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DOCTOR OF PHILOSOPHY

Climate change and Welsh catchments: Implications for hydrological regime, water quality and water abstraction

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Climate change and Welsh catchments: Implications for hydrological regime, water quality and water abstraction

A thesis submitted to Bangor University by
Richard John Harvey Dallison

In candidature for the degree of
Doctor of Philosophy

Supervised by
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Dedicated to the memory of my sister, Rachael Dallison

"Time flies. Suns rise and shadows fall.
Let time go by. Love is forever"

Firstly, I would like to thank all of the staff in the School of Natural Sciences who have helped to shape myself and the research contained within this thesis, during my time as a student at Bangor. I am particularly deeply indebted to both Dr Sopan Patil and Dr Prysor Williams for their continued supervision, support, guidance, and patience during the PhD process. Sopan, firstly thank you for encouraging me to undertake this opportunity to begin with, and for your continued encouragement throughout. Without your expertise in hydrology and hydrological modelling, the thesis quite simply would not be complete. Furthermore, your championing and support of opportunities such as attendance and participation at conferences and workshops, as well as paper submissions to journals, has benefitted both me and the research immensely. Prysor, your valuable advice, constructive feedback, continued encouragement, and especially keen eye for detail, have all helped to improve the research completed and communicated hugely. Thank you both especially for your time in reading the steady stream of paper and chapter drafts in the final few months of the PhD process, your feedback really has been invaluable. Additionally, without the efforts of Mr Ian Harris in sourcing further computing power, this research would not have been completed on time. I am therefore very grateful for both this and you support, advice and expertise during all of my time at Bangor.

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Finally, thank you to my Mum who has always encouraged me to follow my ambitions and aspirations and believed in me to achieve anything. Your continued love and support has kept me going through difficult times and always helps me to find the best route forward. I would not be where I am today without you and your unwavering belief in me.

EXECUTIVE SUMMARY

Historical and future climate change is likely to be one of the key drivers of alterations seen in catchments globally. The implications of changing precipitation patterns in particular range from increased seasonality of flows, to changing frequency, duration, and severity of extreme events, to variations in pollutant sourcing and transport. These changes display regional differences, but it is also reasonable to expect catchment level variation. Factors such as topography, land use/land cover and soil type all cause variation of regional trends. Such alterations could have consequences for all water users, but flow regime changes in particular will directly impact those abstracting water from rivers. In this work, hydrological regime change is investigated for five catchments in Wales (Clwyd, Conwy, Dyfi, Teifi, Tywi), both historically and under a future worst-case scenario of global greenhouse gas emissions. For the future period water quality is also considered. Subsequently, impacts on abstraction for public water supply (PWS) and hydroelectric power (HEP) are also quantified.

The first study investigates historical trends in average and extreme precipitation, air temperature and streamflow, before correlating these factors with actual total abstraction data for PWS (as a proxy for overall water demand). A strong warming trend in autumn average temperatures in all catchments is observed (Sen's slope range: 0.38-0.41, $p < 0.05$), with a north-south divide detected in streamflow and extreme temperature trends. A positive correlation between abstraction volume and temperature in four catchments is established (Spearman's ρ range: 0.094-0.403, $p < 0.01$; Pearson's r range 0.073-0.369, $p < 0.01$). The study provides new insight into the relationship between hydroclimatic factors and total PWS demand and highlights local variation in broader regional changes.

The second study uses the Soil and Water Assessment Tool (SWAT) to model future average and extreme streamflow and water quality. The 12-model ensemble UK Climate Projections 2018 dataset, based on Representative Concentration Pathway 8.5 (RCP8.5) conditions, is used for future daily weather input (2021-2080). A small decline in mean annual flow is observed (-4% to -13%), with much larger variations seasonally. Spring and autumn streamflows are most affected, increasing and decreasing by up to 41% and 52%, respectively; these changes corresponded with increased frequency of high flow events in spring, and low flow events in autumn. Water quality generally declines in all catchments and seasons, with increased concentrations of suspended sediment, nitrogen, and phosphorous, and decreased dissolved oxygen. Results suggest a double threat for water abstractors, especially for PWS, of both declining flows and water quality, in summer and autumn in particular.

