	Idle, Rother
awc	available soil water capacity	mm H_2O/ mm soil	absval / 0.01 | 1	NSE_{inv}, KGE	Idle, Rother
bd	biomass density	kg/m3	absval / 0.9 | 1.8	KGE, VE	Idle, Rother
bf_max	baseflow rate when entire area is contributing to baseflow	mm	absval / 0.1 | 2		
cbn	soil carbon content	%	pctchg / -50 | 50		
flo_min	minimum aquifer storage to allow return flow	m	abschg / -5000 | 5000	bR^2, pbias, VE, KGE	Idle, Rother
k	saturated hydraulic conductivity	mm/h	pctchg / -60 | 60	NSE_{inv}	Rother
latq_co	plant ET curve number coefficient	-	abschg / -1 | 1		Idle
revap_co	amount of evaporation from the shallow aquifer	-	absval / 0.02 | 2	KGE, NSE_{inv}	Idle
revap_min	threshold depth of water in the shallow aquifer for revap to occur	m	relchg / -0.7 | 0.7	NSE_{inv}	Idle
z	soil depth	mm	pctchg / -60 | 60	KGE, pbias, VE	Rother, Idle
Basin response					
dorm_hr	time threshold to define dormancy	hours	absval / 0 | 24		

Tabel B.2 Continued: SWAT+ parameters included in the sensitivity analysis and in the calibration and validation.

evlai	leaf area index at which no evaporation occurs from water surface	-	absval / 0 | 10		
evrch	reach evaporation adjustment factor	-	abschg /-0.5 |0.5		
snofall_tmp	mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain	℃	abschg / -10 | 10	VE	Rother
snomelt_lag	the influence of the previous day's snow pack temperature on the current day's snow pack temperature	-	abschg / -1 | 1		
snomelt_max	melt factor for snow on June 21	mm H_2O/ degree/ day-℃	absval / 0 | 10		
snomelt_min	melt factor for snow on December 21	mm H_2O/ degree/ day-℃	absval / 0 | 10		
snomelt_tmp	snow melt threshold temperature	℃	abschg / -10 | 10		
surlag	surface runoff lag coefficient	days	absval / 0.05 | 24		
trnsrch	fraction of permanent transmission losses from channel	fraction			

* abschg = absolute change, pctchg = percentage change, absval = change by absolute value, relchg = relative change

Table B.3: Mean monthly percentage change in streamflow across the UKCP18 ensemble members (ens) by the far future period (2061-2080) as compared to the reference period (2001-2017), Rother (above), Idle (below).

	ens1	ens4	ens5	ens6	ens7	ens8	ens9	ens10	ens11	ens12	ens13	ens15
Rother												
Jan	9.7	18.7	-0.2	56.8	-9.2	2.6	19.7	24.8	26.0	36.1	-24.9	33.6
Feb	35.2	25.5	24.5	73.0	42.3	29.2	9.1	26.1	31.8	19.7	76.9	38.8
Mar	29.9	-6.8	34.2	16.6	16.0	26.4	17.8	4.1	9.2	7.2	0.9	21.3
Apr	8.4	7.7	32.3	-0.6	14.9	14.4	-16.1	-1.2	-14.8	-11.0	-17.7	8.0
May	-11.2	-6.4	-7.1	9.3	4.4	0.1	-15.6	-8.4	-21.0	1.6	-25.5	-1.1
Jun	-15.0	-9.0	-11.6	-14.5	-17.5	-2.6	-21.4	-27.7	-12.4	-16.8	-32.0	-10.8
Jul	-24.6	-9.7	-24.3	-19.0	-17.1	-18.0	-22.9	-22.9	-26.2	-13.8	-36.4	-11.6
Aug	-25.2	-15.5	-30.6	-17.9	-20.8	-15.8	-30.2	-26.0	-32.0	-18.9	-35.9	-11.5
Sep	-24.5	-8.0	-23.0	-12.4	-20.5	3.6	-18.1	-14.8	-25.9	-19.1	-31.0	-13.6
Oct	-25.4	10.3	-22.1	-29.1	-21.5	13.2	-18.9	-10.7	-27.4	-29.9	-19.1	-7.0
Nov	-23.1	12.9	-8.3	-5.8	-15.9	-7.3	-5.1	-2.2	-28.2	-40.1	-32.5	-29.6
Dec	-10.1	59.4	-27.2	-5.0	34.2	7.3	-1.8	4.0	-18.1	22.7	-14.4	9.5
annual	1.6	14.9	-1.4	13.5	4.1	8.1	1.2	5.2	-1.5	5.4	-13.1	14.4
Idle												
	ens1	**ens4**	**ens5**	**ens6**	**ens7**	**ens8**	**ens9**	**ens10**	**ens11**	**ens12**	**ens13**	**ens15**
Jan	-20.1	6.5	-28.4	-18.5	-6.8	-15.4	-29.0	-11.0	-5.4	2.2	-37.3	-3.4
Feb	2.4	14.6	-16.8	1.3	13.2	0.3	-23.1	-3.5	-8.6	2.0	9.3	22.4
Mar	-13.4	-11.5	-11.7	-5.4	0.0	3.7	-25.2	-14.1	-4.1	-2.2	-21.8	15.4
Apr	-16.0	1.0	-11.9	-11.9	-4.2	-7.2	-21.2	-13.5	-27.3	-17.4	-29.9	4.2
May	-22.9	-9.3	-11.6	-15.1	0.3	-12.9	-30.4	-14.4	-24.3	-11.9	-35.9	-10.8
Jun	-27.5	-7.4	-22.1	-24.4	-12.4	-15.6	-33.9	-24.5	-24.1	-17.9	-38.0	-16.4
Jul	-30.4	-9.5	-29.0	-24.4	-15.7	-22.4	-31.8	-21.0	-26.4	-16.6	-37.3	-14.2
Aug	-28.7	-14.2	-34.5	-24.8	-16.0	-21.9	-39.0	-29.5	-26.7	-20.1	-41.1	-9.1
Sep	-34.3	-7.9	-25.1	-24.4	-17.0	-20.4	-35.2	-29.8	-25.7	-17.2	-39.3	-10.6
Oct	-25.9	-1.6	-25.3	-20.0	-12.0	-14.6	-32.4	-24.7	-24.3	-16.1	-32.9	-0.6
Nov	-40.3	-3.2	-24.1	-27.7	-18.6	-4.7	-39.2	-17.1	-30.8	-20.5	-23.0	-18.5
Dec	-33.6	10.6	-32.3	-34.1	0.4	1.7	-35.6	-16.1	-19.1	-12.2	-29.2	-27.4
annual	-23.9	-0.6	-21.8	-18.4	-7.3	-10.6	-29.9	-17.1	-18.4	-10.7	-29.6	-2.5

Table B.4: Mean monthly percentage change in streamflow across the euro-CORDEX (eCX) ensemble members by the far future period (2061-2080) as compared to the reference period (2001-2017), Rother catchment.

RCP8.5	**CNRM-ALADIN**	**NCC-HIRHAM**	**IPSL-WRF**	**IPSL-REMO**	**MPI-ALADIN**	**HAD-HAD**
Jan	15.1	11.2	32.9	-1.5	31.6	-8.3
Feb	17.8	16.4	30.8	-7.7	37.4	17.6
Mar	25	22.3	38.1	29.8	11.3	17.7
Apr	5.2	-1	42.3	29.3	11.6	6.3
May	11.9	5.2	19.9	-0.4	-12.9	-3.7
Jun	-4.4	-5.5	22.5	-11.4	7	-11.1
Jul	6.9	-12.6	18.5	-19	-4.8	-13.3
Aug	0.6	-7.4	17.5	-14.4	-2.7	-17.6
Sep	8.2	7	19.1	-15.3	-1.1	-7.7
Oct	-11.3	26.6	27.6	-23.3	11.6	8.8
Nov	-16.7	-8.6	45.3	-28.3	28.6	0.7
Dec	11.7	24.5	38.6	1.1	27.7	34.5
annual	9.4	10	32.2	-2.3	16.2	5
RCP4.5	**CNRM-RACMO**	**EC-RCA**	**IPSL-RCA**	**NCC-REMO**	**IPSL-WRF**	**HAD-RACMO**
Jan	2.8	-2.1	41.1	14.1	33.2	24.6
Feb	0.7	10.2	20.9	-17.7	16	4.5
Mar	3.1	7.9	26.6	-1.9	16.4	-8
Apr	-4.9	35.5	14.8	-7.5	4.2	19.5
May	-1	18.8	16.3	-8.5	23.3	24
Jun	-10.3	-14.5	6.3	-7.9	3	18
Jul	8.1	-10	8	-14	-3.9	3.5
Aug	-3.8	-0.6	0.7	-13.5	5.2	1.9
Sep	-16.3	3.1	8.9	-17.1	13.5	13.1
Oct	25	1	-5.7	-19.3	10	30.9
Nov	26.7	13.9	-17.5	-16.1	12.4	-18.7
Dec	13.5	14.9	2.6	51.1	7.2	21.6
annual	8.7	8.8	13.2	-0.3	13.4	9.5
RCP2.6	**CNRM-RACMO**	**EC-RCA**	**EC-HIRHAM**	**MPI-RCA**	**NCC-REMO**	**HAD-HAD**
Jan	-5.8	-6.5	-1.7	9	2.5	26.4
Feb	-7.9	-3.7	-3.9	7.9	-1.4	21.9
Mar	-12.2	38.9	-4.3	-15.9	10.4	-7
Apr	-20.2	20.6	14.7	0.2	29	7.7
May	-12.8	24.5	14.5	3.5	11.3	14.3
Jun	-9.7	25.7	0.8	-4	3.2	14.5
Jul	-6.9	1.8	-16.6	-4.2	1.5	4
Aug	-2.5	7.7	-9	1	1	-0.8
Sep	22.8	8.9	23.8	7.2	3.5	6.1
Oct	55	-8	19.9	16.2	-12.3	28.6
Nov	19	-2.8	16.6	19.8	14.6	51.3
Dec	9.9	23.5	11.2	16.5	18.9	130.2
annual	1.3	8.5	7.6	6.8	8.1	24.8

Table B.5: Mean monthly percentage change in streamflow across the euro-CORDEX (eCX) ensemble members by the far future period (2061-2080) as compared to the reference period (2001-2017), Idle catchment.

RCP8.5	**CNRM-ALADIN**	**NCC-HIRHAM**	**IPSL-WRF**	**IPSL-REMO**	**MPI-ALADIN**	**HAD-HAD**
Jan	-2.1	-4.0	18.3	-12.1	7.3	-22.4
Feb	6.8	6.9	27.1	2.9	20.4	-20.5
Mar	-2.9	-12.3	11.1	-10.7	11.2	-23.4
Apr	-7.2	-16.7	11.2	-1.0	-6.9	-23.0
May	-9.6	-13.9	10.7	-13.1	-9.3	-19.5
Jun	-25.9	-15.0	7.8	-16.7	-4.4	-24.9
Jul	-15.8	-13.6	5.0	-20.4	-0.1	-22.7
Aug	-29.2	-14.5	6.6	-9.8	-5.2	-26.7
Sep	-19.3	-11.4	5.6	-20.6	-6.3	-25.8
Oct	-14.1	-9.0	8.1	-11.3	2.8	-2.1
Nov	-13.6	-5.8	14.3	-4.6	11.9	-16.8
Dec	-10.7	2.1	10.7	-16.6	-4.5	2.1
annual	-10.0	-8.0	11.5	-10.7	1.5	-21.0
RCP4.5	**CNRM-RACMO**	**EC-RCA**	**IPSL-RCA**	**NCC-REMO**	**IPSL-WRF**	**HAD-RACMO**
Jan	24.0	3.0	23.2	6.7	35.5	9.8
Feb	20.4	4.7	6.4	5.1	13.2	-6.6
Mar	6.1	-0.2	18.6	-2.1	2.7	-7.3
Apr	4.9	-1.3	9.8	-3.1	18.2	1.6
May	14.1	-5.6	5.1	-3.5	7.3	-7.1
Jun	-5.8	-12.6	0.2	-12.9	6.3	0.5
Jul	10.7	-9.4	0.1	-0.2	8.5	3.8
Aug	1.2	-7.8	8.4	-3.7	7.3	-5.4
Sep	6.1	-6.9	10.8	-2.4	9.5	1.6
Oct	18.2	5.7	5.7	7.7	12.8	9.7
Nov	40.4	8.4	1.2	18.6	12.0	0.4
Dec	42.7	-1.4	20.1	21.0	21.6	3.0
annual	15.0	-0.5	8.8	1.9	11.9	-0.1
RCP2.6	**CNRM-RACMO**	**EC-RCA**	**EC-HIRHAM**	**MPI-RCA**	**NCC-REMO**	**HAD-HAD**
Jan	6.6	4.5	-6.2	13.9	-8.6	26.3
Feb	-0.7	-2.1	-4.2	10.8	4.8	13.3
Mar	-1.2	10.4	-7.1	-4.8	-3.3	15.3
Apr	-9.1	0.1	1.9	-3.3	10.6	5.6
May	6.7	3.1	-0.4	-1.2	3.0	-17.2
Jun	11.7	-5.9	3.9	4.4	9.9	2.5
Jul	4.9	-0.1	4.7	-1.0	-0.8	6.2
Aug	7.7	-1.3	-7.2	-0.9	-1.3	-1.0
Sep	13.0	1.3	-0.2	-5.6	-3.4	-4.4
Oct	27.0	5.1	1.6	-0.6	-0.3	10.1
Nov	23.4	4.8	-15.2	10.9	-1.9	20.0
Dec	30.2	1.3	4.6	15.4	8.6	66.2
annual	10.0	1.3	-2.2	3.1	0.6	13.2

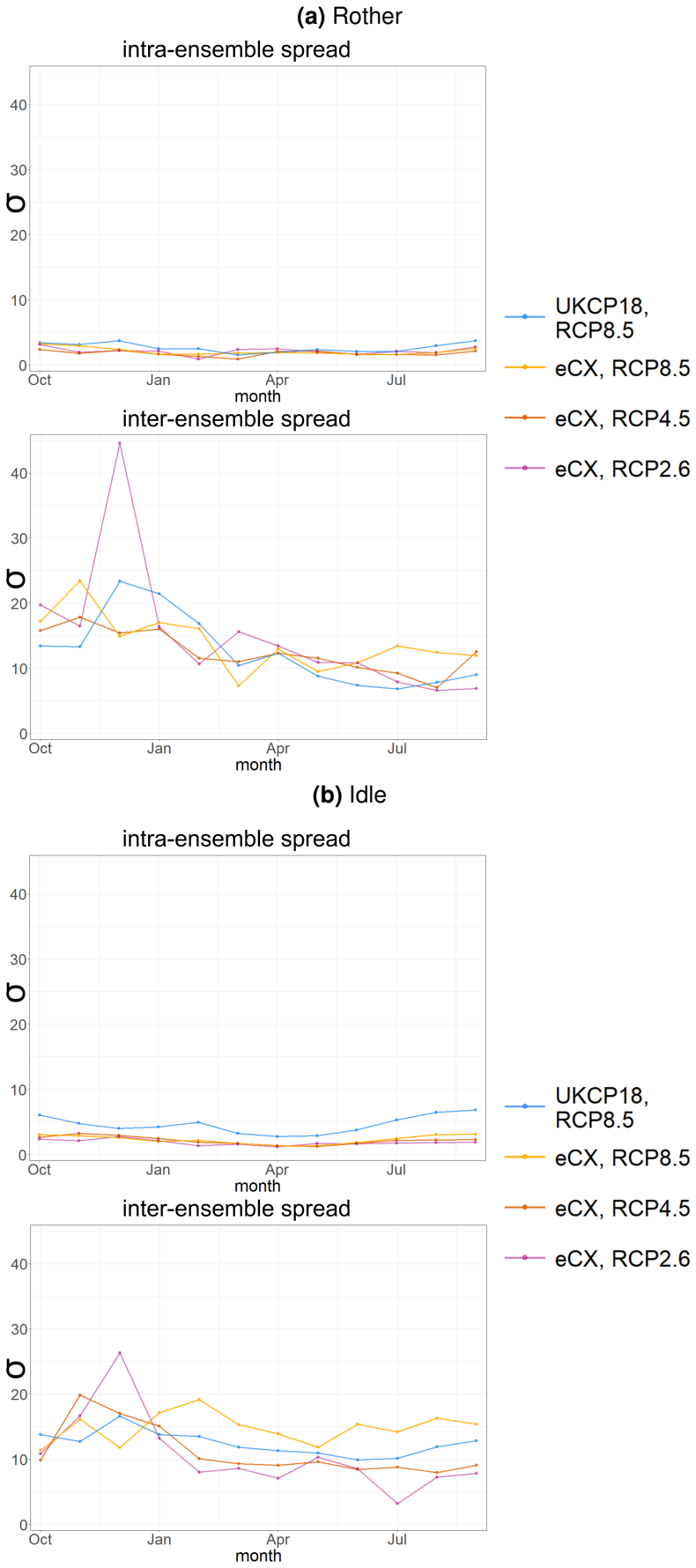


Figure B.1: Variability in projected absolute changes in the far future period as shown through standard deviation (σ) within (intra-ensemble) and between (inter-ensemble) General Circulation Model (GCM)-Regional Climate Model (RCM) ensemble members, simulated with SWAT+ model, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Linear Scaling (LS) for the Rother (a) and Idle (b).

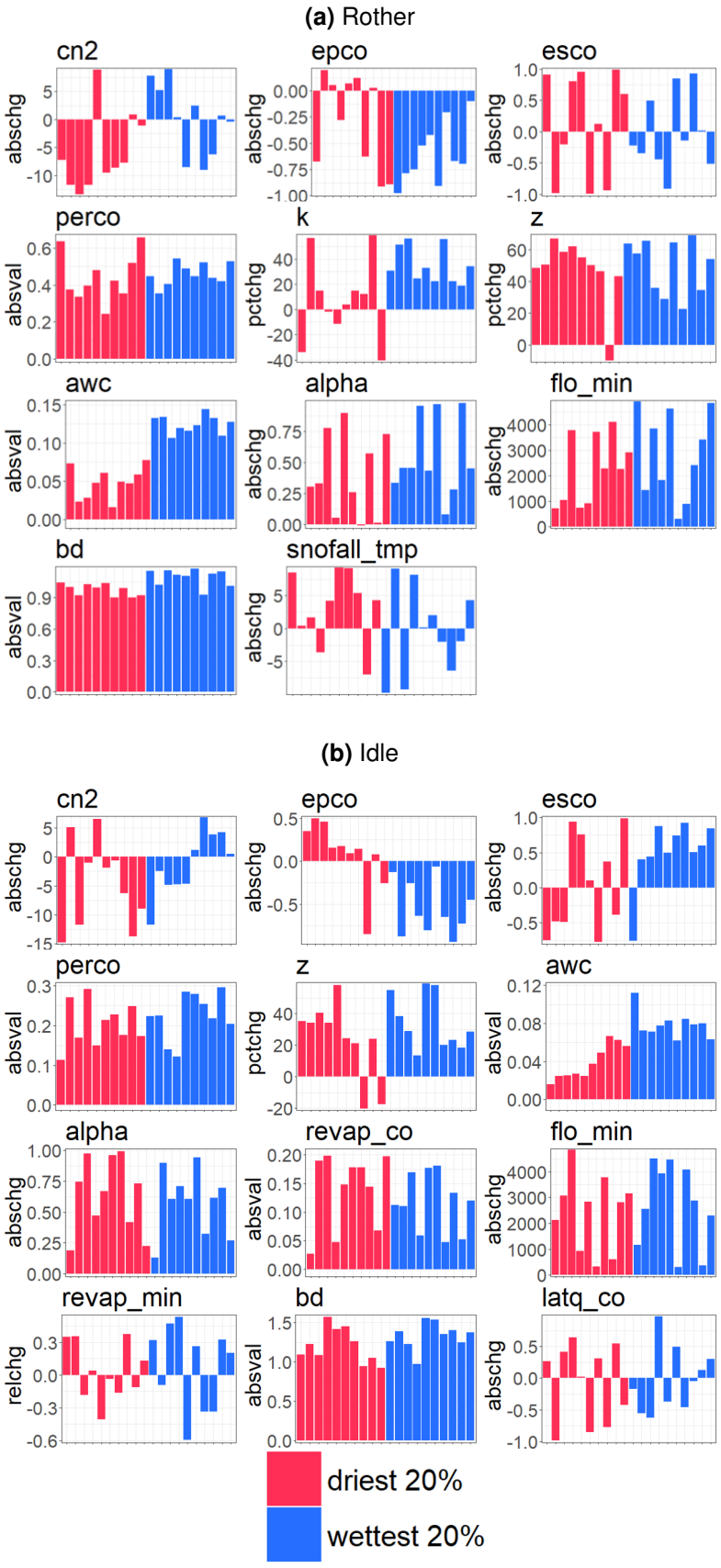


Figure B.2: Change values of the 20% wettest and 20% driest simulations across both UKCP18 and euro-CORDEXn (eCX) for the eight most sensitive parameters for Rother (a) and Idle (b)

B.3 Comparison of Bias Correction Methods

Chapter 3 applied a simple linear method to correct biases between RCM simulated daily temperature and precipitation and observations. The bias-corrected climate projections were used to drive SWAT+ in the historical period and were tested for their ability to represent observed discharge dynamics. Bias correction is an important part of the modelling chain as it has been shown to affect hydrological simulations, magnitude, and direction of projected climate impacts (Hagemann et al., 2011; Shrestha et al., 2017a; Teutschbein and Seibert, 2012). The LS method (Lenderink et al., 2007) chosen for this thesis strongly decreased the RCM's biases on a monthly scale. It was also shown that this simple bias correction can reduce biases in high flow volume (hfv) that are determined by running the HM at a daily time step. Moreover, SWAT+ performed well in simulating low flow volume (lfv) under LS-corrected projections in the Rother. However, performance was limited in simulating observed low flows in the Idle where performance increased only slightly through bias correction with LS. These results show that bias correction, whilst improving flow estimations overall, cannot eliminate the systematic dry bias of the calibrated HM.

The uncertainty introduced by bias correction was not a focus of this study. However, a brief overview of the implications of bias correction can be illustrated as results were produced under LS and under two additional methods for correcting precipitation, one of which also provides a methodology for correcting temperature. section B.3.1 describes the methodological process of the two additional bias correction approaches, section B.3.2 compares the performance across all three methods during the observations period and section B.3.3 briefly discusses bias correction as a source of variability and provides all results obtained under the two additional correction methods. Finally, section B.3.4 discusses bias correction as a source of uncertainty.

B.3.1 Bias Correction Methods

Two methods for correcting both temperature and precipitation were assessed – LS (Lenderink et al., 2007) and the trend preserving approach developed for the ISIMIP (Hempel et al., 2013; Warszawski et al., 2014). Bias correction for precipitation was additionally tested with a third method developed by Gutjahr and Heinemann (2013), in the following called GPQM. Unlike LS, the GPQM and ISIMIP methods rely on parametric quantile mapping.

The transfer functions for all three methods were calculated based on a 0.25° ($\sim$6 km) grid, this means the 1 km ($\sim$0.01°) observations were bilinearly interpolated to 0.25°. The aim was to prevent the overcorrection of the drizzle effect as described by Maraun (2013) that occurs when applying quantile mapping across large scale differences between observations and projections. In (semi-) distributed hydrological models such as SWAT+, this overcorrection might lead to an inflation of flood flows (Maraun, 2013). Furthermore, the signal of climate change is preserved better when the resolution mismatch

is small (Casanueva et al., 2020). The transfer functions were derived for the historical period 1980 – 2005 and applied to 1998 – 2080 for all three methods.

B.3.1.1 The ISIMIP Method

By adding a constant offset to the entire time series, this method achieves trend preservation for temperature and precipitation through the same process as LS. This offset is the average difference between observations and simulations for the historical period (20 years in this case). This preserves the absolute change as well as the variability of the simulated temperature in the projections. The trend preservation for precipitation is achieved with a multiplicative factor received by dividing the total observed precipitation by the total simulated precipitation in the historical period. The upper limit for the correction factor is set to 10 to avoid too high precipitation. This approach alters the projected absolute change in precipitation but preserves the relative change.

To account for higher spatial resolution and hence temporal variability expected at smaller scales, the ISIMIP methods adjusts the daily variability of the RCM data to that of the observations. The correction is done on a calendar month specific basis. For temperature the method is based on adjusting the residual distribution of the RCM to that of the observations. Based on the assumption that temperature follows a normal distribution, a linear fit is considered a good approximation. The transfer function consists of a slope and the rank ordered observational as well as the rank ordered RCM dataset for a given calendar month over the historical period. Note that the same correction value for temperature is applied to different absolute temperatures and consequently different weather situations which can strongly differ in their variability in reality. However, as the correction is done on a calendar month basis, temperature is unlikely to display high variability.

The variances of precipitation are calculated after normalising the daily data with the monthly mean. The ISIMIP method assumes that both the RCM as well as the observations dataset are well approximated by a gamma distribution (not considering days with no precipitation as gamma is not defined at zero). To receive a transfer function a parametric quantile mapping with three parameters and a nonlinear fitting algorithm based on the gradient-expansion method (Marquardt, 1963) is performed (for adjusting the intensity). Since the gamma function is not defined at zero the frequency and the intensity of precipitation must be corrected in separate steps. For this purpose, the frequency of dry days is corrected by counting the number of observed dry days during the historical period. It is assumed that days with less than 1mm of precipitation are dry days. This number determines how many days are set to zero in the RCM daily dataset and days with the lowest precipitation are excluded first. The respective days are excluded from the generation of the transfer function used in the correction of the intensity of precipitation. If the trend is to be preserved, the exclusion of wet days affecting the monthly means must be accounted for. This is achieved by uniformly redistributing the amount of precipitation during dry days among the wet days. The correction of the

precipitation intensity for wet days is achieved through a transfer function derived from nonlinear regression on the rank ordered normalised wet days over the historical period. Three parameters – the offset, the slope of the linear part of the function as well as the decay constant of the exponential part then have to be fitted.

B.3.1.2 The GPQM Method

The GPQM method suggested by Gutjahr and Heinemann (2013) corrects the frequency of dry days in the same way the ISIMIP method does by counting the number of observed dry days with less than 1mm of precipitation during the historical period. This number of days are subsequently set to zero in the RCM datasets. As shown by Vlček and Huth (2009) the gamma distribution does not adequately approximate daily precipitation for most regions (Figure B.3). Therefore, GPQM was developed to overcome this limitation by employing another approach for fitting precipitation distributions with the aim to improve the correction of extreme precipitation. The transfer function bases on a fit of a combination of gamma distribution and a Generalised Pareto Distribution (GPD). The threshold for dividing the fit in gamma and GPD was set at the 95th percentile as suggested by Yang et al. (2010) (Rother: $\sim$13.8 mm, Idle: $\sim$9.0 mm/day). Four more parameters – the scale and shape of both gamma and GPD had to be fit.

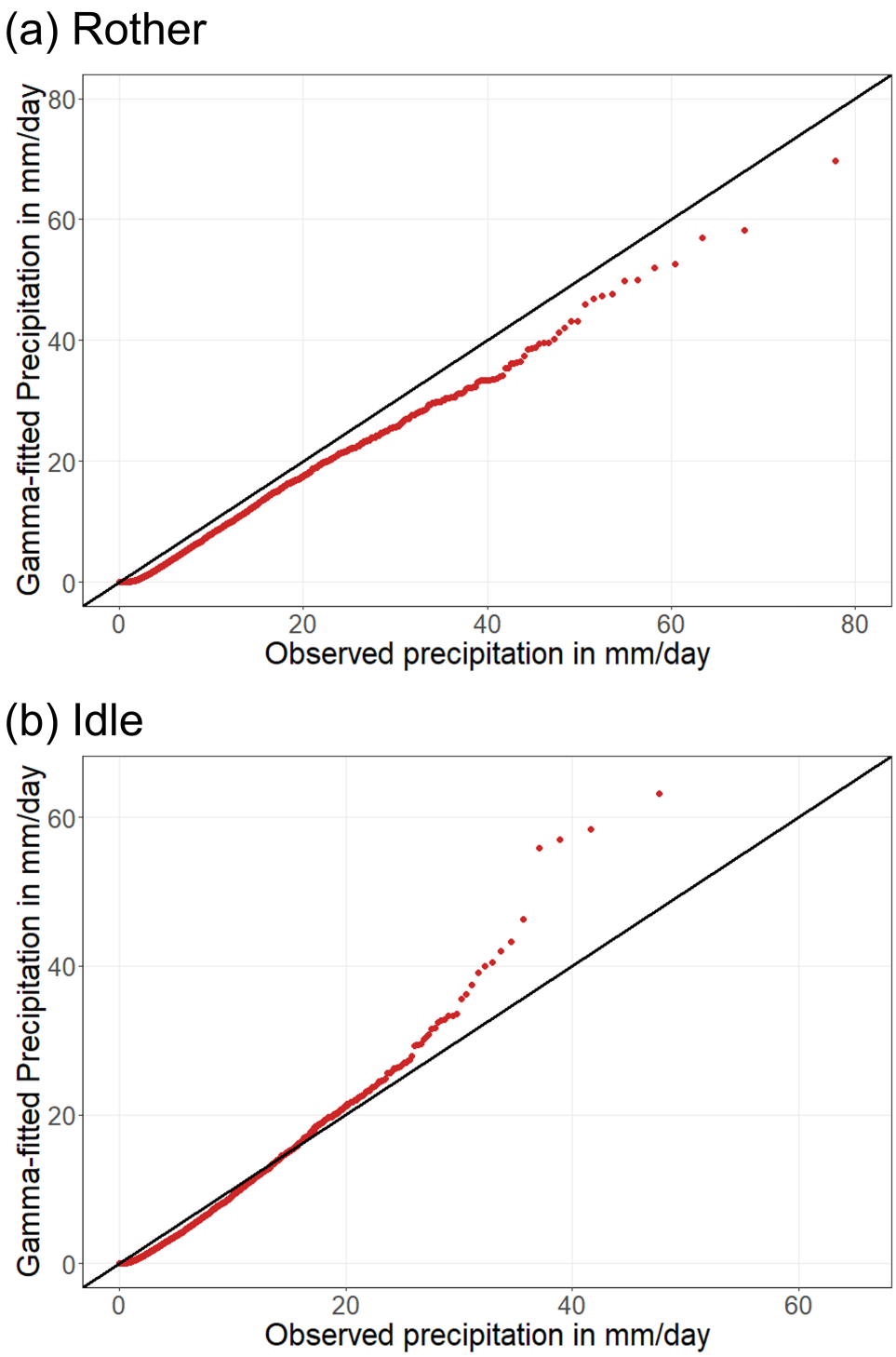


Figure B.3: Quantile-quantile plot of the fitted gamma distributions versus actual quantiles in daily precipitation observations of the Rother catchment (a): $\alpha = 0.39$, $\beta = 0.1$ and Idle catchment (b): $\alpha = 0.41$, $\beta = 0.17$

B.3.2 Performance during the Observation Period

Figure B.7 and Figure B.8 align with Figure 3.7 and show the percentage changes in long-term mean monthly temperature and precipitation corrected with ISIMIP and GPQM. The latter contains LS-corrected temperature as GPQM was solely applied for precipitation correction. Figure B.4 and Figure B.5 provide a comparison of simulated mean monthly discharge during the observations period under ISIMIP and respectively GPQM. These figures align with what Figure 3.5 presents for LS-corrected projections. Figure B.6 provides a direct comparison of all three bias correction methods. It shows what Figure 3.6 depicts for only LS; a comparison of models run with bias corrected climate, observed climate (simobs) and with uncorrected "raw" simulated UKCP18 and euro-CORDEX (eCX) climate.

ISIMIP-corrected climate in the Rother shows few differences to climate corrected with LS. The spread between ensembles members is slightly higher and the seasonality differences are less pronounced. In the Idle, changes projected to temperature also align very closely between LS (Figure 3.7b) and ISIMIP (Figure B.7). The mean and median in projected changes to precipitation is also similar, however the range of projections, particularly under eCX for RCP2.6 is larger under ISIMIP. In both Rother and Idle, GQPM-corrected climate aligns very closely in mean and median to LS-corrected climate but the spread between different ensemble members is higher.

In the Rother, GPQM performs best of the three methods in reproducing observations as well as simulations under observations. ISIMIP is closer to the observations in winter however not closer to simulations (simobs) and many of the projections are too wet in winter. In the Idle, ISIMIP is overall wetter during the observations period. Unlike, LS the dry bias is removed under high emissions. The success in corrections under ISIMIP is however more variable with a high range of simulations. This particularly applies to the two high emissions scenarios and in winter. GPQM aligns very closely with the performance under LS-corrected projections in both UKCP18 as well as RCP4.5, yet only under high emissions eCX it removes the dry bias. Under both eCX a8.5 and 2.6 simulates a much higher range than LS.

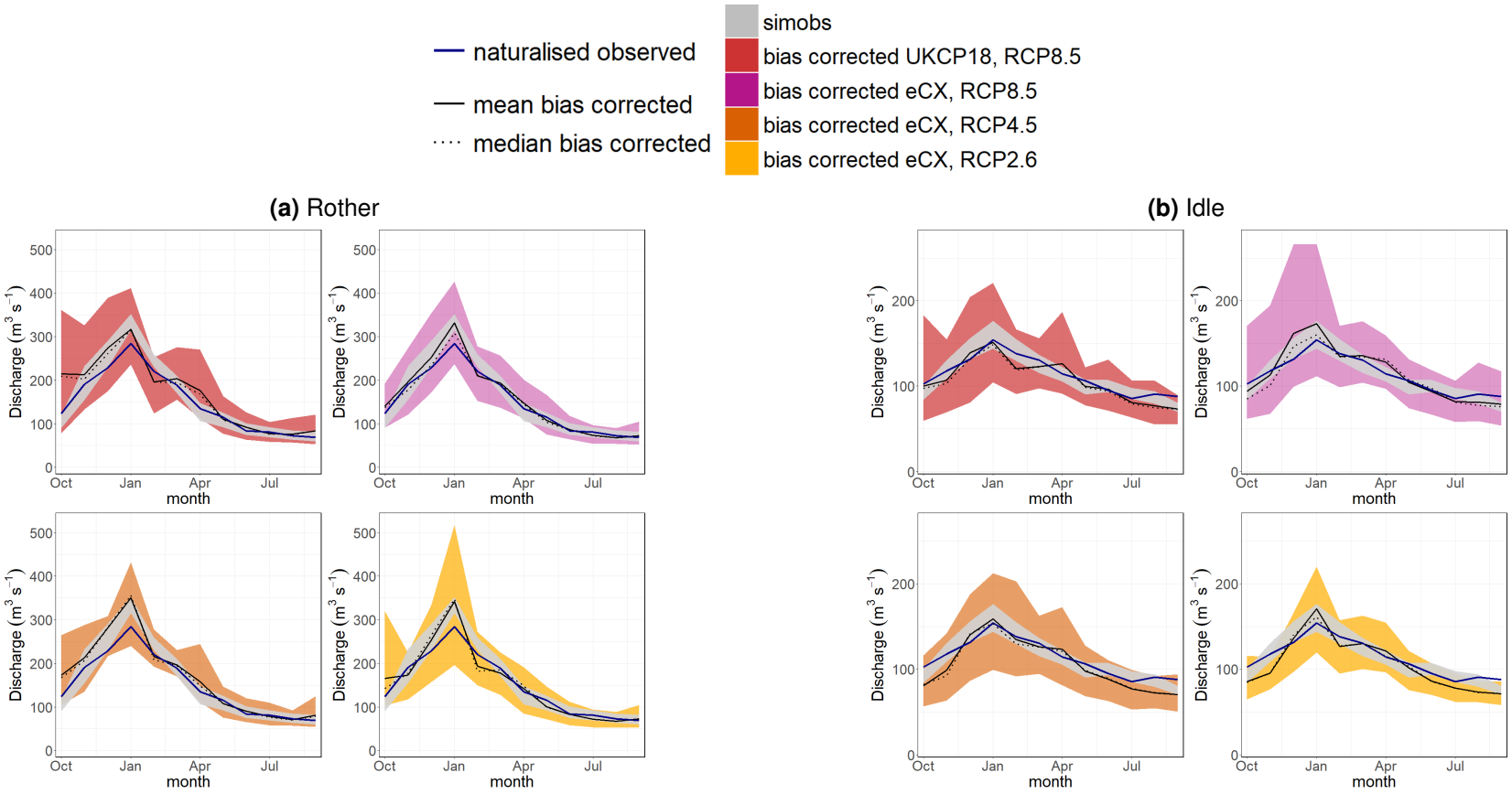


Figure B.4: Comparison of simulated mean monthly discharge driven by observations (simobs) and by the UKCP18 and euro-CORDEX (eCX) climate projections bias corrected with the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) method with naturalised flow observations over the reference period (2001 – 2017) for the Rother (a) and Idle (b).

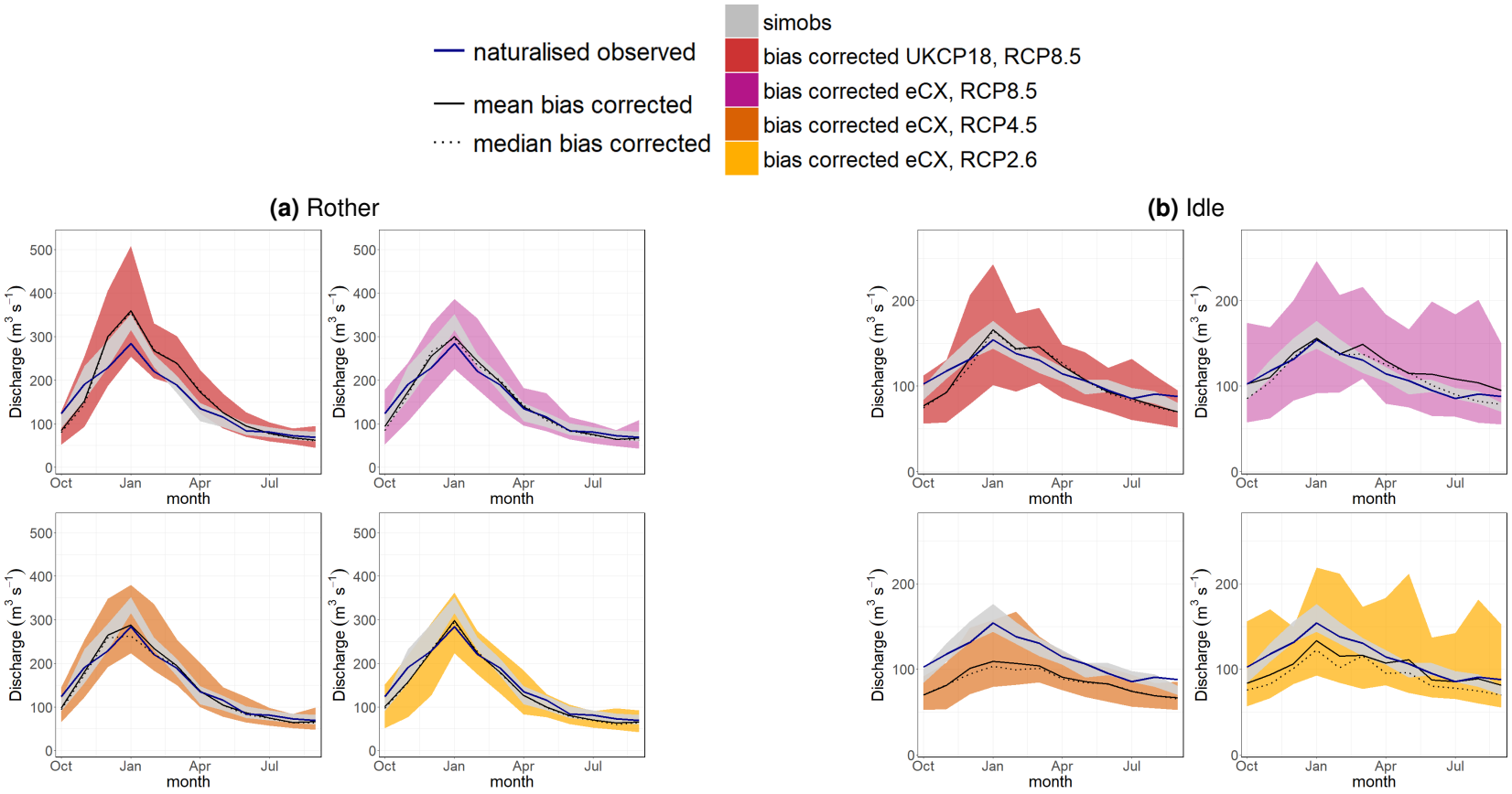
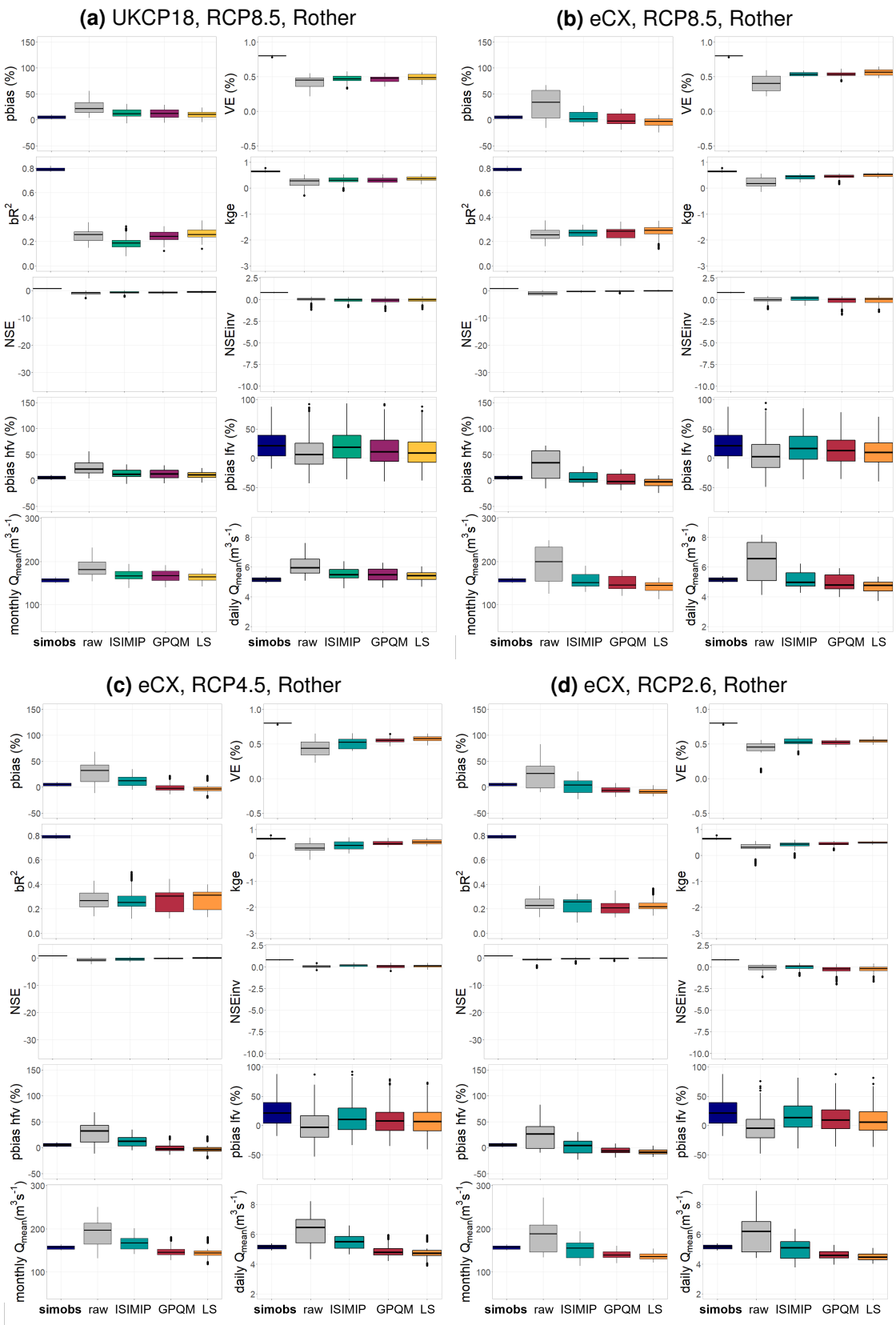


Figure B.5: Comparison of simulated mean monthly discharge driven by observations (simobs) and by the UKCP18 and euro-CORDEX (eCX) climate projections bias corrected with the gamma-Pareto Quantile Mapping (GPQM) method with naturalised flow observations over the reference period (2001 – 2017) for the Rother (a) and Idle (b).


(a) UKCP18, RCP8.5, Rother
(b) eCX, RCP8.5, Rother
(c) eCX, RCP4.5, Rother
(d) eCX, RCP2.6, Rother
pbias (%)
VE (%)
bR2
kge
NSE
NSEinv
pbias hfv (%)
pbias lfv (%)
monthly Qmean(m3s-1)
daily Qmean(m3s-1)
simobs raw ISIMIP GPQM LS

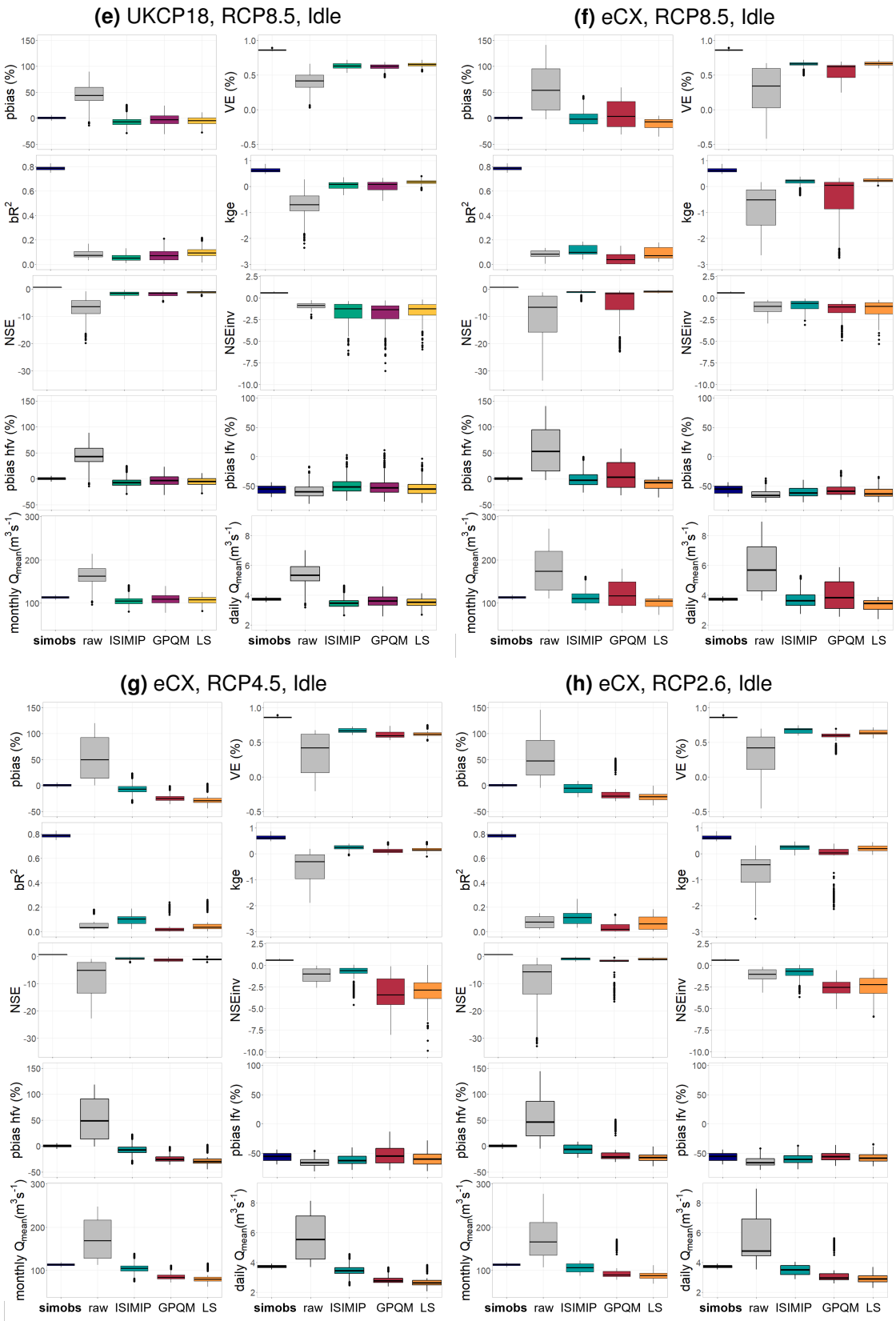


Figure B.6: Model performance during the calibration and validation period (2001-2017), for model runs with observed climate (simobs), uncorrected "raw" simulated UKCP18 and euro-CORDEX (eCX) climate and with climate simulations bias-corrected with Linear Scaling (LS), Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and gamma-Pareto Quantile Mapping (GPQM). Monthly performance according to percent bias (pbias), Volumetric Efficiency (VE), modified Coefficient of Determination (bR^2), Kling-Gupta Efficiency (KGE), Nash-Sutcliffe Efficiency (NSE), inverse NSE (NSE_{inv}) and in mean monthly flows, daily performance according to pbias in high flow volume (hfv, Q_{30} to Q_5) and low flow volume (lfv, Q_{70} to Q_{95}) and in mean daily flows for the Rother (a-d) and Idle (e-h).