The implications of projected hydrological regime changes are investigated in the third study, with a focus on PWS and HEP. A key PWS abstraction in the Tywi is studied using the Water Evaluation And Planning (WEAP) system. The temperature-demand relationship established in the first study is used to project future total water demand under RCP8.5 conditions; static and reducing demand scenarios are also considered. Under all scenarios there is an increase in occurrences of insufficient streamflow to satisfy demand. Alterations in HEP operations are analysed for sixteen sites in the Conwy, and nine in the Tywi. Results suggest a decrease in total annual abstraction volume, resulting in a loss of generation potential, this is especially pronounced up to the mid-2050s. Further work is needed to quantify the financial and environmental implications of observed trends; additional work on water quality changes would also strengthen PWS planning.

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ABBREVIATIONS

AR5	Fifth Assessment Report (by the IPCC)
ASC	Adaptation Sub-Committee (of the CCC)
CCC	Committee on Climate Change
CEH	Centre for Ecology & Hydrology
CHESS	Climate, Hydrology & Ecology research Support System
CMIP5	5th phase Coupled Model Intercomparison Project
DCWW	Dŵr Cymru Welsh Water
DEM	Digital elevation model
DO	Dissolved oxygen
EEA	European Environment Agency
EU	European Union
FDC	Flow duration curve
FFH	Future Flows Hydrology (dataset)
FiT	Feed-in-Tariff
GCM	Global climate model
GHG	Greenhouse gas
HEP	Hydroelectric power
HoF	Hands-off-flow
HRU	Hydrological Response Unit
IPCC	Intergovernmental Panel on Climate Change
KGE	Kling-Gupta efficiency
LULC	Land use/land cover
MK	Mann-Kendall (trend analysis)
MOHC	Met Office Hadley Centre
NAO	North Atlantic Oscillation
NIC	National Infrastructure Committee
NRFA	National River Flow Archive
NRW	Natural Resources Wales
PPE	Perturbed parameter ensemble
PSO	Particle Swarm Optimisation
PWS	Public water supply
RCM	Regional climate model
RCP	Representative Concentration Pathway
SDGs	Sustainable Development Goals (from the UN)
SNHT	Standard Normal Homogeneity Test
SS	Suspended sediment
SWAT	Soil and Water Assessment Tool (hydrological model)
SWAT-CUP	SWAT Calibration and Uncertainty Programme
TN	Total nitrogen
TP	Total phosphorus
UK	United Kingdom
UKCIP02	UK Climate Impacts Programme 2002
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UN	United Nations
WEAP	Water Evaluation And Planning system
WMO	World Meteorological Organisation
WSP	Water service provider
Z2 / Z3	Zone 2 / Zone 3 (HEP sites)

CHAPTER 1: INTRODUCTION

1.1 Study context

Global climatic change, chiefly caused by anthropogenic inputs of greenhouse gases (GHGs) to the atmosphere (IPCC, 2013), has fundamentally altered the hydrological cycle in various ways (IPCC, 2014a). Changing precipitation patterns, altered snowmelt timing and speed, and increases in extreme weather events have all caused variation in the hydrological regime of river systems (IPCC, 2014a). Such alterations have had numerous impacts on river systems across the globe, such as changes to ecology/river health (Durance & Ormerod, 2007; Lynch *et al.*, 2016; Stagl & Hattermann, 2016; Bussi *et al.*, 2018), variation in flood characteristics (Hattermann *et al.*, 2013; Kundzewicz *et al.*, 2018; Langhammer & Bernsteinová, 2020; Tramblay *et al.*, 2020), thermal regime changes (Isaak *et al.*, 2012; Arora *et al.*, 2016; Islam *et al.*, 2019; Jin *et al.*, 2020), and riverbed morphology alteration (Rumsby & Macklin, 1994; Ashmore & Church, 2001; Slater & Singer, 2013; Slater *et al.*, 2019). In terms of human systems, one of the most important consequences is for change in available water resource (Vörösmarty, 2000; Arnell, 2004a; Alcamo *et al.*, 2007; Konapala *et al.*, 2020), which can be abstracted for uses such as public water supply (PWS), hydroelectric power (HEP), agriculture, and heavy industry. Water resource availability globally is undoubtably under pressure from various factors, including urbanisation (Astaraie-Imani *et al.*, 2012; McGrane, 2016), agricultural intensification (Watts *et al.*, 2015b; Holden *et al.*, 2017), and population increase (Vörösmarty *et al.*, 2010; Staddon & Scott, 2018). However, climate change and the impacts that increased global temperatures and changing precipitation patterns will have on water availability is arguably one of the most challenging.