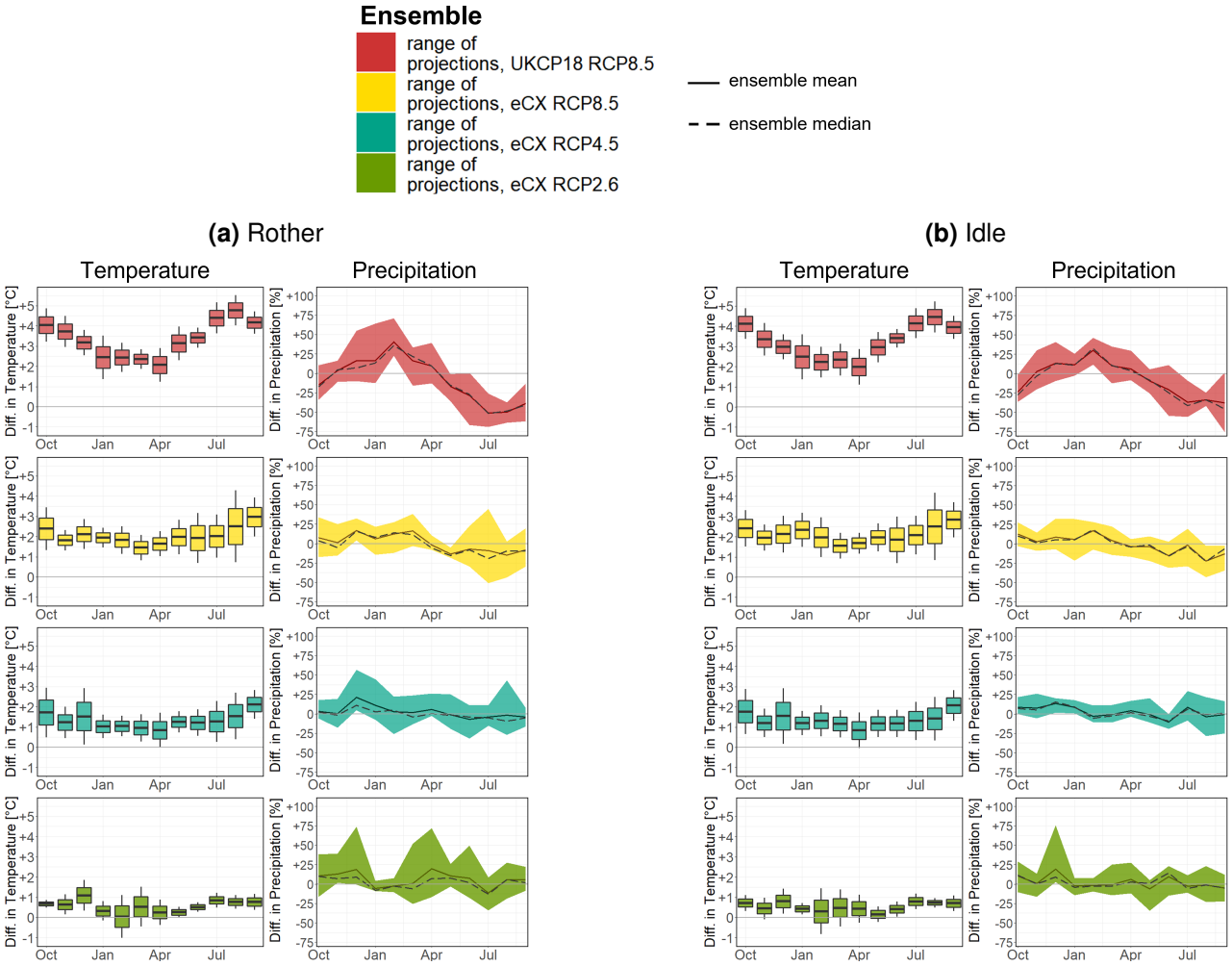


Figure B.7: Projected percentage changes in long-term mean monthly temperature and precipitation between the reference and far-future time slices, projected by the UKCP18 and euro-CORDEX (eCX), bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the Rother (a) and Idle (b).

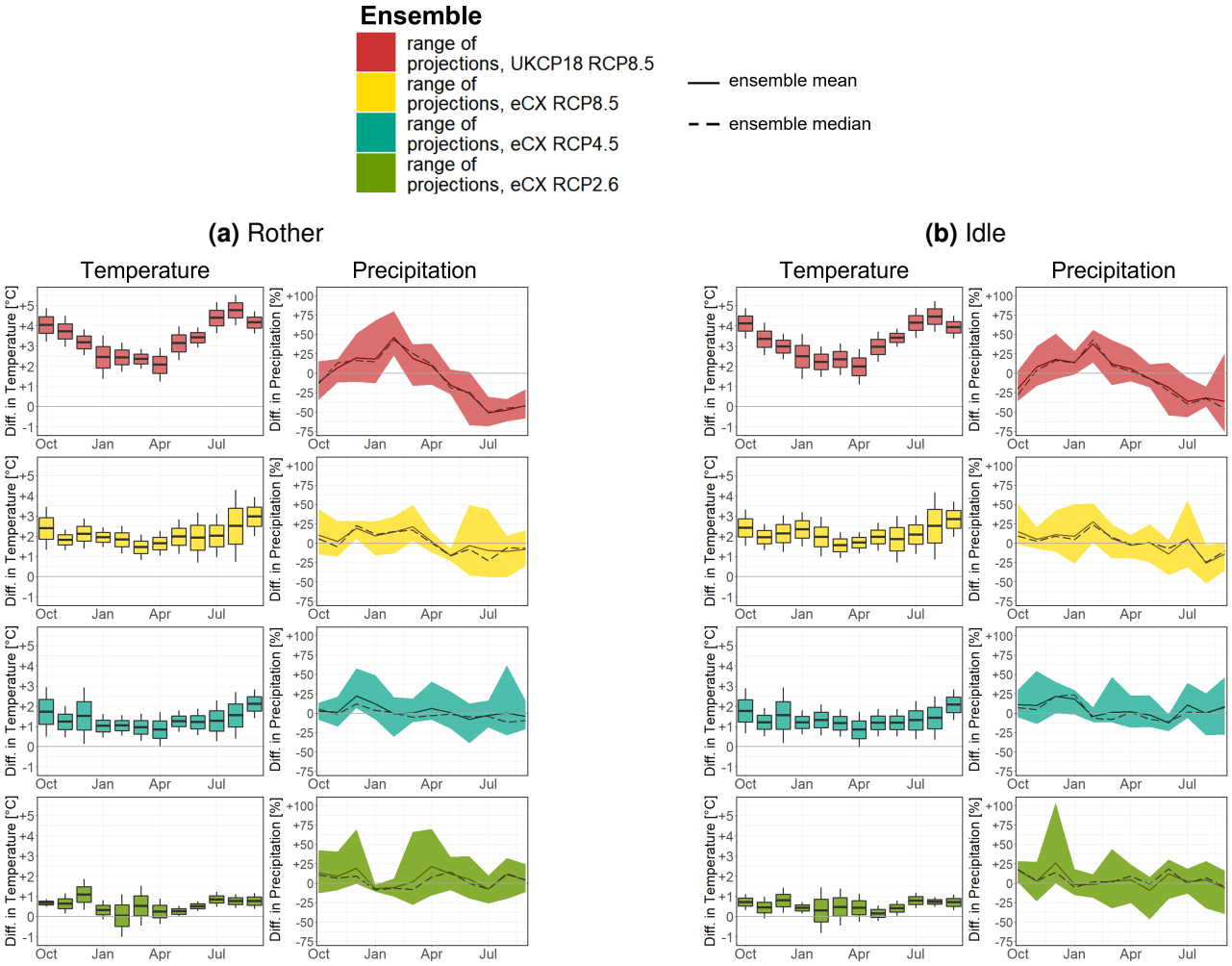


Figure B.8: Projected percentage changes in long-term mean monthly temperature and precipitation between the reference and far-future time slices, projected by the UKCP18 and euro-CORDEX (eCX), bias corrected with gamma-Pareto Quantile Mapping (GPQM) for the Rother (a) and Idle (b).

B.3.3 Supplementary Results - Supplementary Results under ISIMIP & GPQM

Figure B.9 shows a comparison of four different sources of variability: bias correction of temperature, bias correction of precipitation, GCM-RCM and respectively PPE member (inter-ensemble variability) and the SWAT+ parameter set (intra-ensemble variability). In the Rother, the variability of different GCM-RCM and respectively PPE members makes up the highest share, followed by the variability introduced by different bias correction methods for precipitation. In the Idle, for the UKCP18 it is the other way round with the three different bias correction methods for precipitation introducing the largest share of variability followed by different ensemble members. The eCX introduce a similar share of variability as the climate ensemble members in the Idle. In both catchment models temperature-bias correction procedures (Figure B.9 second column) had much more narrow bounds than the three other sources of variability. This variability pattern is visible in both observation and far future period.

Figure B.10 provides the projections for annual streamflow, Figure B.12 those for flow duration curve statistics Figure B.14 for monthly streamflow, Figure B.16 for seasonal streamflow and Table B.6 provides monthly changes across ensemble members under climate projections bias corrected with ISIMIP. Figure B.11, Figure B.13, Figure B.15, Figure B.17 and Table B.6 show the same under projections corrected with the GPQM method [7]. The results highlight that the implications of bias correction can be considerable. For the eCX, results under the ISIMIP methods align very closely with the projected changes under the LS-corrected projections. However, for the UKCP18, this method implies a considerably more pronounced increase in seasonality in the Rother and significantly drier projections across the whole year for the Idle compared to LS-corrected projections. Aligning with the findings on the performance during the observation period, the GPQM method aligns very closely with all LS-corrected ensembles in the Rother with slightly higher winter increases. Projections under GPQMin the Idle for the two high emission ensembles are wetter in winter, while the eCX for RCP2.6 are more variable than under those projections corrected with LS.

[7] the respective results under LS-corrected projections are given in Figure 3.8, Figure 3.9, Figure 3.10, Figure 3.11 and Table 3.6

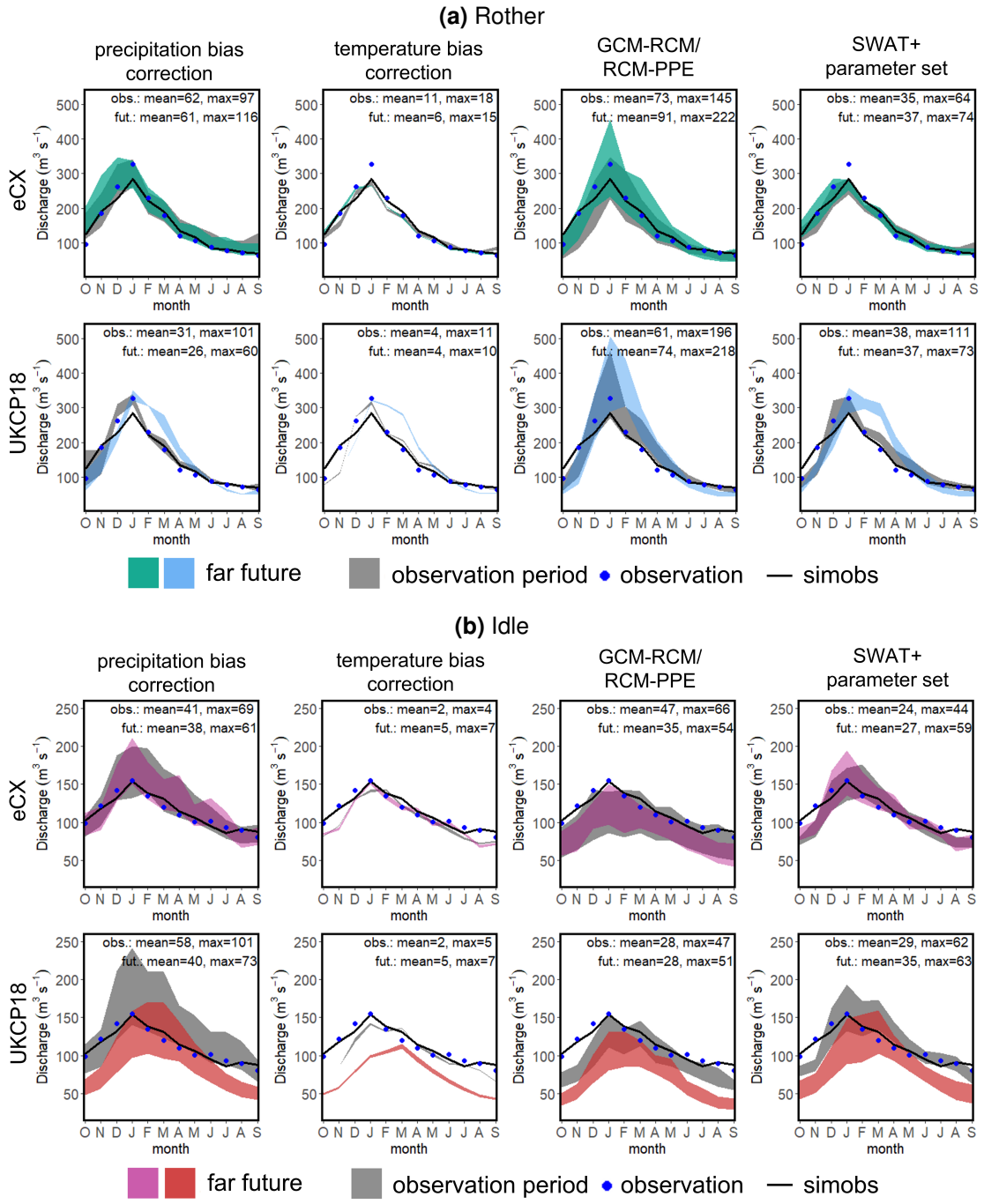


Figure B.9: Comparison of variability introduced through precipitation bias correction (Linear Scaling (LS), Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), gamma-Pareto Quantile Mapping (GPQM)), temperature bias correction (LS, ISIMIP), ensemble member and SWAT+ parameter set, mean and max monthly standard deviation, observation and far future period (2061-2080)

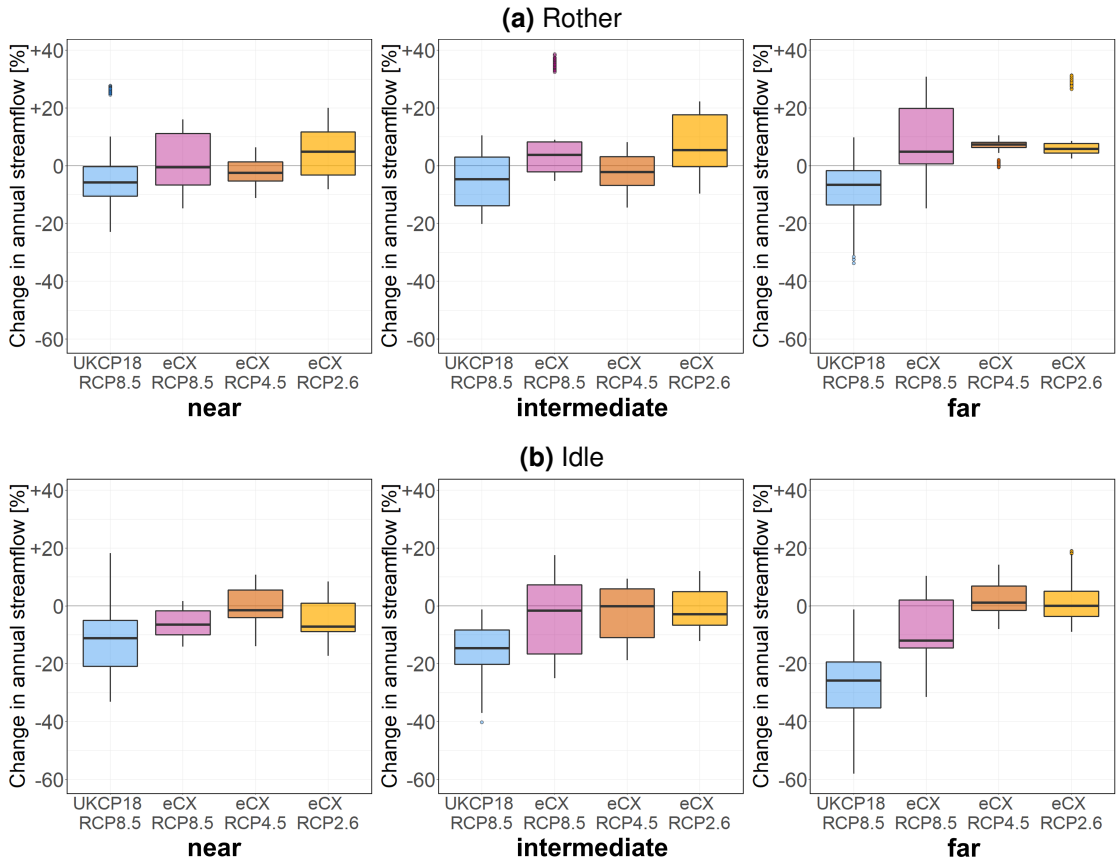


Figure B.10: Percentage change in mean annual streamflow in the near, intermediate and far future simulated with SWAT+, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the Rother (a) and Idle (b).

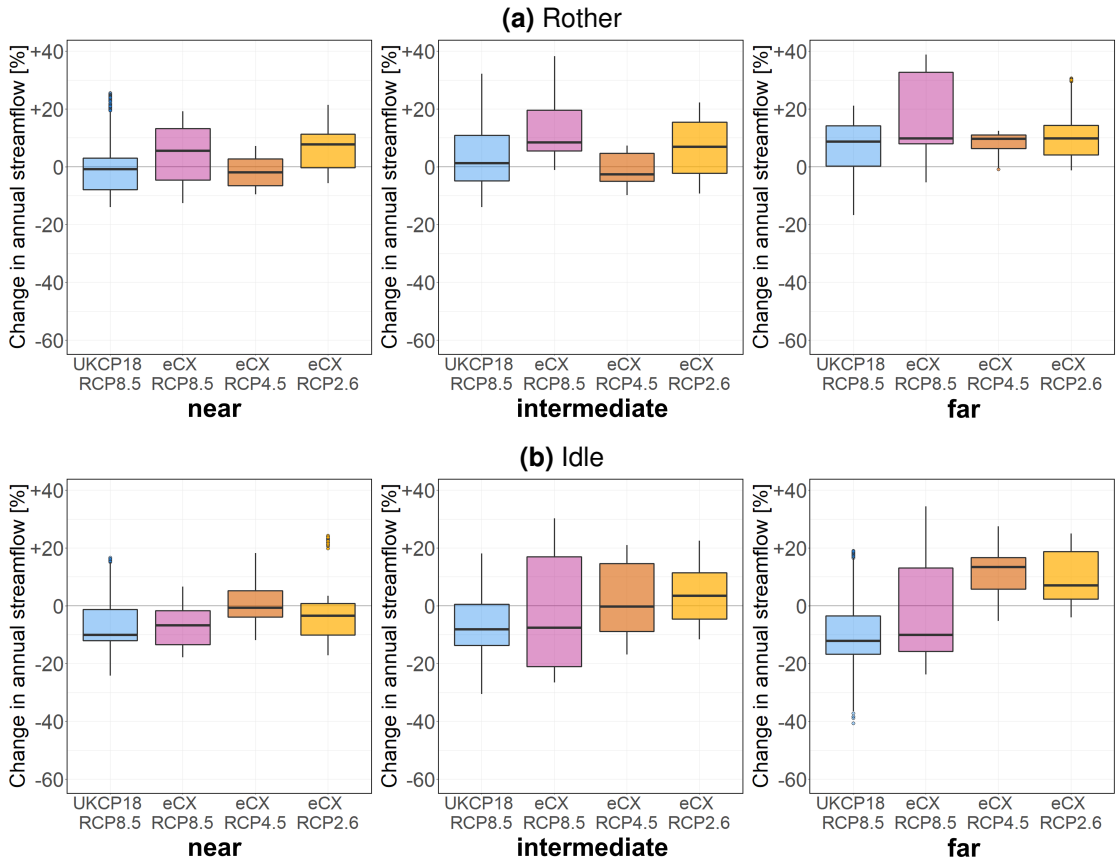
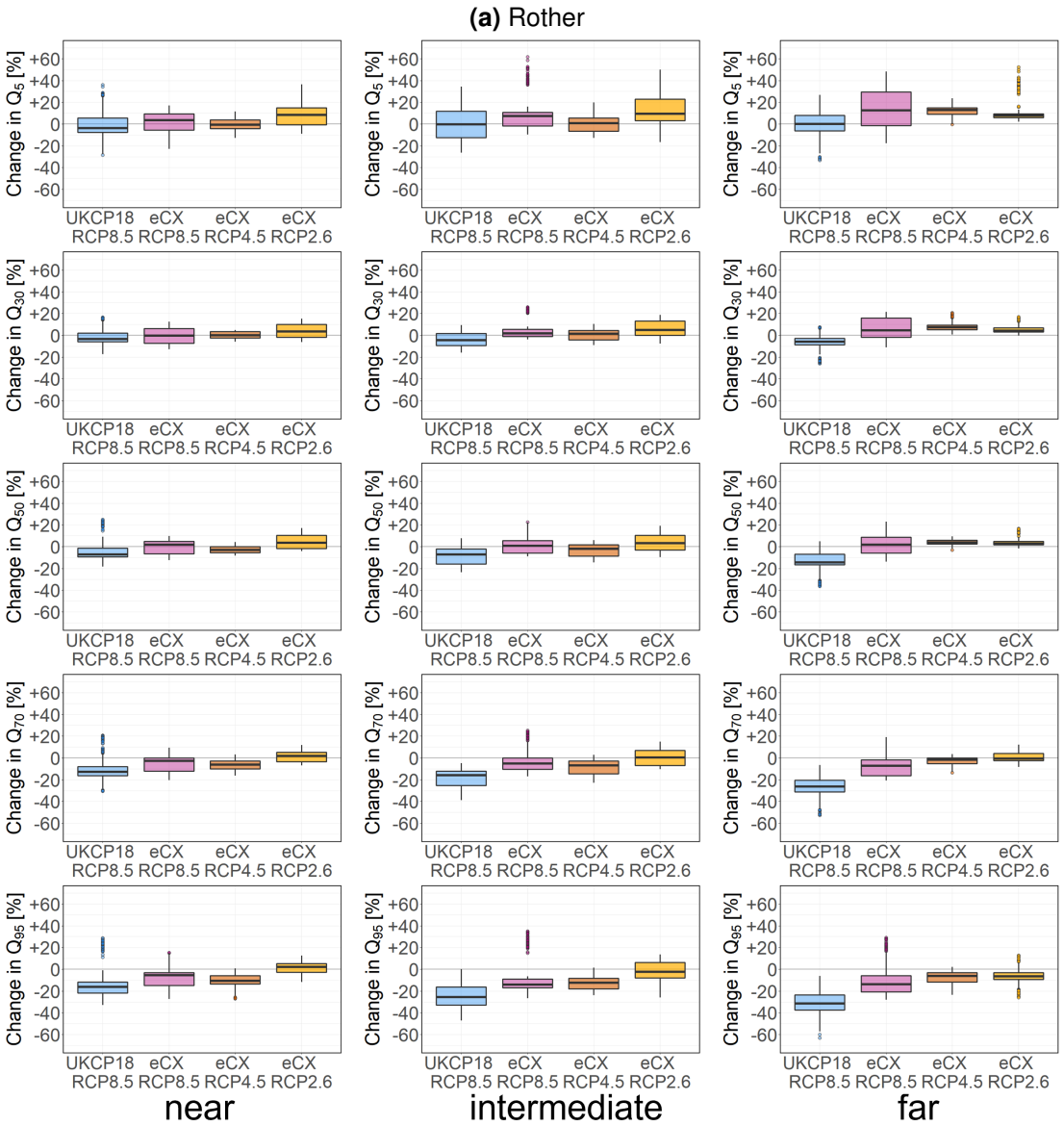


Figure B.11: Percentage change in mean annual streamflow in the near, intermediate and far future simulated with SWAT+, driven by the UKCP18 and euroCORDEX (eCX), bias corrected with gamma-Pareto Quantile Mapping (GPQM) for the Rother (a) and Idle (b).


(a) Rother
Change in Q5 [%]
Change in Q30 [%]
Change in Q50 [%]
Change in Q70 [%]
Change in Q95 [%]
+60
+40
+20
0
-20
-40
-60
UKCP18 RCP8.5
eCX RCP8.5
eCX RCP4.5
eCX RCP2.6
near
intermediate
far

(b) Idle

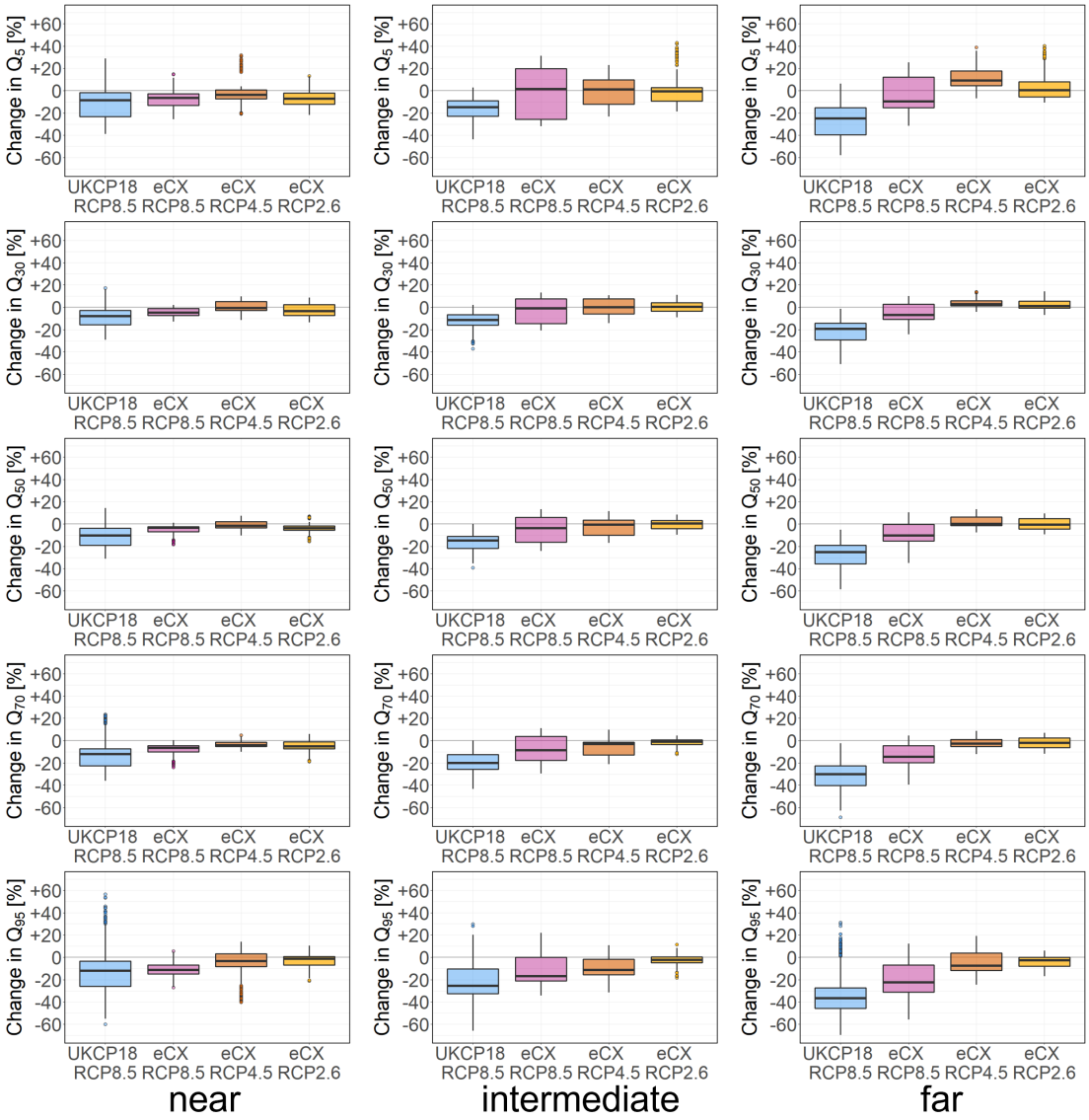
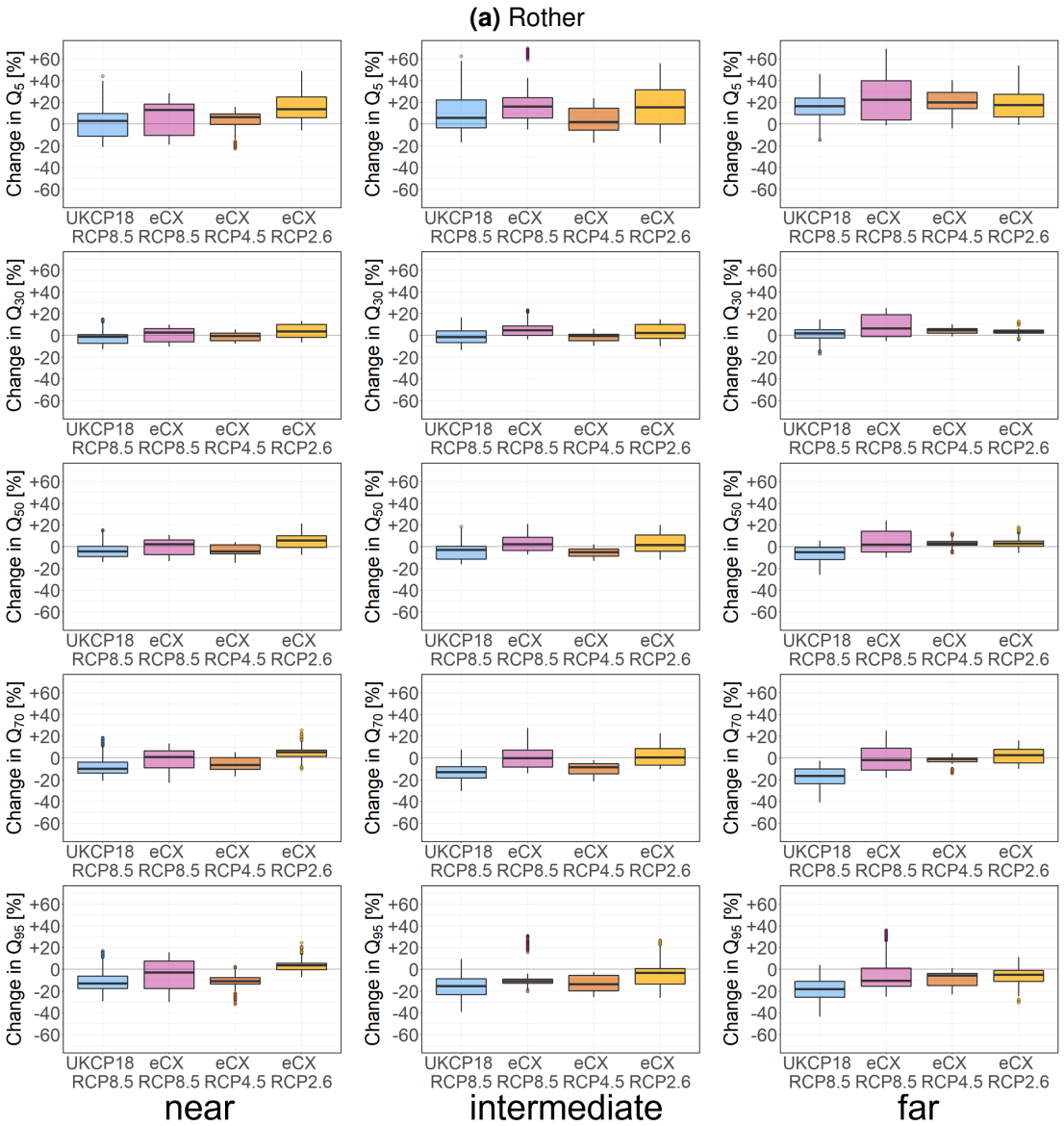


Figure B.12: Comparison of percentage changes in flow duration statistics (Q_5, Q_{30}, Q_{50}, Q_{70}, Q_{95}) in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the Rother (a) and Idle (b).


(a) Rother
Change in Q5 [%]
Change in Q30 [%]
Change in Q50 [%]
Change in Q70 [%]
Change in Q95 [%]
+60
+40
+20
0
-20
-40
-60
UKCP18 RCP8.5
eCX RCP8.5
eCX RCP4.5
eCX RCP2.6
near
intermediate
far

(b) Idle

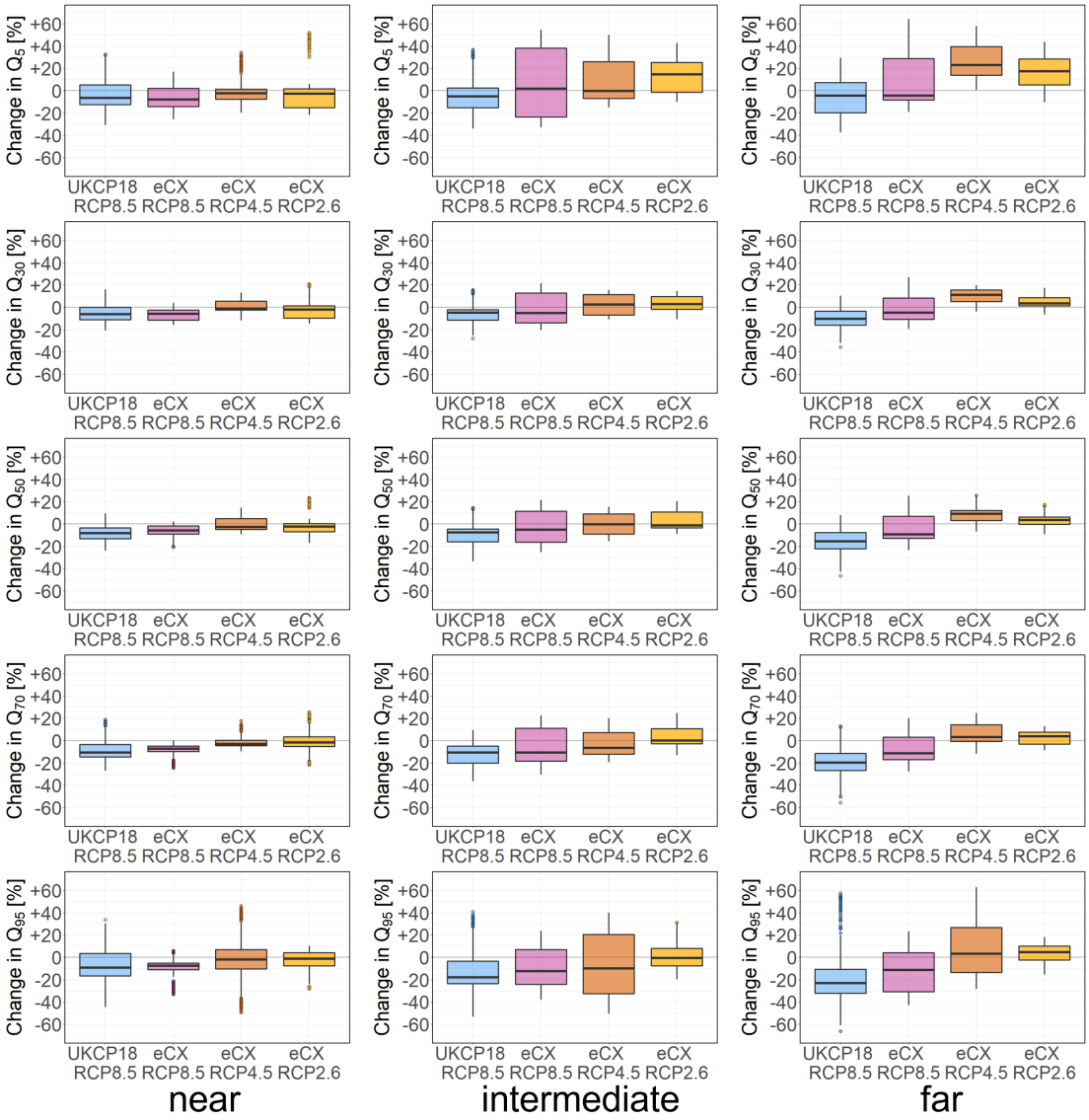
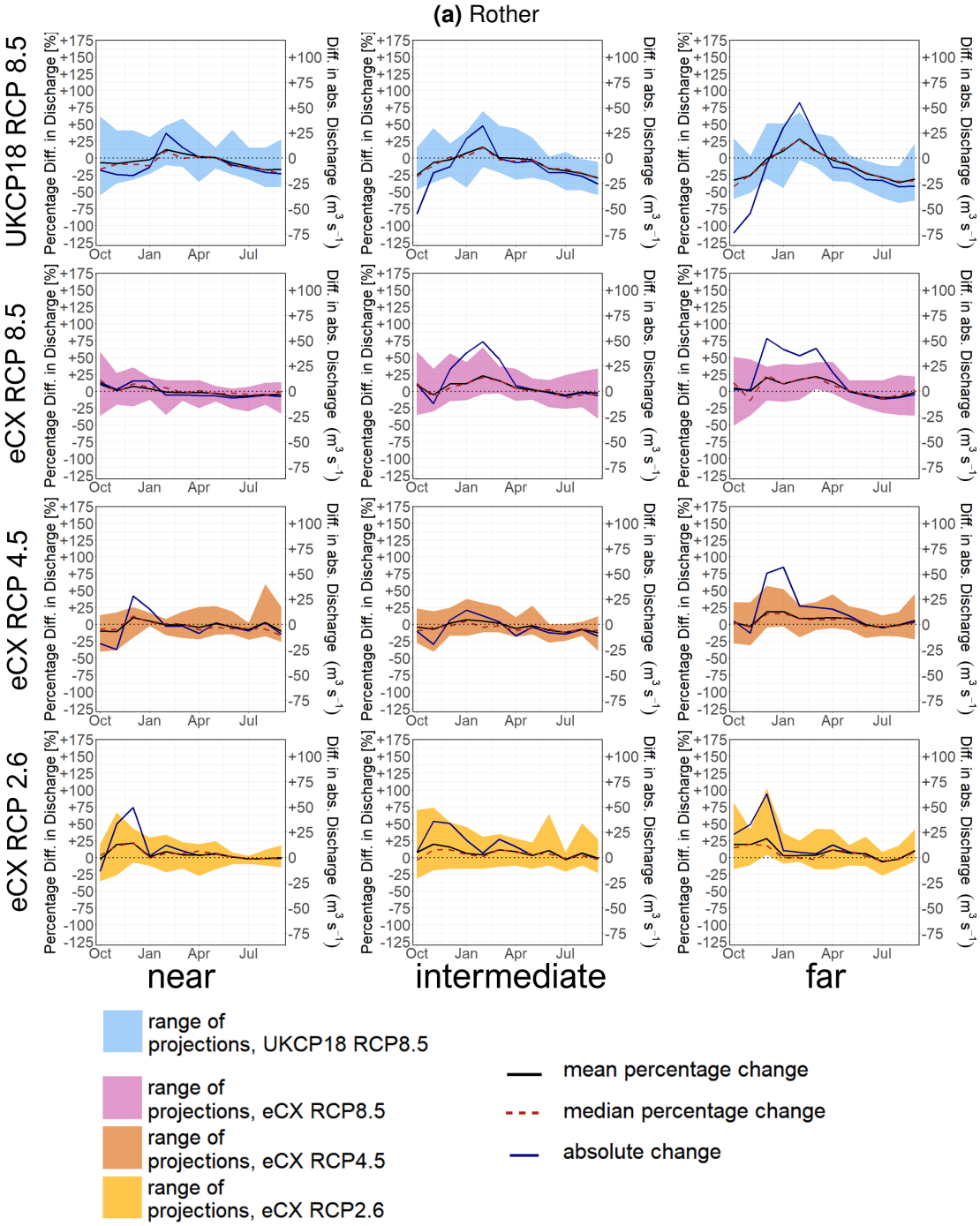


Figure B.13: Comparison of percentage changes in flow duration statistics (Q_5, Q_{30}, Q_{50}, Q_{70}, Q_{95}) in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with gamma-Pareto Quantile Mapping (GPQM) for the Rother (a) and Idle (b).


(a) Rother
UKCP18 RCP 8.5
eCX RCP 8.5
eCX RCP 4.5
eCX RCP 2.6
Percentage Diff. in Discharge [%]
Diff. in abs. Discharge (m3 s-1)
Oct
Jan
Apr
Jul
near
intermediate
far
range of projections, UKCP18 RCP8.5
range of projections, eCX RCP8.5
range of projections, eCX RCP4.5
range of projections, eCX RCP2.6
mean percentage change
median percentage change
absolute change

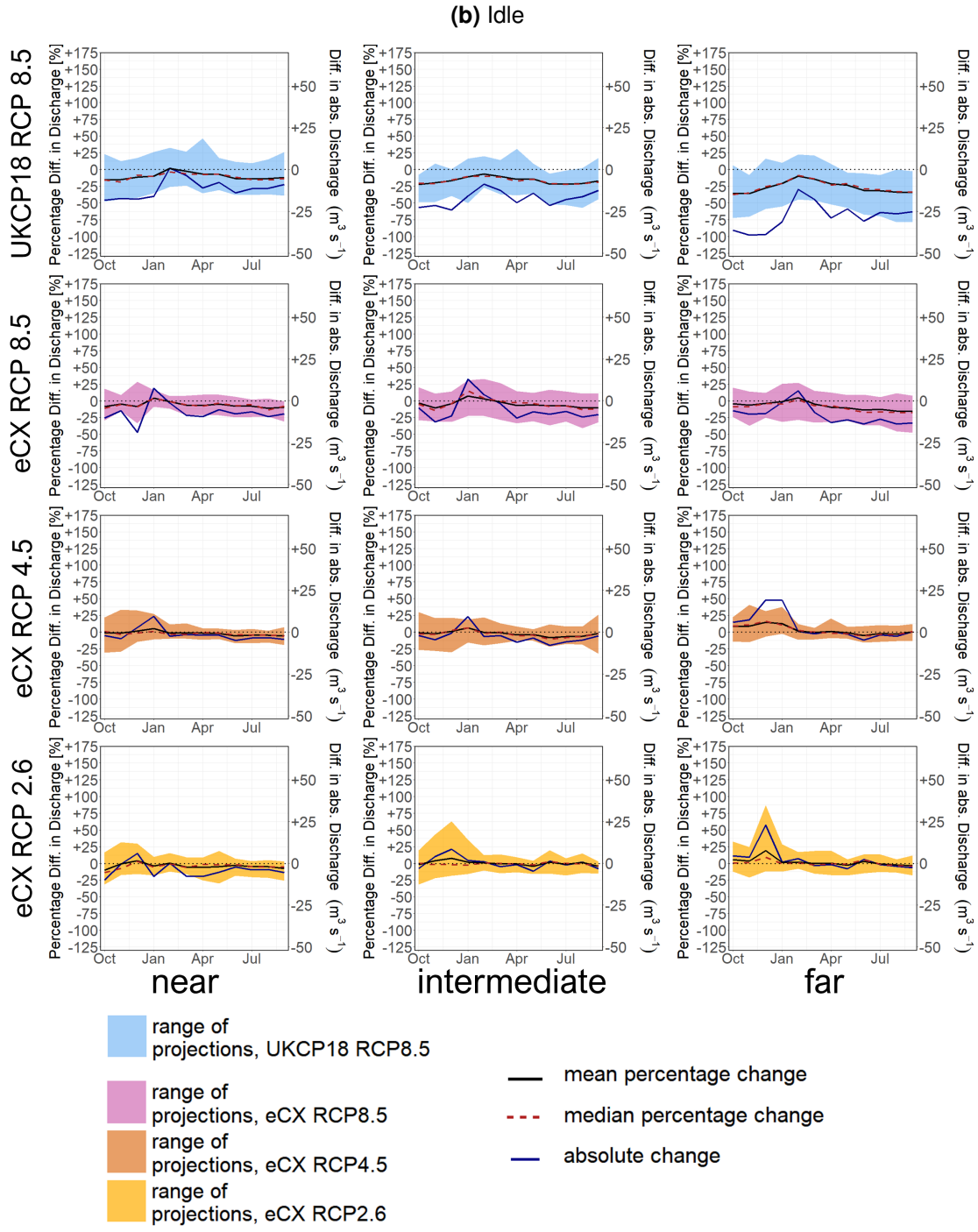
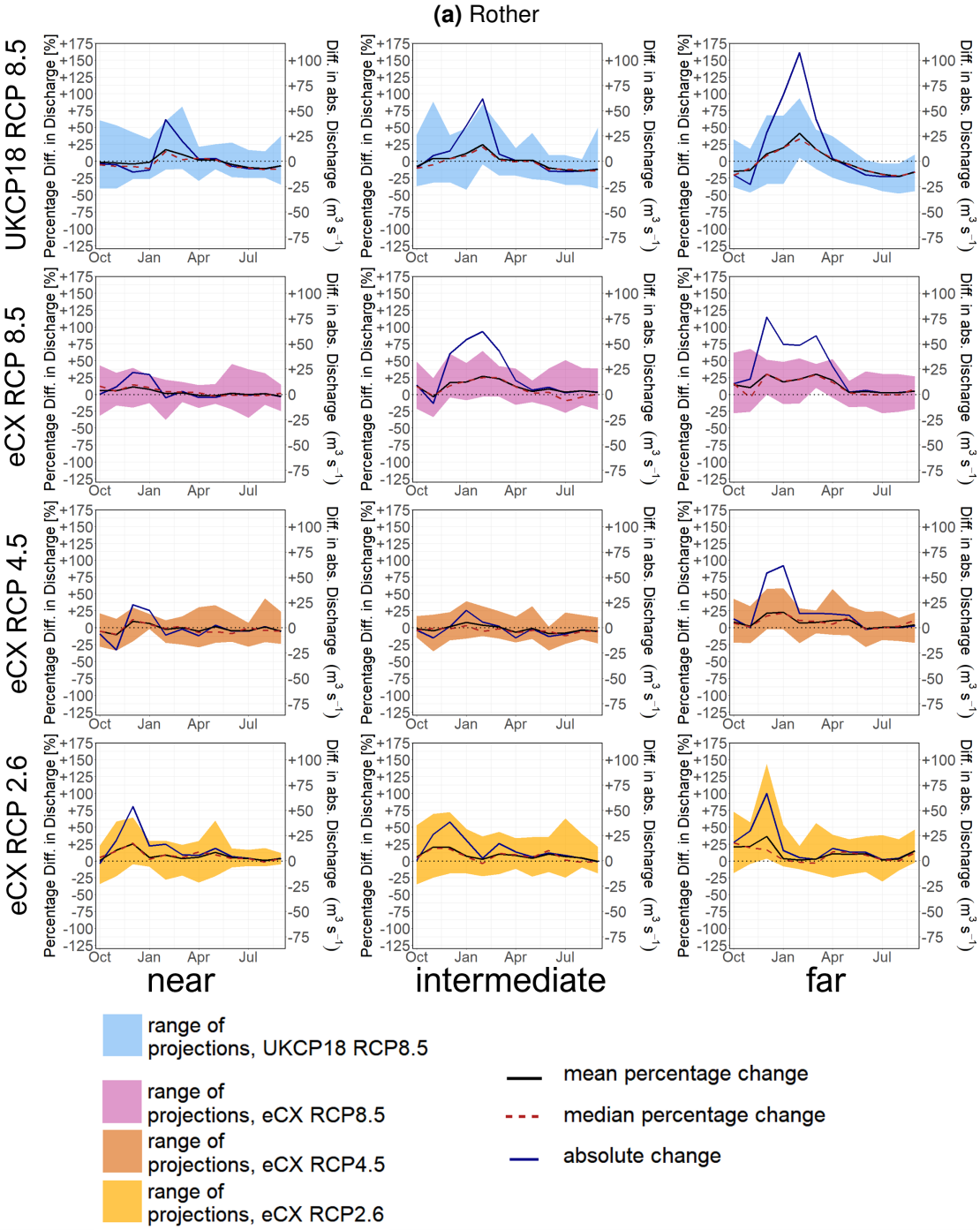


Figure B.14: Comparison of the percentage changes (on the left y-axis) and absolute long-term mean annual dynamics (on the right y-axis) of discharge in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+ model, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the Rother (a) and Idle (b).