Climate change not only has the ability to impact on the supply of water, but is also likely to have an impact on demand for water. Domestically, increased air temperature, humidity and sunshine hours can increase water use in the UK, especially for purposes such as bathing and garden watering (Downing *et al.*, 2003; Goodchild, 2003; Green & Weatherhead, 2014; Xenochristou *et al.*, 2020). Furthermore, likely increases in temperature and decreases in rainfall have the potential to generate much greater demand for water from the agricultural sector, for irrigation of crops and water supply for animals (Downing *et al.*, 2003; Knox *et al.*, 2010; Rio *et al.*, 2018; Hess *et al.*, 2020). This creates a two-part threat to future water security and water resource availability.

Another concern for catchments under future climate change is the impact on water quality, which could have far-reaching consequences for PWS (Wilby *et al.*, 2006; Whitehead *et al.*, 2009b; Mo *et al.*, 2016). Water quality is expected to decline because of alterations in flow regime, in particular extreme flows, as well due to changing precipitation patterns (Watts *et al.*, 2015a; Sayers *et al.*, 2016; Collet *et al.*, 2018; Rau *et al.*, 2020). Increasing discharge volumes cause both greater erosion of the riverbed and banks, as well as increasing the transport capacity of the flow (Delpla *et al.*, 2009; Mortazavi-Naeini *et al.*, 2019). Furthermore, intensification of extreme precipitation and flood events also allows for greater washing of pollutants from the land surface to streams, increasing pollutant concentrations (Delpla *et al.*, 2009; Whitehead *et al.*, 2009b; Ockenden *et al.*, 2017; Hashempour *et al.*, 2020). In addition, increases in the intensity and frequency of low flow events gives less opportunity for dilution of pollutants; this is particularly problematic downstream of point-sources of pollution (Delpla *et al.*, 2009; Watts & Anderson, 2016; Miller & Hutchins, 2017).

In Wales, it is expected that future climate change will take the form of warmer temperatures year-round, with exaggerated seasonality of precipitation when compared to current conditions, meaning drier summers and wetter winters (Welsh Government, 2013; ASC, 2016a; Lowe *et al.*, 2018). A greater number of extreme weather events are projected, with more frequent and intense precipitation events (Welsh Government, 2013; ASC, 2016a; Lowe *et al.*, 2018). These changes have the potential to substantially impact on the availability of surface water resources in the country, a resource that is highly relied upon in Wales for several sectors, in particular PWS (DCWW, 2019a). Furthermore, changes in water quality could also have significant impacts on PWS as well as create further challenges for many abstractors. Changes in quality of raw water entering drinking water treatment plants could prove costly, both financially and in terms of energy use, with water potentially requiring additional treatment (Mo *et al.*, 2016; Valdivia-Garcia *et al.*, 2019). As has been demonstrated, it is therefore important to have a thorough understanding of future hydrological regime characteristics under a changing climate for Wales, in order to best plan and adapt for changing water resource availability and quality.