(a) Rother
UKCP18 RCP 8.5
eCX RCP 8.5
eCX RCP 4.5
eCX RCP 2.6
near
intermediate
far
Percentage Diff. in Discharge [%]
Diff. in abs. Discharge (m3 s−1)
Oct
Jan
Apr
Jul
range of projections, UKCP18 RCP8.5
range of projections, eCX RCP8.5
range of projections, eCX RCP4.5
range of projections, eCX RCP2.6
mean percentage change
median percentage change
absolute change

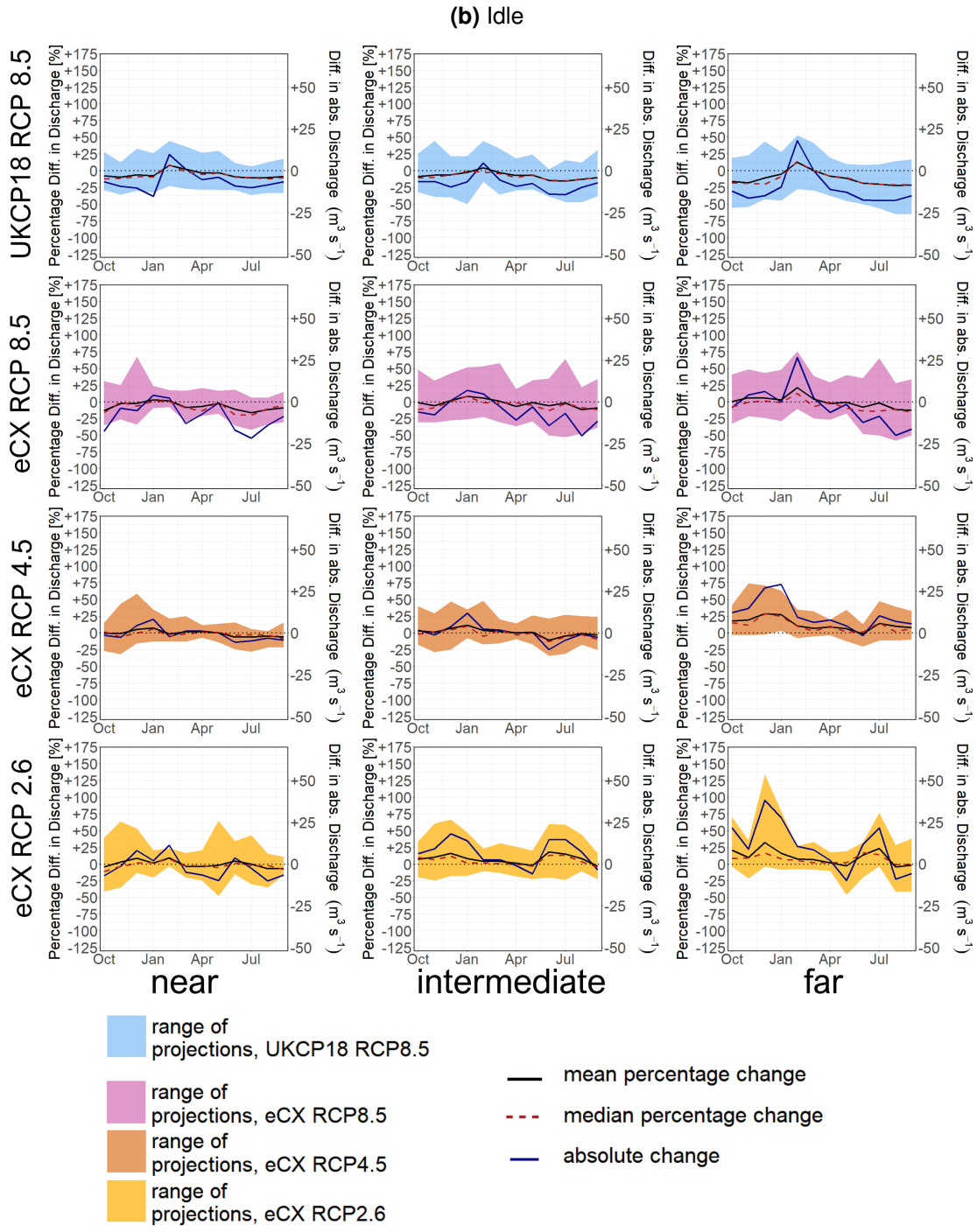
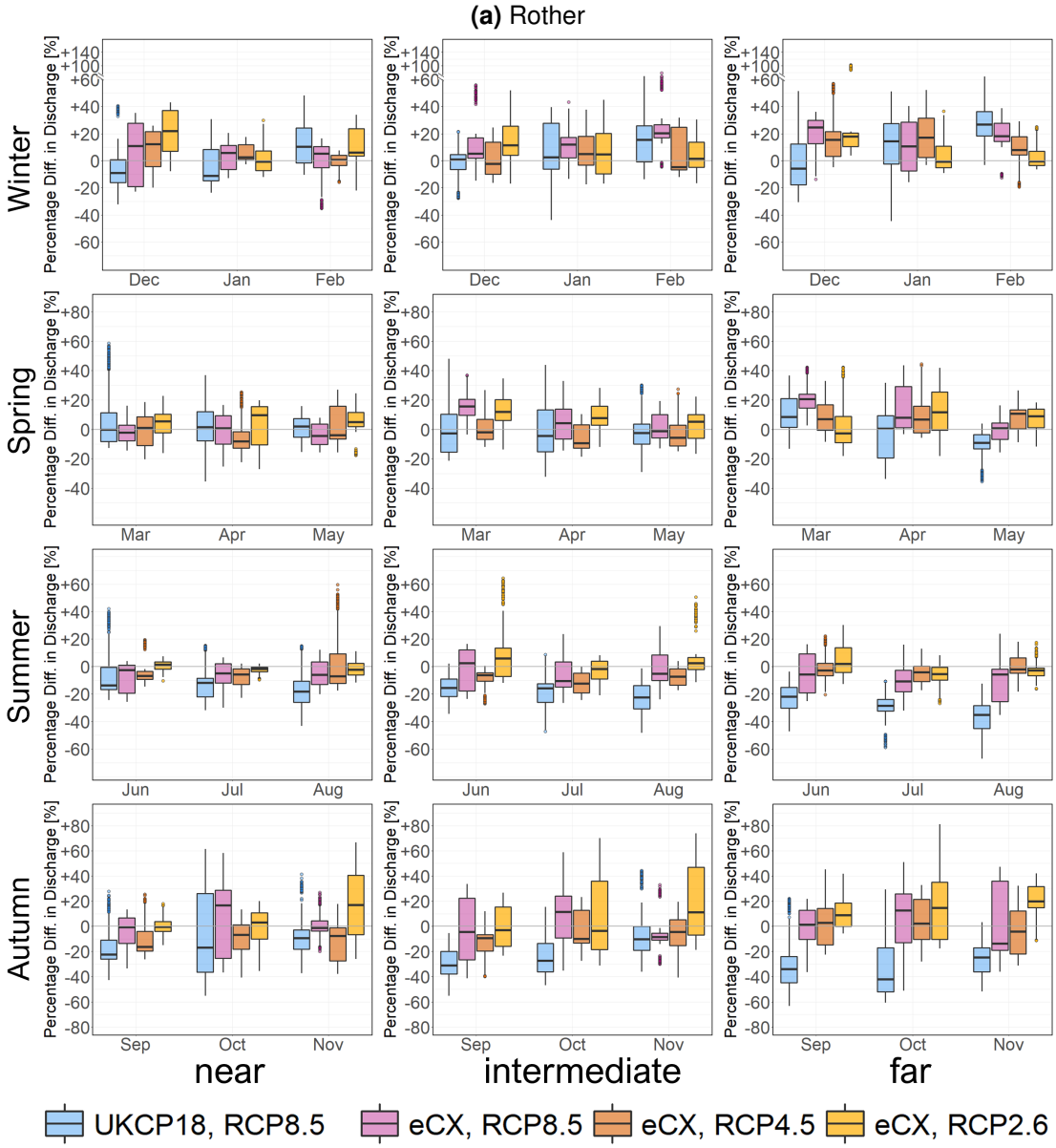


Figure B.15: Comparison of the percentage changes (on the left y-axis) and absolute long-term mean annual dynamics (on the right y-axis) of discharge in the near, intermediate and far future time slices with that in the reference period simulated with SWAT+ model, driven by the UKCP18 and euro-CORDEX (eCX), bias corrected with gamma-Pareto Quantile Mapping (GPQM) for the Rother (a) and Idle (b).


(a) Rother
Winter
Spring
Summer
Autumn
Percentage Diff. in Discharge [%]
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
near
intermediate
far
UKCP18, RCP8.5
eCX, RCP8.5
eCX, RCP4.5
eCX, RCP2.6

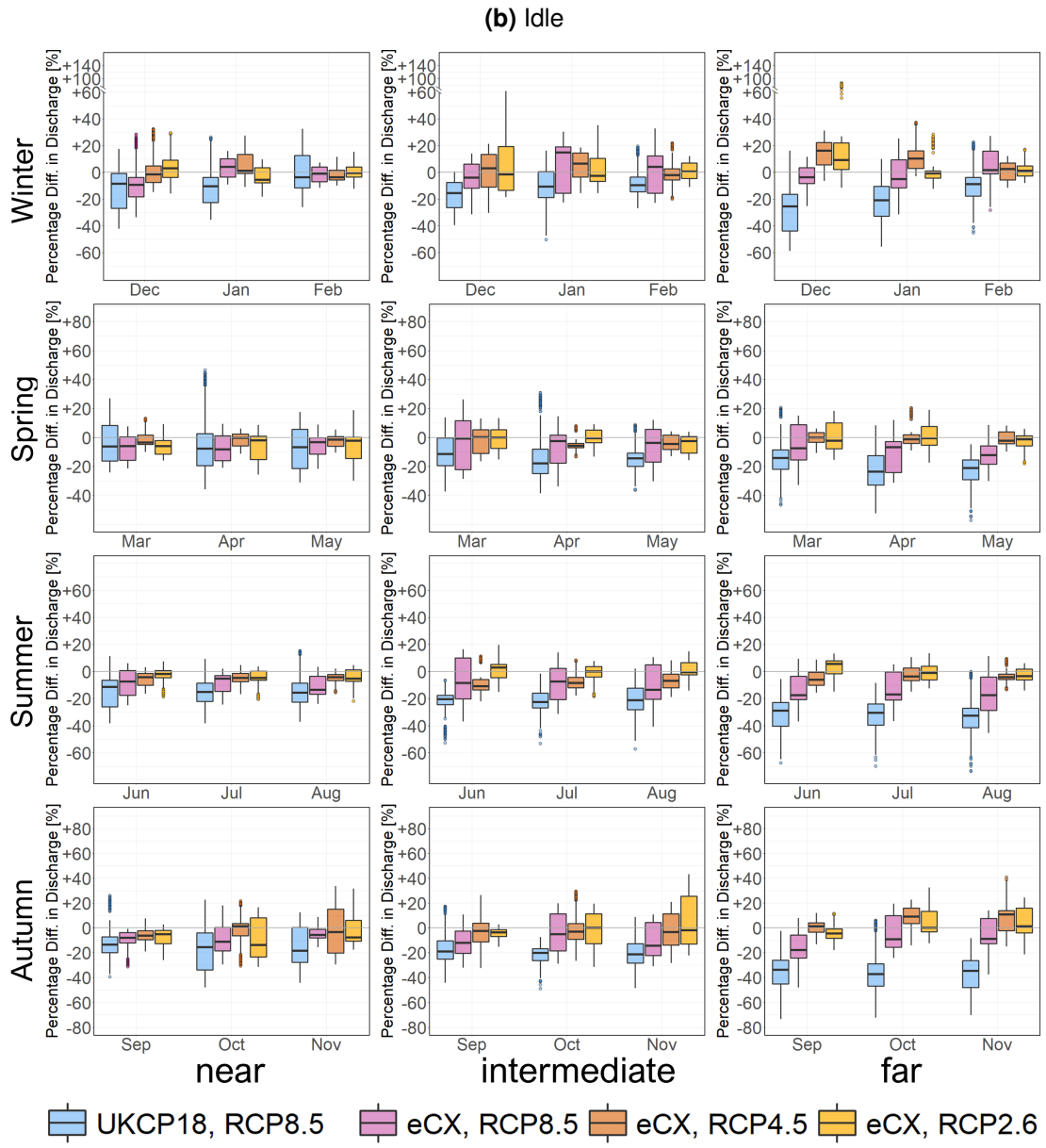
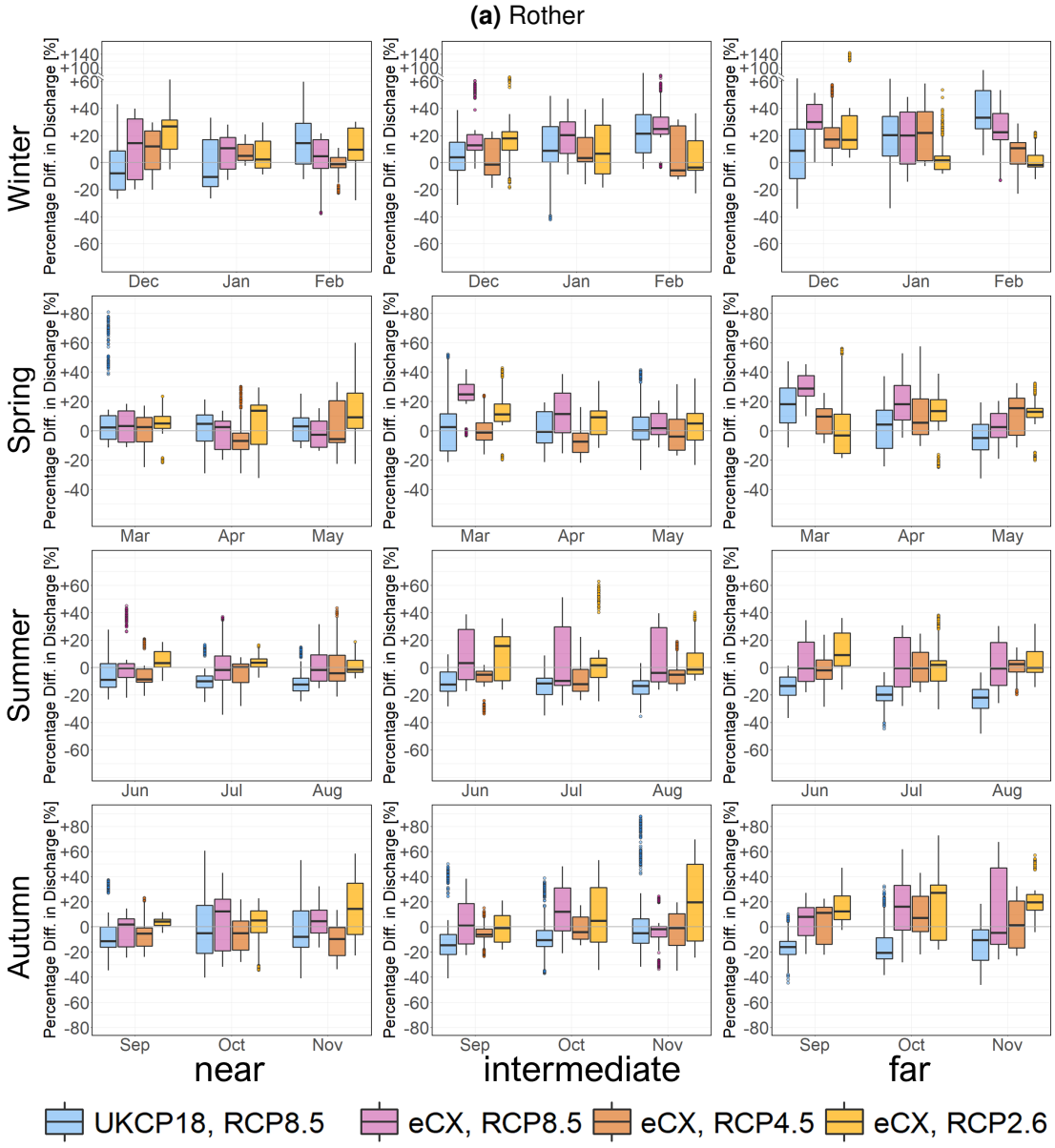


Figure B.16: Monthly percentage change across the four seasons and three future time slices, simulated with the SWAT+ model, driven by the UKCP18 and euroCORDEX (eCX), bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) for the Rother (a) and Idle (b).


(a) Rother
Winter
Spring
Summer
Autumn
Percentage Diff. in Discharge [%]
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
near
intermediate
far
UKCP18, RCP8.5
eCX, RCP8.5
eCX, RCP4.5
eCX, RCP2.6

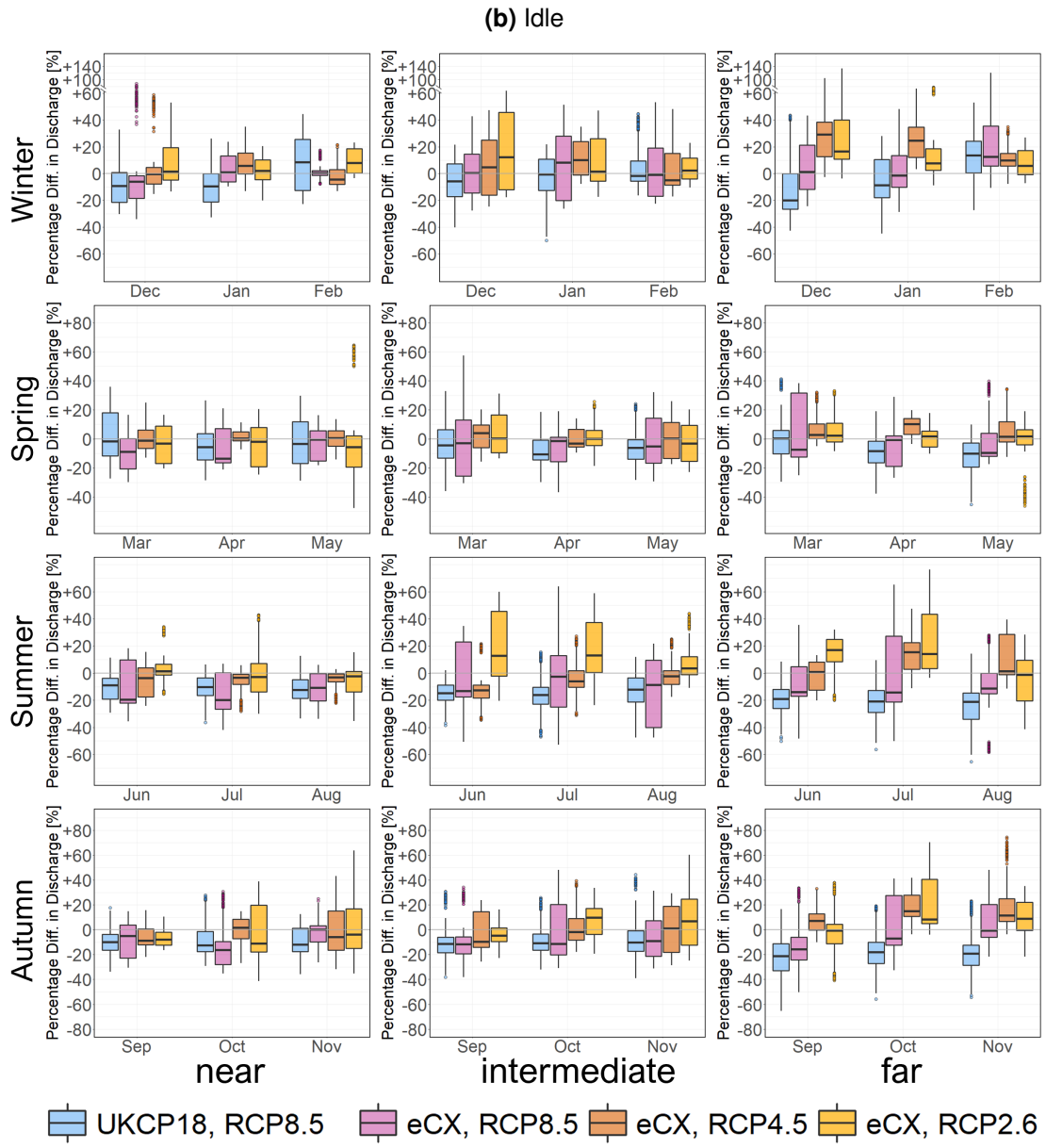


Figure B.17: Monthly percentage change across the four seasons and three future time slices, simulated with the SWAT+ model, driven by the UKCP18 and euroCORDEX (eCX), bias corrected with gamma-Pareto Quantile Mapping (GPQM) for the Rother (a) and Idle (b).

Table B.6: Observed monthly flow in the reference period (2001-2017) and projected mean monthly percentage change in natural streamflow across the euro-CORDEX (eCX) and UKCP18 in the near (2021-2040), intermediate (2041-2060) and far future (2061-2080) compared to the reference period. Climate projections bias corrected with Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

Rother	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	284.8	-2.6	7.1	10.7	3.5	11.4	10.9	4.7	6.6	18.7	1.3	6.1	2.4
Feb	220.6	12.8	16.2	28.1	-1.3	22.7	17.2	-0.9	4.5	8.6	8.5	3.8	3.1
Mar	188.6	6.7	0.5	10.2	-2.2	15.7	21.8	-0.4	1.8	8.9	4.1	11.2	3.2
Apr	135.2	2.0	-0.7	-3.0	-1.7	5.1	13.6	-4.7	-6.3	9.8	3.2	8.6	11.0
May	115.3	0.4	-2.4	-10.2	-3.6	2.1	-0.2	1.0	-2.3	8.2	4.8	2.8	6.5
Jun	83.9	-7.1	-15.6	-22.7	-7.4	-1.4	-4.9	-3.7	-8.9	-0.8	0.8	10.1	5.3
Jul	81.3	-12.7	-18.6	-28.7	-6.8	-6.0	-9.7	-8.0	-12.0	-4.2	-2.3	-3.0	-5.9
Aug	73.0	-17.6	-22.9	-36.4	-5.1	-1.1	-8.5	2.6	-7.4	-0.9	-1.7	6.6	-2.5
Sep	68.8	-16.5	-29.7	-31.3	-5.3	-3.1	-2.0	-10.4	-12.4	3.7	-0.4	-1.1	10.1
Oct	123.8	-6.5	-24.9	-33.0	10.0	8.6	4.7	-10.1	-4.1	2.7	-2.8	7.6	18.9
Nov	190.7	-8.4	-6.9	-26.0	0.9	-5.6	0.0	-11.0	-7.4	-3.0	19.0	19.8	19.0
Dec	228.5	-5.3	-2.5	-1.0	7.0	10.9	20.0	9.7	1.7	18.0	21.1	15.4	28.2
annual	149.1	-1.1	-4.3	-6.1	1.4	8.4	9.4	1.5	-1.2	9.1	7.0	10.6	10.5
Idle	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	154.2	-10.1	-10.7	-21.0	3.7	6.9	-1.3	5.2	6.2	12.8	-4.1	1.8	1.2
Feb	138.3	1.4	-6.7	-9.7	-1.2	2.7	4.4	-1.6	-0.5	1.3	0.5	0.8	2.1
Mar	130.6	-2.4	-10.3	-14.6	-6.7	-1.6	-5.2	-1.3	-1.1	-0.5	-5.6	-0.9	-0.0
Apr	114.5	-7.0	-14.6	-21.6	-7.2	-7.1	-9.4	-1.4	-4.4	1.0	-5.8	-0.5	0.2
May	106.3	-7.2	-14.0	-23.4	-5.1	-5.8	-10.5	-2.1	-3.4	-0.9	-4.9	-4.4	-2.9
Jun	94.9	-13.8	-21.8	-31.5	-8.2	-7.7	-13.9	-5.7	-8.2	-5.1	-2.7	1.7	2.9
Jul	85.7	-14.0	-22.0	-31.7	-8.0	-7.5	-13.0	-4.8	-6.9	-2.0	-5.0	-1.1	-0.7
Aug	90.9	-13.7	-20.9	-33.9	-11.1	-10.8	-15.2	-4.8	-6.1	-3.0	-5.1	1.2	-2.4
Sep	87.7	-11.9	-17.0	-34.4	-9.6	-10.3	-16.1	-5.8	-2.3	0.6	-7.6	-4.5	-3.4
Oct	102.6	-15.8	-22.4	-35.7	-8.6	-3.4	-4.4	-1.3	-1.0	8.3	-10.2	-2.0	5.4
Nov	117.6	-15.2	-20.1	-36.2	-4.7	-10.8	-6.7	-1.8	-2.3	9.0	-1.0	4.1	3.5
Dec	131.4	-11.3	-16.7	-27.6	-8.5	-4.4	-4.1	1.5	1.0	14.5	3.9	7.7	18.9
annual	112.8	-9.7	-15.8	-25.4	-5.9	-3.4	-7.0	-1.7	-2.9	3.8	-4.1	0.4	2.5

Table B.6 Continued: Observed monthly flow in the reference period (2001-2017) and projected mean monthly percentage change in natural streamflow across the euro-CORDEX (eCX) and UKCP18 in the near (2021-2040), intermediate (2041-2060) and far future (2061-2080) compared to the reference period. Climate projections bias corrected with gamma-Pareto Quantile Mapping (GPQM).