Such climate change adaptation planning is in fact mandated in Wales, with the Climate Change Act (2008) requiring Welsh Ministers to regularly produce a report on their objectives, actions, and priorities in terms of the impact of climate change for Wales. At the time of its enactment, the Act set a target of an 80% reduction in GHG emissions compared to 1990 levels by 2050, however, in 2019 a new, more ambitious net zero emissions target was set. The Act also established the Committee on Climate Change (CCC), a statuary body with the purpose of advising the UK and devolved governments on progress towards emission targets and climate change adaptation (CCC, 2020). The Adaptation Sub-Committee (ASC) of the CCC fulfils the requirement of the Climate Change Act (2008) to prepare a climate change risk assessment every five years, the next to be released in June 2021 (Welsh Government, 2019a). Additionally, the Environment Act (Wales) 2016 aims to position Wales as ready to adapt to climate change as part of a low carbon economy. Parts 1 and 2 of the Act specifically relate to sustainable natural resources management, and adaptation to climate change respectively.

The Water Industry Act (1991) identifies the main duties for water service providers in the UK and provides the framework for water services regulation, a role currently performed by Ofwat. Furthermore, the Water Resources Act (1991) developed the environmental regulation and oversight relating to water supply, currently under the jurisdiction of Natural Resources Wales. Additionally, the Water Resources Management Plan Regulations (2007) amended the Water Industry Act (1991) to make it a statuary obligation for water providers in England and Wales to produce a water resource management plan every five years, the latest being released in 2019. Any measures undertaken must ensure compliance with the European Union's (EU) Water Framework Directive in terms of surface water quality (although the future of this Directive is uncertain given the UKs exit from the EU) and the Water Supply (Water Quality) Regulations (Wales) 2018, in terms of drinking water supply standards.

Furthermore, the Wellbeing of Future Generations (Wales) Act 2015 requires the Welsh Government and public bodies in Wales to incorporate long-term thinking into decision making, particularly around seven wellbeing goals set out in the Act. This thesis directly addresses three of these goals, in particular, (1) a prosperous Wales, (2) a resilient Wales, and (3) a globally responsible Wales. In addition, of global relevance to this research are the United Nations' (UN) seventeen Sustainable Development Goals (SDGs; UN, 2015). No less than nine bear relevance to this work (SDGs 3, 6, 7, 8, 9, 11, 12, 13, 14); with Goal 6 (ensure availability and sustainable management of water and sanitation for all), and Goal 13 (take urgent action to combat climate change and its impacts) being the most relevant.

1.2 Study justification

Wales is often viewed as a country with an abundant supply of water and higher than average precipitation when compared to the rest of the UK, indeed for some areas this is true, annual rainfall volumes in the north of the country being some of the highest in the UK (Figure 1.1; MET Office, 2020). However, in terms of PWS, the main water supplier Dŵr Cymru Welsh Water (DCWW) states that there are already regions at risk of seasonal water deficit in Wales (DCWW, 2019a), as well as areas that will face seasonal water scarcity problems in the future unless measures are put in place soon to ensure continued supply (DCWW, 2019b). This vulnerability comes from the heavy reliance on surface waters in the region, with little abstraction from groundwater as a back-up. Importantly, Wales is also an exporter of water to other areas of the UK, for example, up to 360 million litres of water per day are piped 117 km from the Elan Valley reservoirs in mid Wales to supply the Birmingham metropolitan area (Warren & Holman, 2012; DCWW, 2016a). In addition, Lake Vyrnwy in north Powys, along with the River Dee, supply over 230 million litres of water per day to Merseyside and Cheshire (United Utilities, 2018). Lake Vyrnwy is also used to regulated flow in the River Severn in times of drought, ensuring supplies for several water companies in the midlands and west of England (United Utilities, 2018). Recent plans also include the possibility of diverting water from the lake via the Severn system to supply water to London and the southeast of England, by the latter half of this century (Atkins *et al.*, 2016). Although these two key systems do not fall within the catchments studied in this thesis, the results of this work are still relevant to them and the supplies of water to the reservoirs. This current and potentially even greater future reliance of millions of people on the catchments of Wales for drinking water supply alone, makes the country an important region to study. In addition to the heavy reliance of PWS on streamflow, the rivers of Wales also support various other sectors from the important tourism and leisure industry, to heavy industry, to agriculture and to both large- and small-scale HEP generation. HEP in particular, although relatively small in the electricity generation portfolio of Wales, is a sector that has been growing in recent years with over 300 new schemes implemented since 2002, from a starting point of approximately 40 (Welsh Government, 2019b). Despite this substantial increase in the number of new schemes, the installed capacity has only risen by 20 MW from a 160 MW baseline in 2002 (Welsh Government, 2019b). This disparity points to the nature of the schemes developed, the majority being small-scale; these types of schemes are considerably more vulnerable to changing streamflow regimes. While changes to Feed-in-Tariffs (the rate paid for electricity generated through renewable technologies) and business rates in the last two years have seen a decline in in the installation of new schemes (Welsh Government, 2019b), it is still important to understand the performance of installed schemes under future streamflow conditions to enable robust planning in the energy sector to ensure a stable electrical supply.