Rother	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	284.8	-1.7	11.5	19.8	3.5	11.4	10.9	4.7	6.6	18.7	1.3	6.1	2.4
Feb	220.6	17.3	24.8	41.4	-1.3	22.7	17.2	-0.9	4.5	8.6	8.5	3.8	3.1
Mar	188.6	9.8	3.3	18.0	-2.2	15.7	21.8	-0.4	1.8	8.9	4.1	11.2	3.2
Apr	135.2	1.8	1.2	2.3	-1.7	5.1	13.6	-4.7	-6.3	9.8	3.2	8.6	11.0
May	115.3	2.3	1.5	-4.5	-3.6	2.1	-0.2	1.0	-2.3	8.2	4.8	2.8	6.5
Jun	83.9	-4.8	-9.9	-14.2	-7.4	-1.4	-4.9	-3.7	-8.9	-0.8	0.8	10.1	5.3
Jul	81.3	-9.2	-13.2	-19.3	-6.8	-6.0	-9.7	-8.0	-12.0	-4.2	-2.3	-3.0	-5.9
Aug	73.0	-11.2	-14.4	-22.6	-5.1	-1.1	-8.5	2.6	-7.4	-0.9	-1.7	6.6	-2.5
Sep	68.8	-6.9	-11.8	-16.3	-5.3	-3.1	-2.0	-10.4	-12.4	3.7	-0.4	-1.1	10.1
Oct	123.8	-1.6	-7.8	-14.9	10.0	8.6	4.7	-10.1	-4.1	2.7	-2.8	7.6	18.9
Nov	190.7	-2.4	4.3	-13.3	0.9	-5.6	0.0	-11.0	-7.4	-3.0	19.0	19.8	19.0
Dec	228.5	-4.2	3.8	11.2	7.0	10.9	20.0	9.7	1.7	18.0	21.1	15.4	28.2
annual	149.1	1.1	3.7	7.2	3.9	13.9	17.3	1.0	-0.3	10.7	8.6	9.2	11.2
Idle	**flow (m^3/s)**	**UKCP18 RCP 8.5 (%)**			**eCX RCP 8.5 (%)**			**eCX RCP 4.5 (%)**			**eCX RCP 2.6 (%)**		
period	2001 2017	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080	2021 2040	2041 2060	2061 2080
Jan	154.2	-8.0	-2.8	-5.4	3.1	8.0	2.6	7.4	11.4	26.9	1.5	7.9	16.2
Feb	138.3	7.9	4.1	12.4	1.5	5.4	21.0	-1.5	3.9	10.3	9.0	3.8	7.4
Mar	130.6	2.0	-3.4	0.1	-8.4	1.0	3.7	1.5	2.1	6.7	-3.4	3.7	6.3
Apr	114.5	-3.5	-7.2	-8.4	-6.8	-7.0	-2.9	1.4	0.0	8.7	-4.0	1.1	1.7
May	106.3	-2.9	-6.7	-11.6	-2.4	-1.5	-0.7	0.0	1.1	6.1	-2.0	-2.3	-3.1
Jun	94.9	-9.3	-14.8	-18.8	-11.3	-6.1	-8.1	-6.3	-10.9	-1.5	4.5	18.2	13.5
Jul	85.7	-11.0	-15.8	-20.6	-16.6	-1.8	-1.8	-6.3	-4.6	14.2	-0.4	15.0	23.4
Aug	90.9	-10.2	-12.9	-22.6	-11.7	-11.9	-11.9	-4.6	-0.9	9.8	-7.1	8.2	-4.2
Sep	87.7	-9.1	-10.5	-21.3	-8.9	-9.3	-12.6	-6.1	-3.1	7.9	-6.8	-3.6	-1.8
Oct	102.6	-7.7	-8.6	-16.2	-13.5	-1.2	0.4	-1.1	3.1	18.0	-4.2	7.2	20.8
Nov	117.6	-9.7	-6.9	-18.3	-2.7	-6.1	6.1	-1.0	0.9	19.6	3.1	10.3	9.7
Dec	131.4	-6.2	-6.1	-11.1	-2.3	1.9	5.3	5.2	6.8	28.8	8.8	16.1	32.3
annual	112.8	-5.6	-7.7	-10.2	-7.9	-2.5	-0.2	-1.5	-0.6	12.7	-0.7	6.2	10.0

B.3.4 Discussion - Bias Correction as a Source of Uncertainty

The ensembles' overall performance in simulating observed discharge dynamics was strongly improved through bias correction with LS allowing some confidence in the use of these climate projections for simulating future changes in flows (Lobanova et al., 2018). As outlined in introduction of Chapter 3, the choice of appropriate bias correction method strongly depends on the context and cannot overcome limitations in the underlying GCMs (Maraun, 2016). It has furthermore been shown that good performance in reproducing natural variability in precipitation and temperature does not necessarily translate into better ability of bias correction methods to simulate hydrological metrics. Chen et al. (2016) argue that since high natural climate variability renders additional complexity obsolete and that simple bias correction methods are therefore equally appropriate for hydrological climate change impact studies than more sophisticate methods. The differences this study detected between modelled monthly discharge in the observations period under climate data corrected with LS as compared to two other methods relying on quantile mapping strongly depend on catchment and on climate ensemble.

The results received under GPQM-corrected projections align more closely to those received under LS-corrected projections than those under ISIMIP-corrected projections. This is at least partly due to the same correction applied for temperature in these simulations as, unlike ISIMIP, GPQM is a method for correcting precipitation only. GPQM presents as slightly wetter in both catchments with more increases projected for winter in both catchments. Differences to LS in ISIMIP-corrected projections are most pronounced under the UKCP18. In the Rother the seasonality is enhanced while Idle projections are (even) drier.

The use of LS is justifiable for the purpose of this study, the focus of which lay on the uncertainty introduced by GCMs. Further studies, particularly those with a focus on high and/or low flows and floods, where precipitation patterns with a daily resolution such as high intensity rainfall events or dry spells strongly influence hydrological processes and/or that want to achieve even higher uncertainty coverage should aim for an improved daily calibration of the HM and extend the analysis with other, more advanced, bias correction methods (Gao et al., 2019; Song et al., 2020).

Appendix C - Chapter 4

C.1 Water Balance Modelling

C.1.1 Case Study Catchment Details

Table C.1: Catchments considered in the modelling, their class membership as defined in Chapter 2, their National River Flow Archive (NRFA) station number, Abstraction Licensing Strategy (ALS) group and Abstraction Point (AP), Abstraction Sensitivity Band (ASB), Common Standards Monitoring (CSM) category and closest UK Benchmark Network (UKBN) donor station that is part of Enhanced Future Flows and Groundwater (eFLaG) (Environment Agency (2018d)[a], Environment Agency (2018a)[b], Environment Agency (2020e)[c], Environment Agency (2020a)[d], Environment Agency (2020b)[e], NRFA (2019c)[f], NRFA (2019f)[g], NRFA (2022b)[h], NRFA (2022g)[i], NRFA (2022d)[j]).

Class	NRFA Station Number	Name	Location of Gauge	Size (km^2)	Purpose of abstractions and return flows	ALS group (AP)	ASB	CSM category	NRFA Station Number of UKBN eFLaG donor station
1	28015	Idle	Mattersey	529	public water supply, irrigation [a,f]	Idle and Torne*	2*	5, river	-
2	27023	Dearne	Barnsley	118	waste water treatment discharge, industrial, irrigation, minewater drainage [e,g]	Don and Rother (AP5)	2	4, river	68005 28046
3	71014	Darwen	Blue Bridge	128	waste water treatment discharge, public water supply, irrigation, industry [c,i,f]	Ribble, Douglas and Crossens (AP4)	3	5, river	73005 72005
4	41009	Rother	Hardham	346	public water supply, irrigation [b,g]	Arun & Western Streams	2	5, river	-
5	34001	Yare	Colney	231	public water supply, irrigation [d,j]	Broadland (AP12)	2	4, river	32003 33018

$*$ there is no assessment point at this gauge for the Idle, classed as based on the surrounding assessment points

C.1.2 Climate Impact Analysis with Donor Stations

For Idle and Rother the climate scenario results for the far future as described in the second chapter were taken as climate scenario input for the model. For the three other catchments, climate scenarios had to be established another way.

C.1.2.1 The Enhanced Future Flows and Groundwater (eFLaG) Projections

The Enhanced Future Flows and Groundwater (eFLaG) project provides consistent daily hydrological projections for 200 catchments under the UKCP18 12 member Regional Projections from 1981 – 2080 (Hannaford et al., 2022). Four different HMs were used to produce these projections: G2G, GR4J, GR6J and PDM. Unfortunately, eFLaG does not provide simulations under other emissions pathways beyond RCP8.5 used in UKCP18. Therefore, while eFLaG is the appropriate product for establishing high emissions climate scenarios and assess a wide range of risks, a method for illustrating less extreme outcomes, as produced for Idle and Rother under the eCX had to be established. Moreover, projections could not directly be extracted for the catchments in question as these are not benchmark catchments.

C.1.2.2 Donor Projections from UKBN catchments

The assumption guiding the design of climate impact scenarios is that climate impacts within the same region as well as class of catchment (defined in Chapter 2) are similar. The three case study catchments were matched with the two closest benchmark catchments within the same catchment group that eFLaG provides data for (Figure C.1). This cannot replace detailed catchment-scale hydrological modelling (such as undertaken in Chapter 3), however the method was deemed appropriate for the simple modelling undertaken in Chapter 4. eFLaG provided a range of plausible monthly change factors and CAMS allowed naturalising the case study catchments' gauged flows.

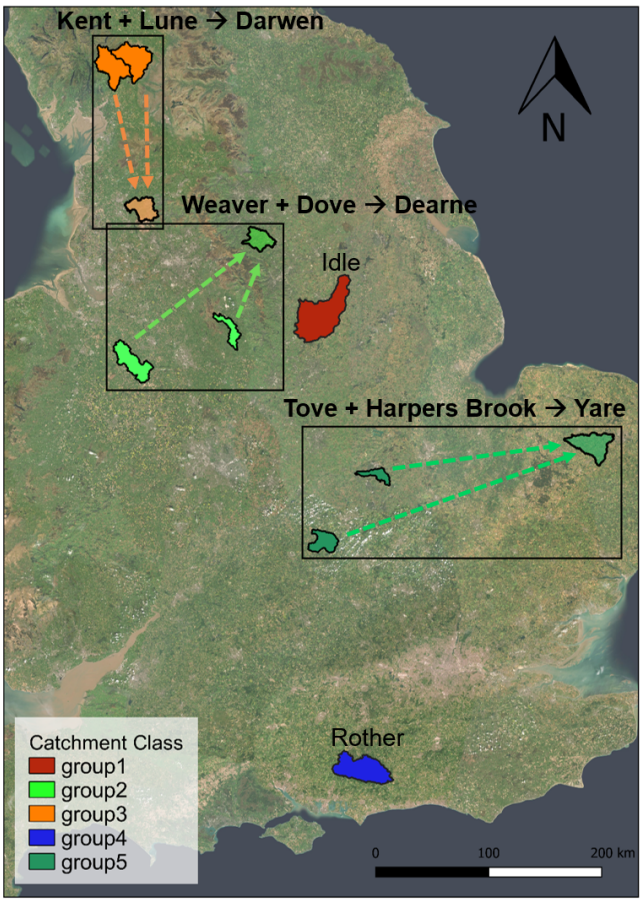


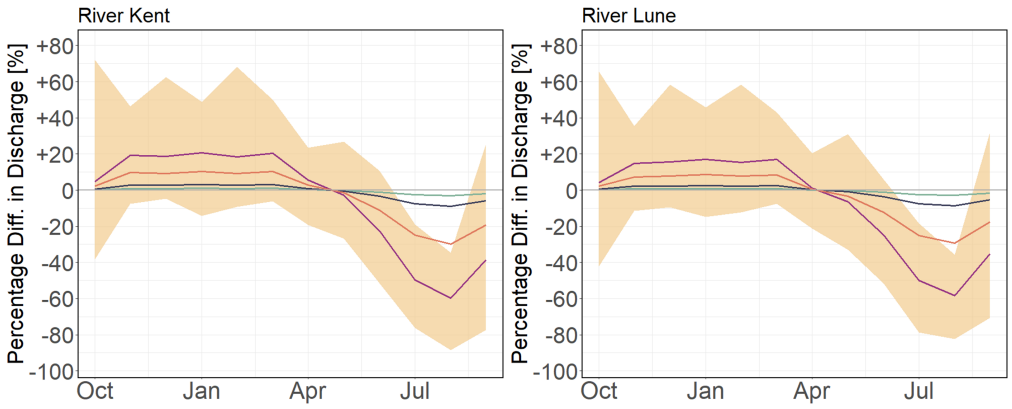
Figure C.1: Location of case study catchments and donor stations from Enhanced Future Flows and Groundwater (eFLaG) within England

The streamflow simulations for the two donor benchmark catchments of each of the case study catchments were analysed and monthly changes for the far future (2061-2080) were extracted for four scenarios ("high", "medium high", "medium" and "low"). This was achieved by averaging these two UKBN "donor" projections. The "high" climate scenarios for Idle and Rother, in detail described in Chapter 3, represented the mean scenario of all UKCP18 runs. Therefore, the mean of the eFLaG projections served as "high" scenario. This "high" scenario therefore most closely aligns between the five catchments.

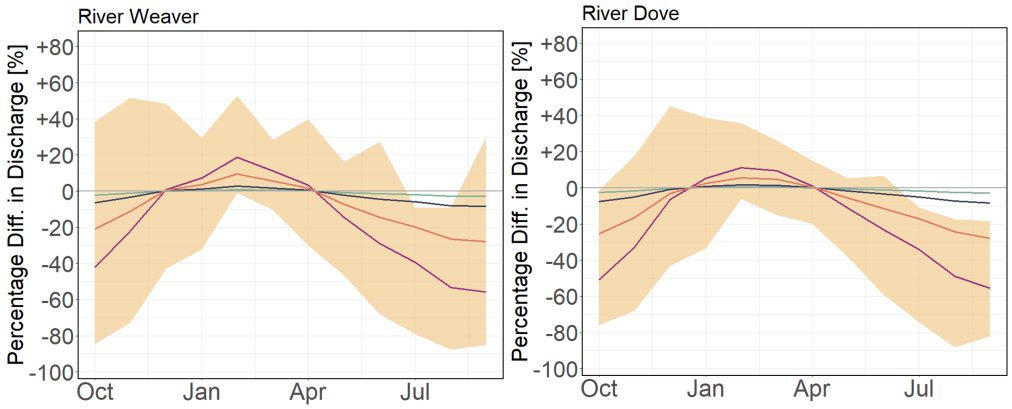
C.1.2.3 Designing climate change scenarios

Large-scale atmospheric processes differ under varying emissions (Lehner and Coats, 2021) and high emissions scenarios cannot be translated into low emissions scenarios. As the analysis in chapter 2 for Idle and particularly for the Rother has however shown, projections under lower emissions scenarios largely result in lower hydrological response. Assuming a linear hydrological response from the low to high climate scenarios, the remaining scenarios ("medium high", "medium" and "low") were designed using the "high" scenario as upper limit. Taking the percentiles across the streamflow

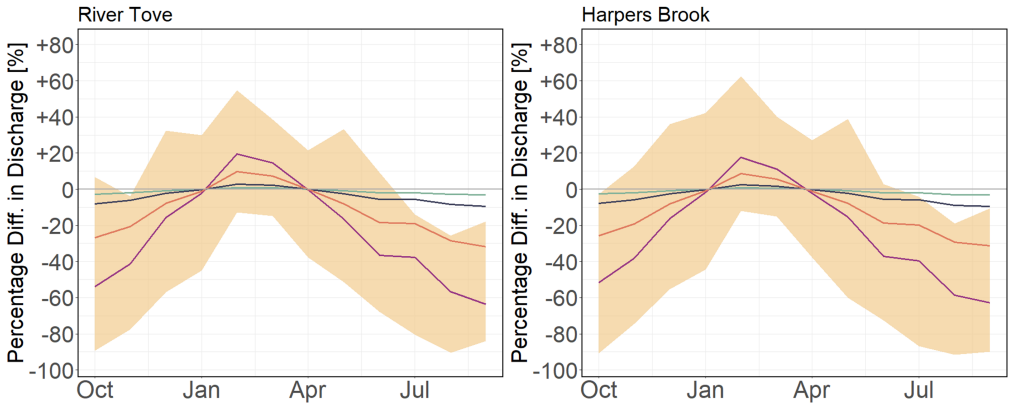
response for the Rother in February as broad orientation, “low”, “medium” and “medium high” scenarios were set at the 5th, 15th and 50th percentile of the mean of the high emissions scenario of eFLaG as shown in Figure C.2. Note how the naming of the scenarios refers to their degree of impact on streamflow and not to the magnitude of emissions. In simple scenarios the direction of change under lower scenarios is always negative when the high scenario is negative and vice versa.



(a) Darwen



(b) Dearne



(c) Yare

Figure C.2: Enhanced Future Flows and Groundwater (eFLaG) Streamflow simulations for the far future (2061 – 2080) as compared to the reference period (2001 – 2017) for the donor stations, simulations produced with Grid-to-Grid (G2G), Génie Rural à 4 paramètres Journalier (GR4J), Génie Rural à 6 paramètres Journalier (GR6J) and Probability Distributed Model (PDM) under UKCP18 Regional Projections.

The projections among the benchmark catchments of the same group are strikingly similar. This suggests that matching the catchments in this way is justified. The range of projected changes is higher than outlined for the Idle and Rother in Chapter 3 under the same UKCP18. This might be due to model set up and other sources of variation such as the higher number of HMs and bias correction. In combination with the simple ap-

proach chosen for delineating lower impact scenarios, this suggests that the uncertainty in climate scenarios applied in chapter 3 is very high.

The results of the water balance modelling for all catchments however show that the environmental flow scenarios are not only driven by climate change but more strongly by the underlying rules of allocation and the pre-existing demand structure. Particularly the “Enhance-Maintain” scenario varies very little across all climate change scenarios. This suggests that the decision on climate change scenarios has little influence on the overall results.

C.1.3 Results for remaining Catchments

C.1.3.1 Changes in Over-abstraction and Over-discharge

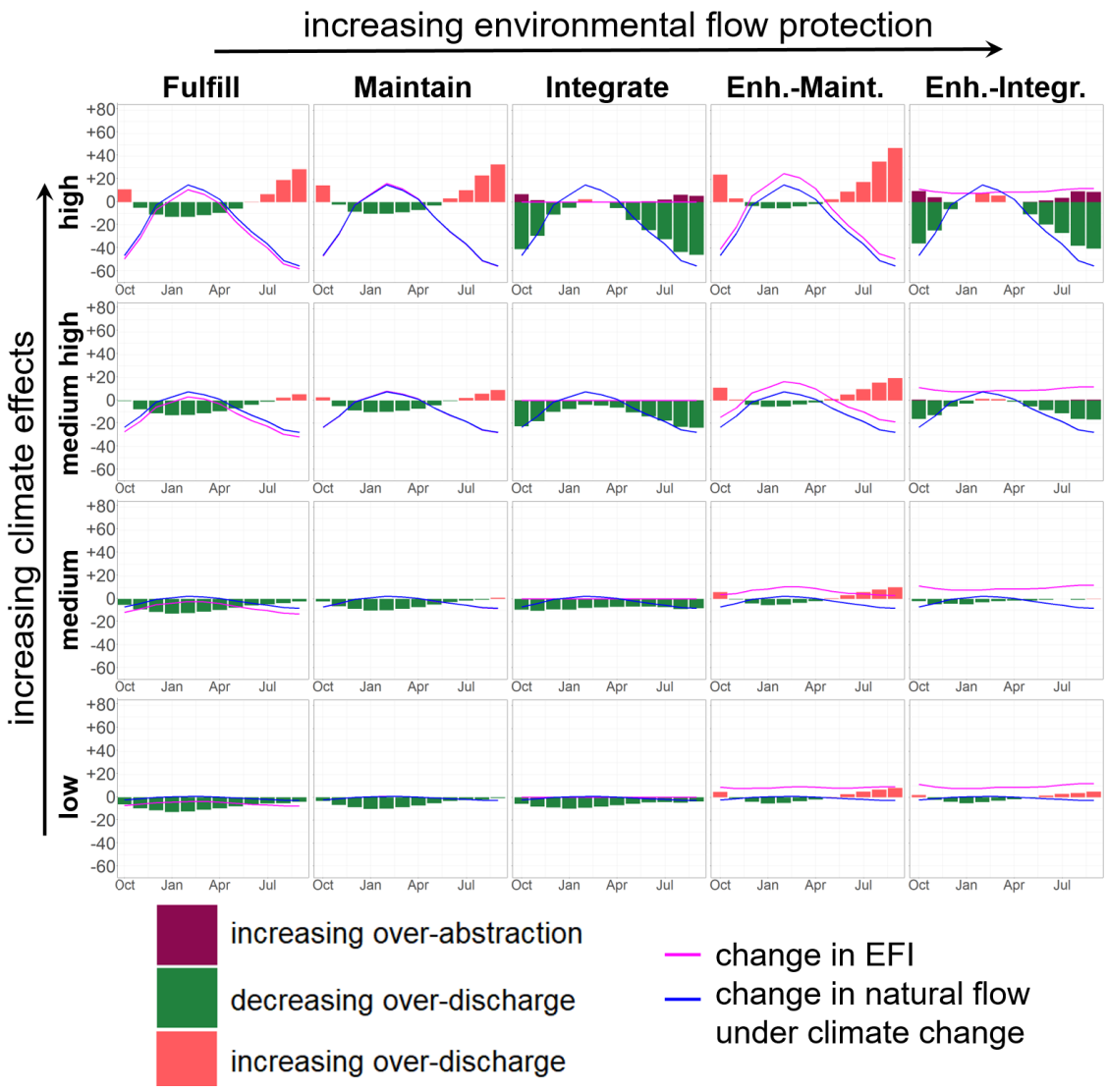


Figure C.3: Change in mean monthly share of over-abstracted and over-discharged environmental flows under five environmental flow and four climate change scenarios, in percent (%), Dearne.

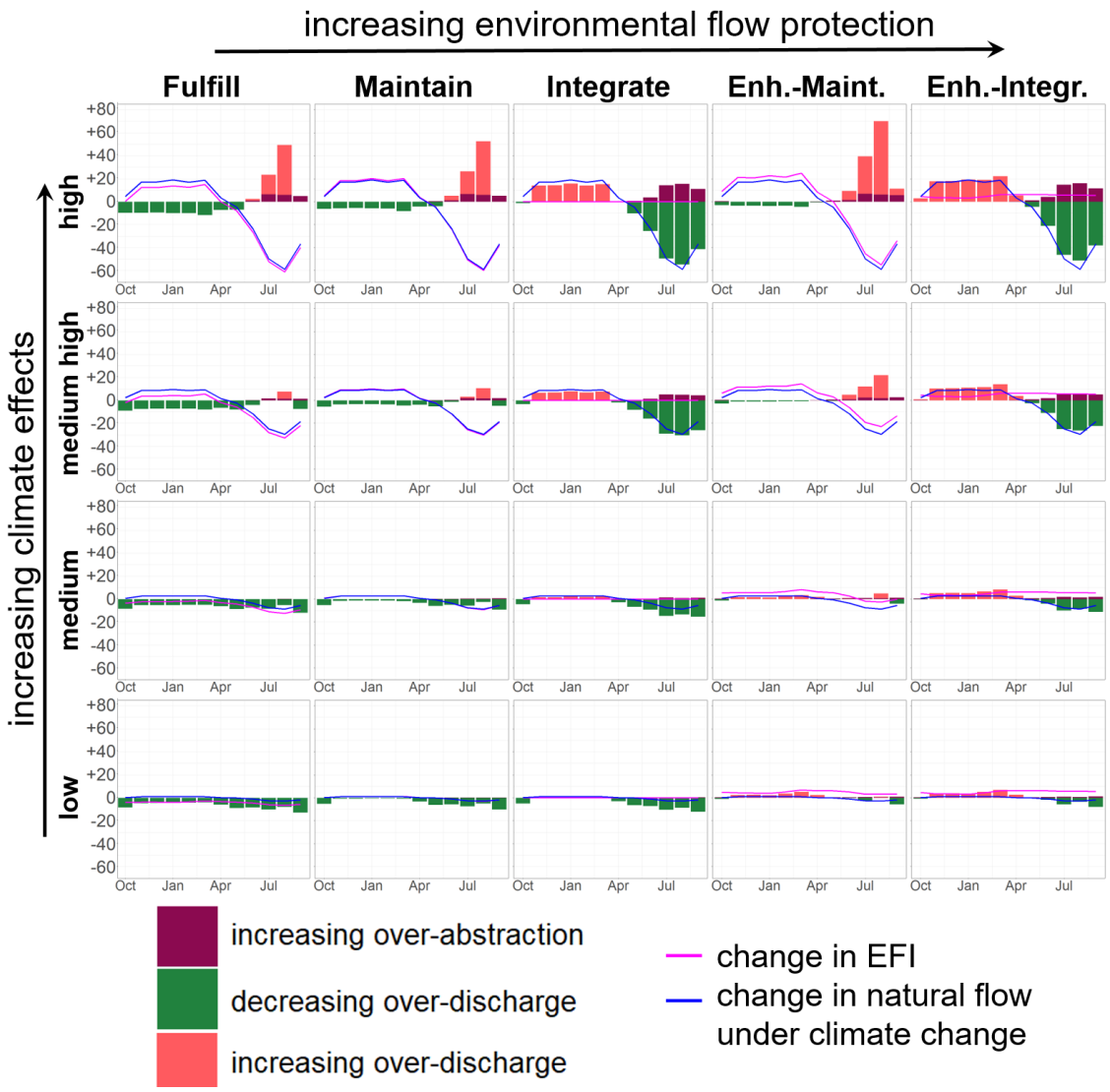


Figure C.4: Change in mean monthly share of over-abstracted and over-discharged environmental flows under five environmental flow and four climate change scenarios, in percent (%), Darwen.

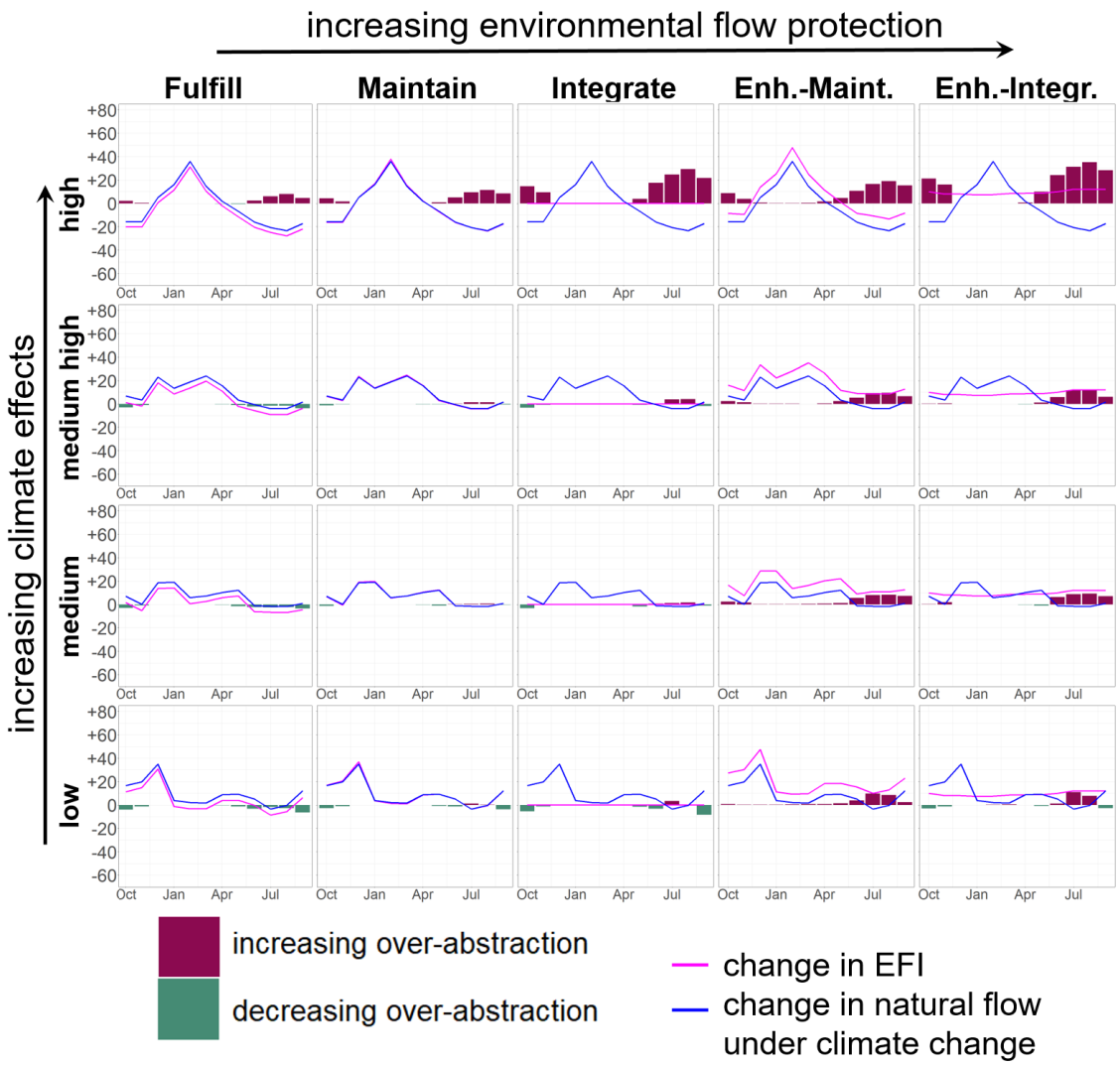


Figure C.5: Change in mean monthly share of over-abstracted environmental flows under five environmental flow and four climate change scenarios, in percent (%), Rother.

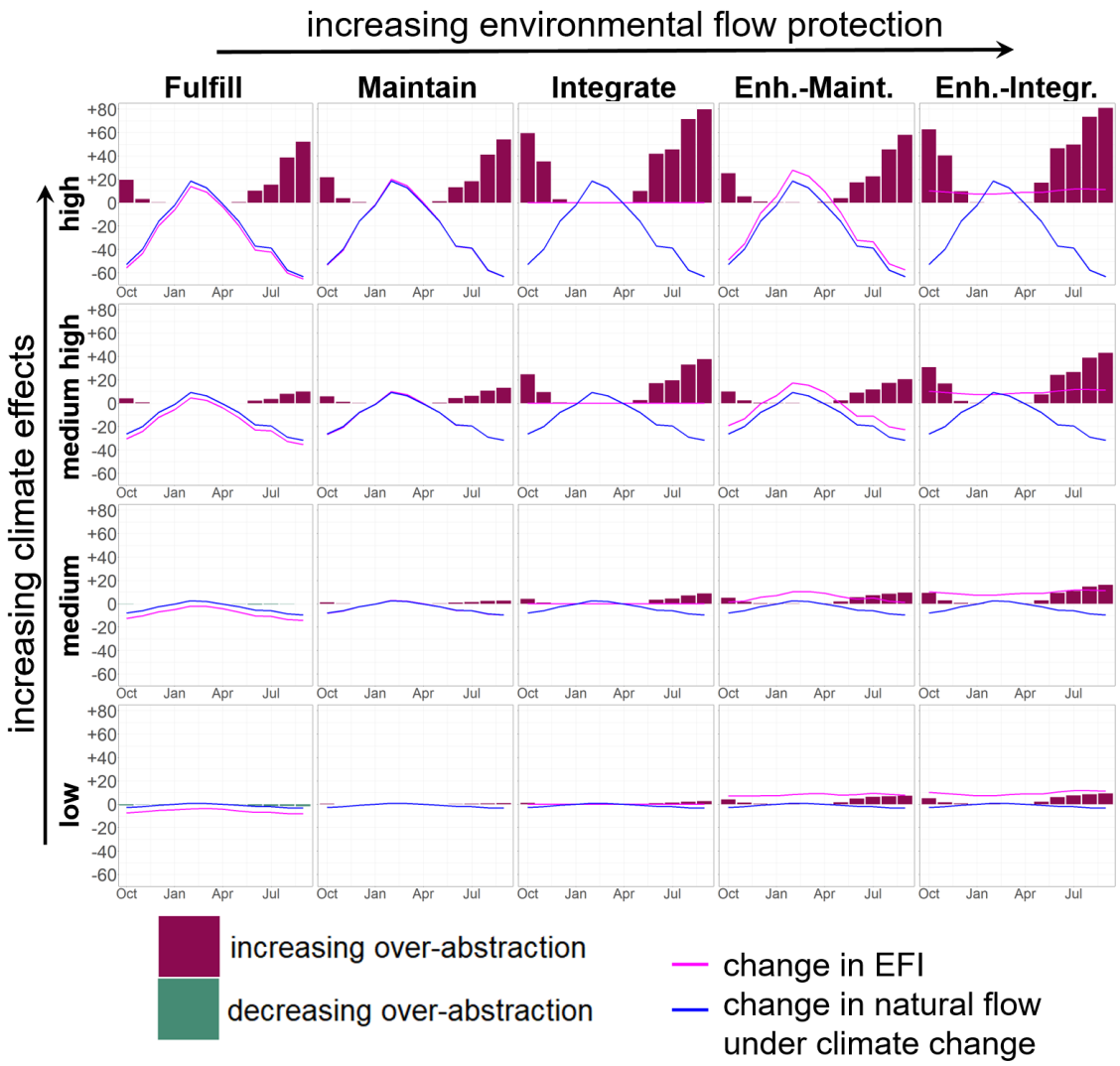


Figure C.6: Change in mean monthly share of over-abstracted environmental flows under five environmental flow and four climate change scenarios, in percent (%), Yare.

C.1.3.2 Required Reductions and allowed increases in Abstraction and return Flows to meet and, respectively, stay below EFIs

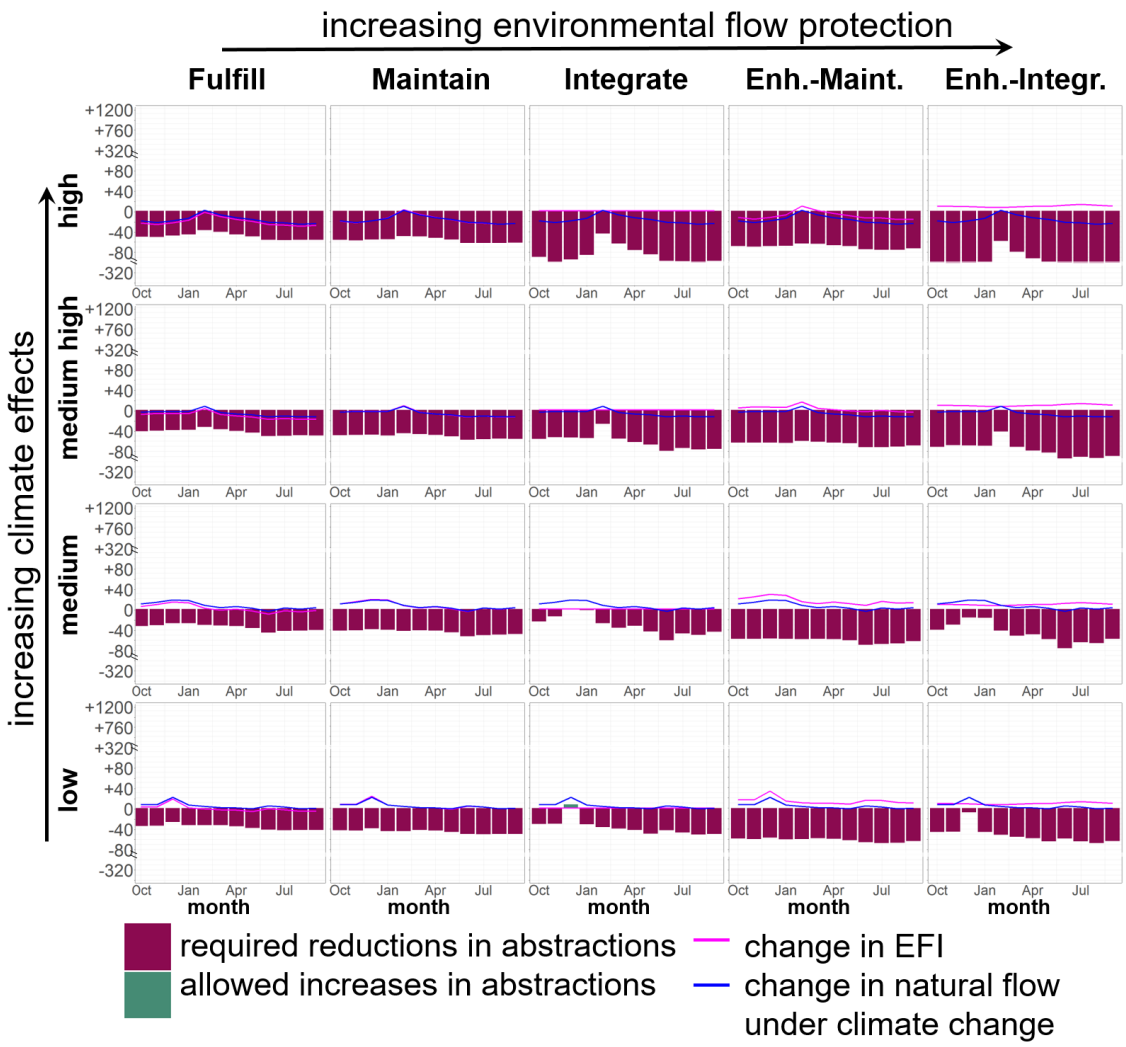


Figure C.7: Mean monthly required reductions and allowed increases in abstraction to stay within the Environmental Flow Indicator (EFI), in percent (%) of current abstraction, Idle.

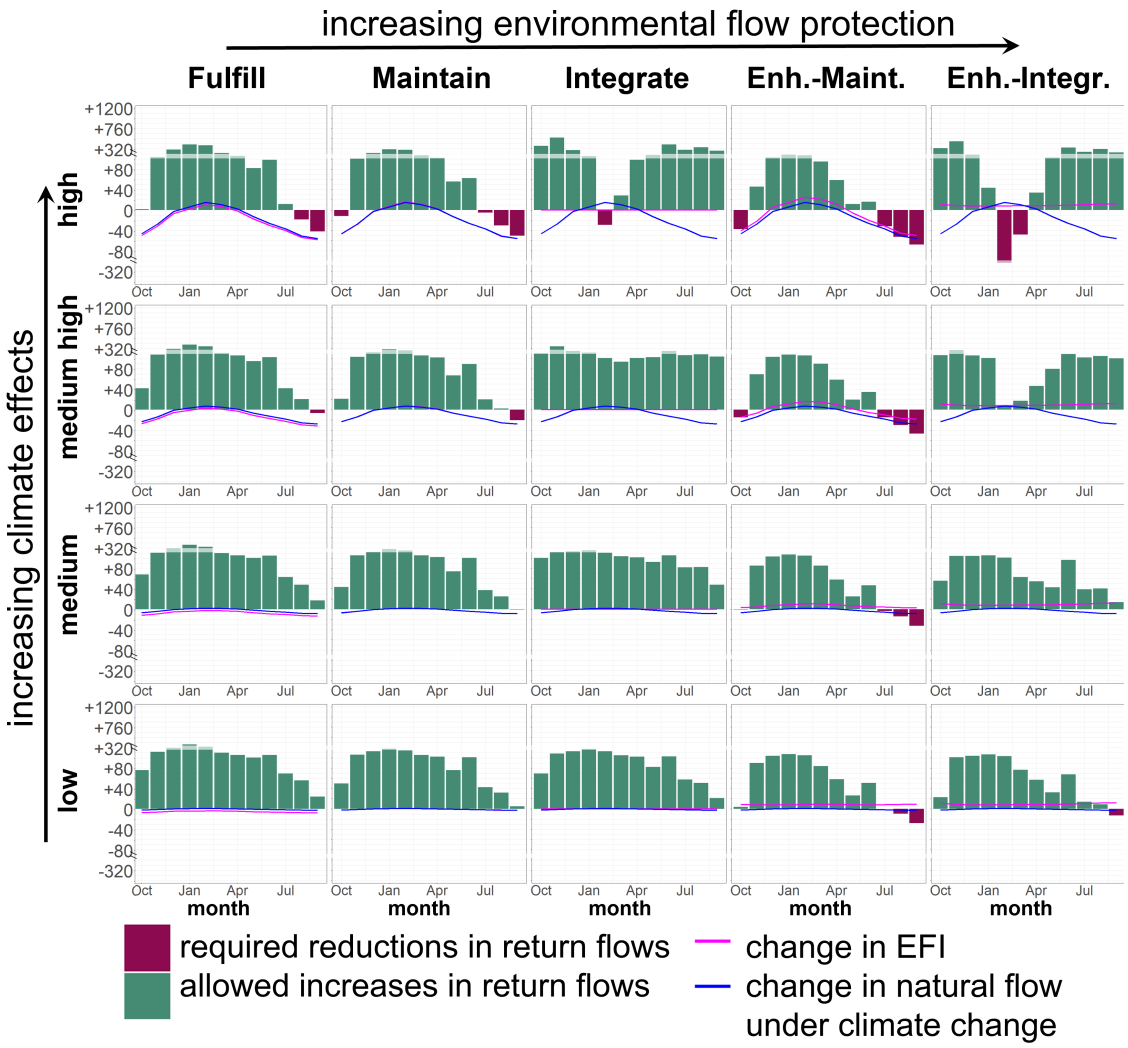


Figure C.8: Mean monthly required reductions and allowed increases in return flows to stay within the Environmental Flow Indicator (EFI), in percent (%) of current discharge, Dearne.

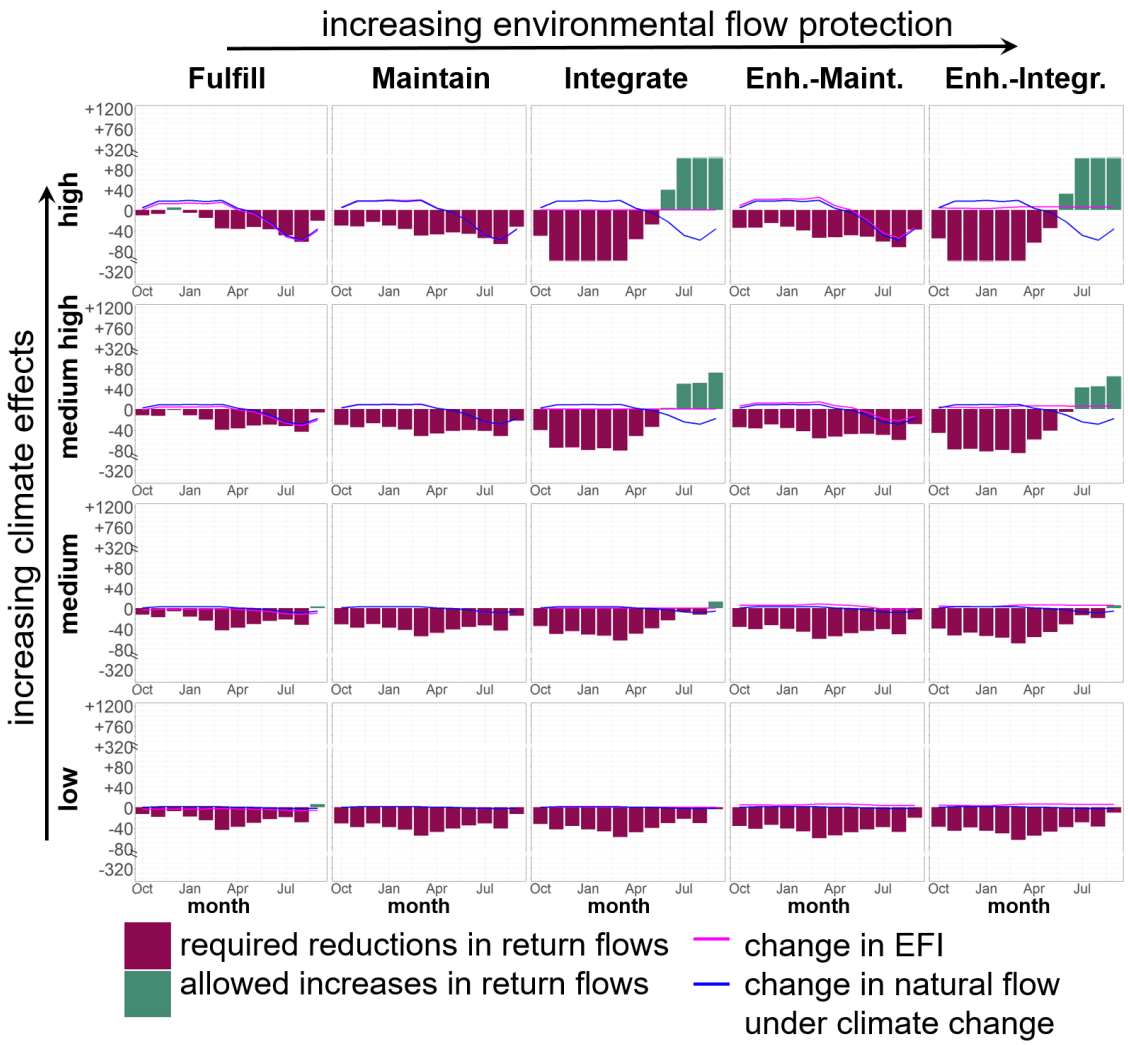


Figure C.9: Mean monthly required reductions and allowed increases in return flows to stay within the Environmental Flow Indicator (EFI), in percent (%) of current discharge, Darwen.

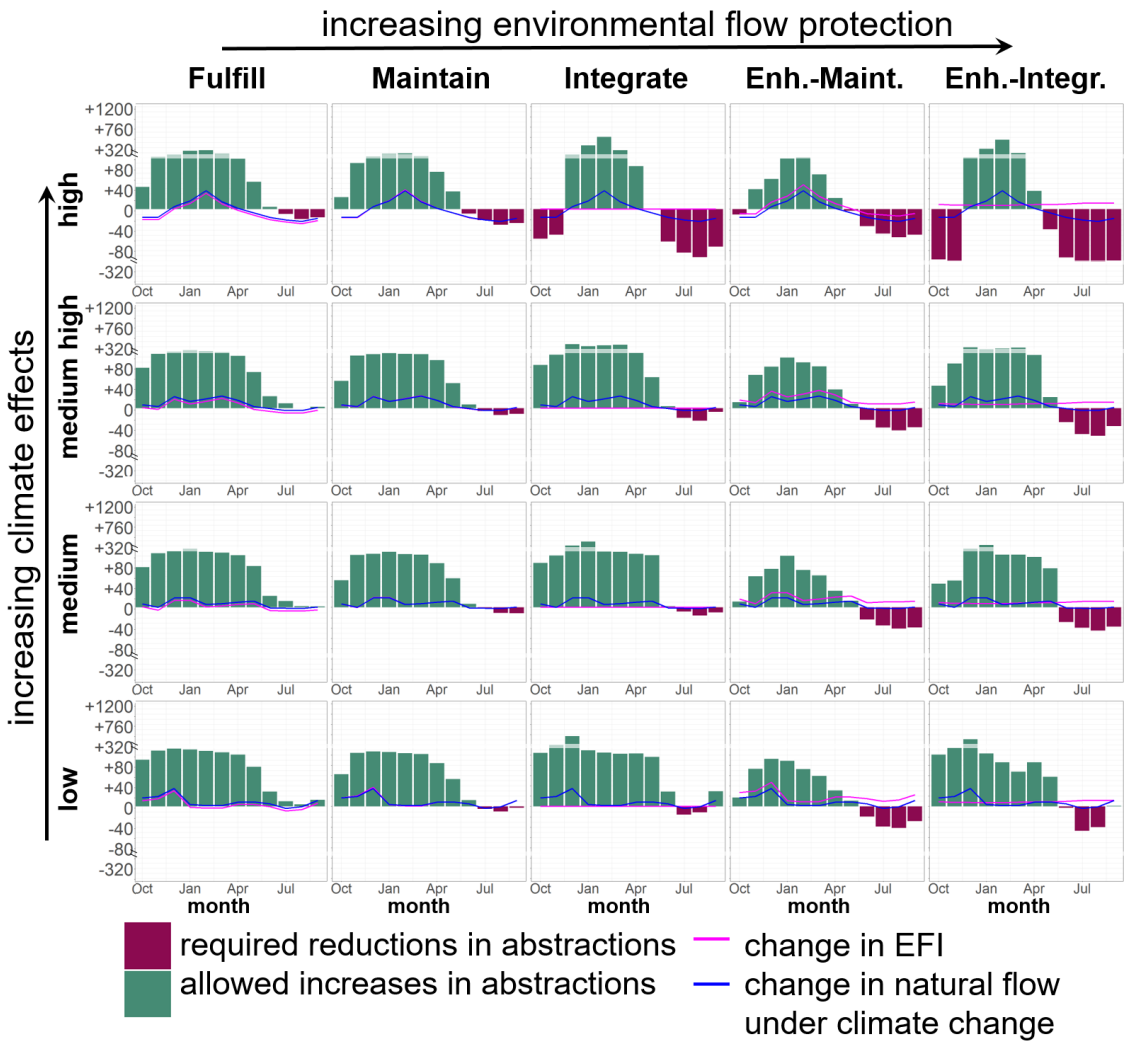


Figure C.10: Mean monthly required reductions and allowed increases in abstraction to stay within the Environmental Flow Indicator (EFI), in percent (%) of current abstraction, Rother.

C.2 Guide for semi-structured Interviews

1. **Introductions & Audio Check.**
2. **Get consent.**
3. **Background and Aim**

Main aim: assess how environmental flow protection at the catchment scale including non-flow pressures can be improved

Draw recommendations on how to integrate climate change into environmental flow management

In this context it is extremely important to assess local practitioners' opinions to be able to get a holistic picture of all issues concerning water use in the catchments.

4. **Interviewee Background**

4.1. Role within Organisation

- Can you shortly summarize your role within <organisation> for me?

if applicable:

- Have you been involved in the priority catchment project?
- Which projects are you currently involved in?
- Which projects have you previously been involved in?

4.2. Details on specific past and ongoing projects

- Background and reasons for the projects' initiation? What issues are addressed?
- Who are the project partners?
- Relevant challenges/findings?
- Issues at heart – e.g. which changes are required to incorporate new findings? How is this project carried forward? What hinders best outcomes?

4.3. Water use in catchment(s)

if applicable:

- which projects are you currently working on?

if relevant:

- Which catchments do you work in or mostly work in?

if relevant:

- What is the abstraction structure in these catchments?
- What type of abstractors are there?
- Licensing situation, scope for new abstractions
- What projects are going on in these catchments that aim to improve the aquatic environment?

- What are the reasons for varying use across the year, what influences demand of the abstractors?

1. **Environmental protection**

   1.1. if applicable: Environmental projects and challenges (in specific catchments or addressed/uncovered through projects)

   - What environmental sensitivities does your/do these catchment(s) display?
   - What are the major environmental problems/challenges in your catchments?
   - What are the main reasons for them to not achieve good ecological status?
   - How does climate change impact environmental protection?
   - Is climate change specifically considered in your work?
   - What other groups are active and which projects are ongoing in these catchments?
   - Do you work with farmers?
   - Are you involved in projects with the water companies in your regions?
   - What is your opinion on the EFI?

2. **Specific Solutions (for water companies)**

   - High flow abstraction
   - Water storage
   - Water transfer
   - Developing new supplies
   - Leakage reduction
   - Rapid trading system
   - Environmental Flow Protection

3. **Range of Planning (for abstractors)**

   - Looking into the future, how is demand likely going to change? (let them specify time frame themselves)
   - What are the influencing factors of demand?
   - Can you give an outlook to potential changes in <organisation's> water demand in the years to come?
   - When are decreases in demand most likely?
   - What ranges of decrease in demand over summer do you think are likely?

4. **Adaptation to decreasing Availability**

   - Is there a particular season for which decreasing availability would be particularly harmful? - If yes, why?

- What would be the implications if over a period of time <organisation or the organisations/sectors they know> are not allowed to abstract?
- In the preceding survey a large majority of respondents evaluated their sectors ability to adapt to decreasing water availability as limited. Do you agree with this? What do you see as the main barriers to improve this capacity of adaptation?
- What are the main measures <organisation> is taking to adapt to decreasing water availability?
- How do you think the licensing system/regulator/legislation can support efficiency increases? (how do they wish to be supported and what information needs do they have?)

5. Support

- How would you like to be supported in improving the outcomes for the environment?
- How can the protection of water for the environment become more realistic?
- What would be the main things that would have to happen to improve the aquatic environment in the catchments you work in?

5.1. if applicable: Cooperation with the Regulator(s)

- How can reductions in demand be supported by the regulator?
- How do you evaluate working with the EA?
- How can the regulatory environment be strengthened to address <challenges named above>?

End & Thank you

C.3 Summary of scoping Survey Results

Climate change and environmental flows – reconciling water withdrawals for human demand and flows for healthy freshwater ecosystems

Cordula Wittekind, c.i.wittekind@leeds.ac.uk, Dr Megan Klaar, Prof Julia Martin-Ortega

Survey on the Future of Freshwater Abstraction Following Climate Change

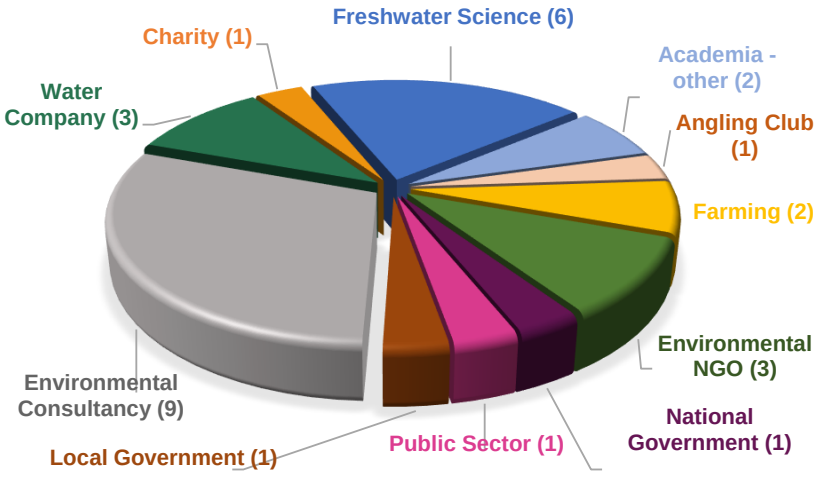
Background

Climate change will have considerable effects on future river flows and water availability. The aim of this project is to quantify those effects until the 2080s and to test current and alternative abstraction and environmental flow allocation scenarios based on stakeholder preferences. Our survey sought to determine perceptions of the main shortcomings of the current abstraction system, future climate change impacts and priorities for future freshwater abstraction.

Who took part?

We aimed our survey at anyone working in a sector concerned with water abstractions as well as everybody interested in the topic. We are pleased that the 30 survey participants reflect a broad range of professional backgrounds.

Figure 1: Participants' professional backgrounds



Summary of main findings:

- none of the respondents rate their sector's ability to adapt to decreasing water availability as adequate
- existing over-abstraction is perceived as a larger challenge than climate change
- two alternative licensing options - high flow abstraction and water trading are viewed rather critically
- current environmental flow protection is considered insufficient and not applicable for protecting the environment from further demand increases and climate change
- recently suggested options for reforming the environmental flow indicator were hard for respondents to evaluate, further information on their implications on catchment scale is required
- the survey highlights that competition for water is likely to increase under all future scenarios

What do the respondents see as the main issues in water abstraction?

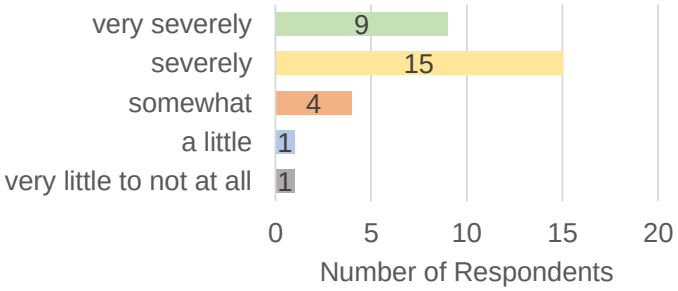
Concerns over security & reliability of supply, competition for water, efficient water use and the ramifications of over-abstraction and pollution were common themes in the survey responses.

The Environment Agency's (EA) work on the abstraction reform is known to almost everyone with some respondents directly involved as consultees, advisors, external peer reviewers, working groups or as EA employees.

To what degree do participants see their line of work affected by climate change?

Awareness of climate change was very high among the participants. The majority of respondents expect it to affect their region and/or sector to a high degree. Insufficient/changing water availability, unreliability and uncertainty in planning and exacerbation of droughts were named as the main issues.

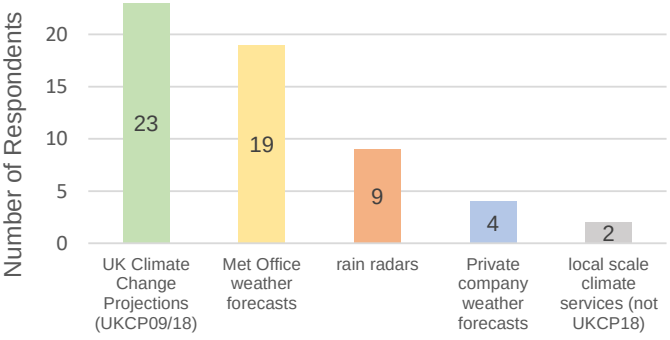
Figure 2: The degree respondents expect their sector to be affected by climate change



Preparing for Climate Change

The most commonly used climate information product was the UKCP18 dataset which was mainly applied in general resources modelling and for scenario development. The majority of respondents stated that long time horizons of up to and beyond 25 years are considered in their water resources planning. The majority of respondents also confirmed that their sectors are already preparing for changing water availability due to climate change.

Figure 3: Commonly used types of products for weather and climate (change) information in the respondents' field of work



Measures that have already been taken to adapt to climate change included:

- improved planning e.g. revision of supply-demand balance forecasts, wastewater resilience and drought planning
- the development of improved tools (e.g. for resources modelling)

- the reduction of leakage
- research into possible ways to reduce abstraction (through water companies)
- research into new, alternative and improved sources
- catchment partnerships and user groups to explore and trial different ways of improving access to water

When and how is the lack of water felt the most?

None of the respondents rated their sector's ability to adapt to strongly decreasing water availability as "good". A lack of available water through the combination of over-licensing and low resource availability was identified as a problem for a number of respondents' sectors in the past. The effects of (further) resource decreases reported include a lack of groundwater recharge, drying of rivers, poor crop harvest, abstraction bans, drought restrictions and further regulation requirements in addition to the closure of canals and respective impact on canal users. The effects of climate change are mostly felt during summer months. These months are also clearly the most important in terms of freshwater availability.

Figure 4: Months in which freshwater availability is most important in the respondents' sectors

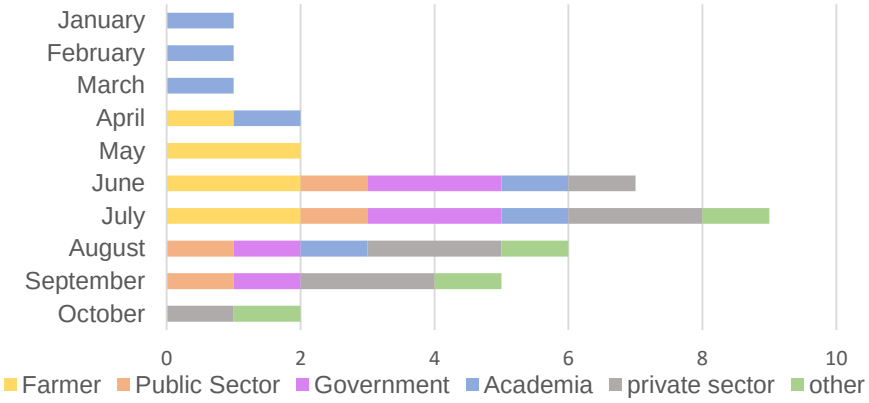
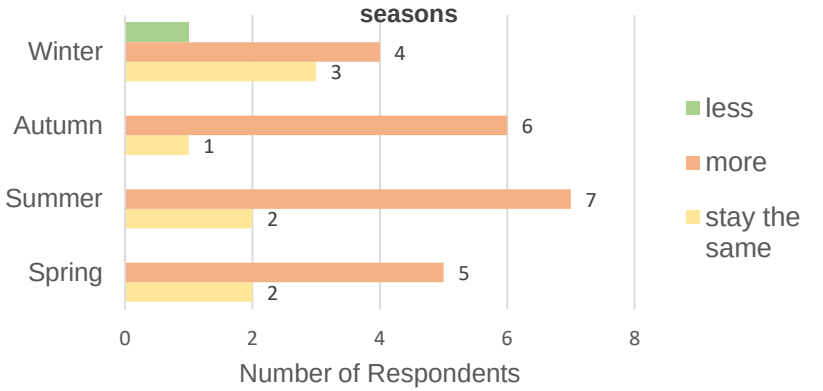


Figure 5: Expected changes in overall water demand across seasons



Suggested Options – high flow abstraction and water storage & trading

The two options included in the survey as options to alleviate the pressures of climate change and water availability received mixed opinions. The major concerns raised against high flow abstractions were water quality related issues and the lack of available storage options.

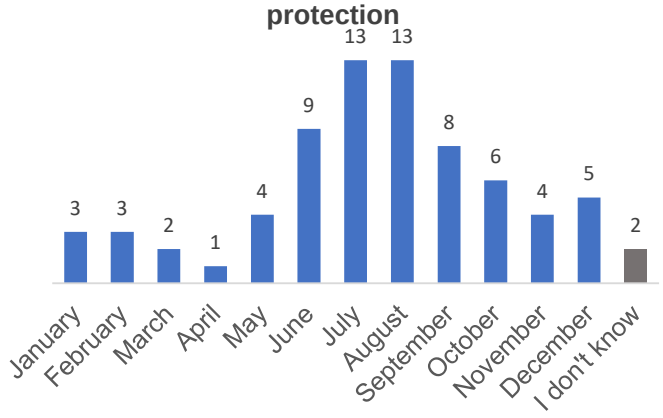
A wide range of obstacles were raised for water trading, including:

- the unlikely prospect of success in relieving pressures while increasing supply
- lack of water available to trade and a lack of new sources particularly in summer
- the bureaucracy, time and financial resources required to run such a system and the complexity associated with changing licenses
- potential problems with accountability
- the possibility that only those license holders with unused water will trade which might lead to an increase in overall water use
- the uncertainties associated with its influences on freshwater ecosystems which would require new environmental assessments

Environmental Flows and their Protection

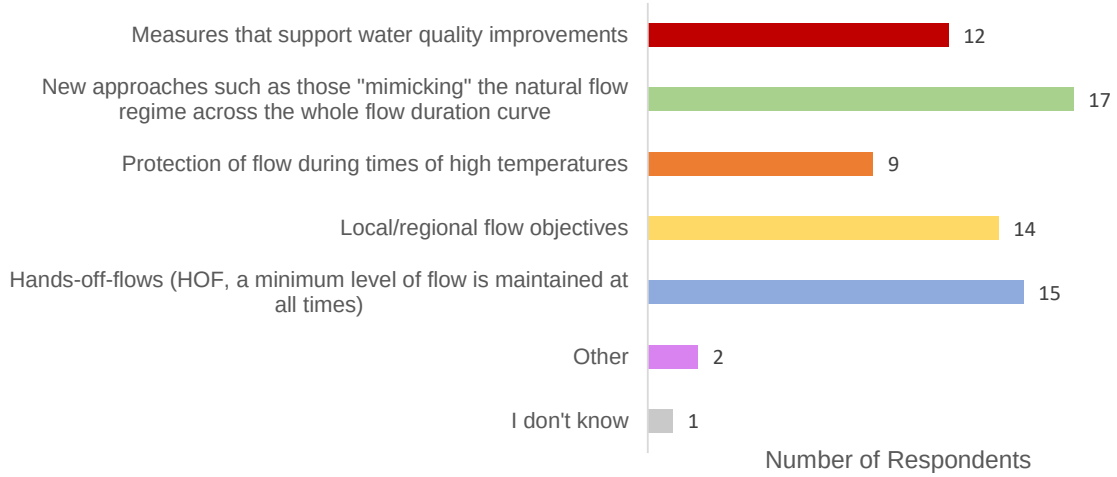
The majority of respondents working in a sector concerned with freshwater protection stated that the freshwater habitats in the catchment they work in are currently affected by high levels of abstraction. Current environmental flow protection was considered insufficient by 60% of respondents. The summer season was deemed to be most important for the protection of flows for the environment and for the need of abstractions to reduce during this season. The respondents' main concerns relate to existing over-abstraction that might be worsened by climate change's extension and amplification of low flows. The effects of over-abstraction that respondents have noticed in the catchments they work in include:

Figure 6: Respondents expect these months to become more important for frehswater protection



- reduced flows and artificial drying of perennial streams
- a reduction of flushing events
- increased dry phase length in temporary streams
- poor ecology, decline in habitat quality and quantity

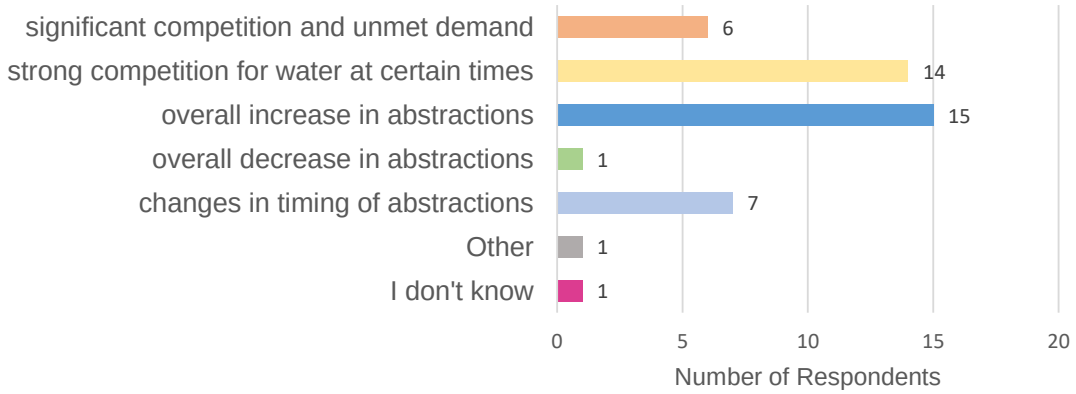
Figure 7: Environmental flow protection approaches that respondents expect to become more relevant under climate change in the catchments/areas they work in



How do respondents rate the environmental protection options proposed by the EA?

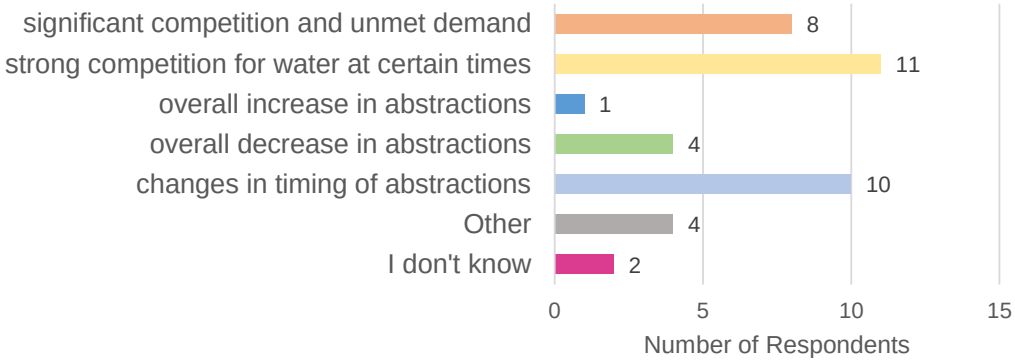
Respondents stated that they found it difficult to evaluate the suggested approaches[1] for environmental flow protection due to a lack of clarity in what they represent, particularly at a local level. One respondent remarked that it would have to be made clear how exactly climate change is taken into account in freshwater protection. Furthermore, one respondent commented that the last three approaches would likely require more raw water storage. The following figures illustrate the respondents' agreement with possible impacts of the four approaches for environmental flow protection.

Approach One: In some rivers demand is allowed to be fulfilled. Freshwaters are not explicitly protected against climate change impacts.

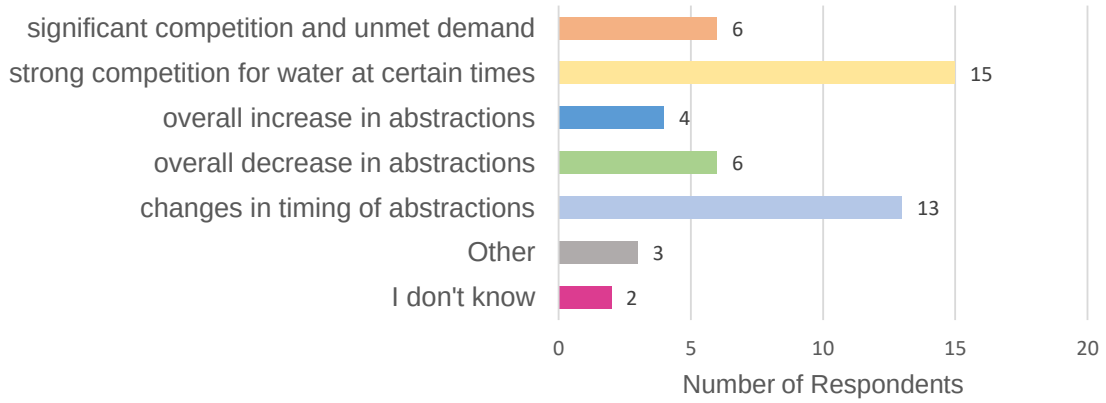


[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/872344/Appendix_4_Longer_term_environmental_water_needs.pdf

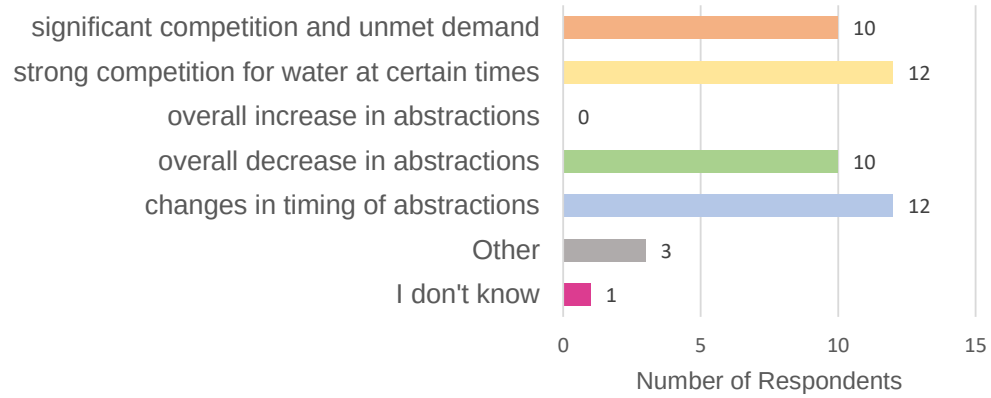
Approach Two: The proportion of natural flow allowed to be abstracted is not changed and the currently protected volume of water is protected in the future, disregarding climate change effects on natural flows.



Approach Three: The same percentage of natural flow as before is protected and climate change's impacts on the natural flow are taken into account.



Approach Four: Increase the amount of water available to the environment by increasing the environmental flow standards.



What next?

As a next step we will model different environmental flow protection approaches under a range of scenarios for climate change to evaluate their performance in different types of catchments. The results of this survey will inform the priorities for environmental flow protection, the demand scenarios and the evaluation criteria.

Thank you for your participation!

For any further questions, please write us under c.i.wittekind@leeds.ac.uk or check our twitter for more research on environmental flows under https://twitter.com/EuroFLOW_ITN/.

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