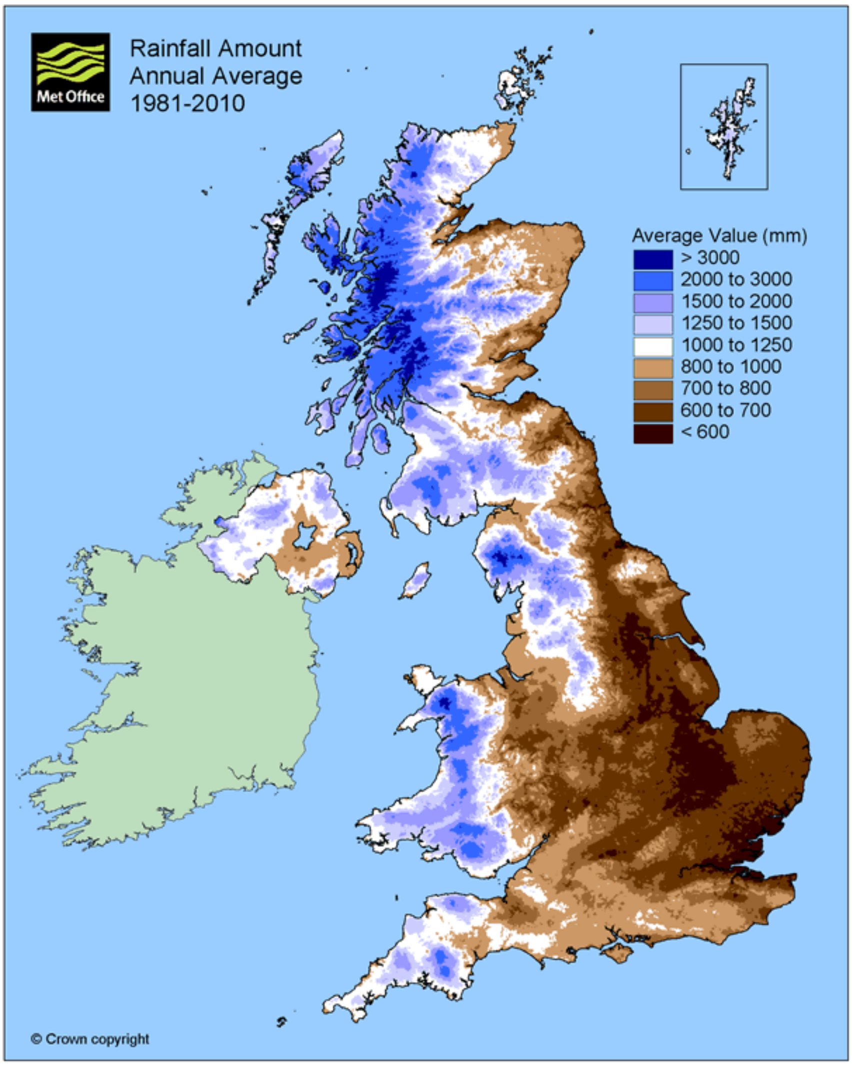

Figure 1.1. UK annual average rainfall for the period 1981-2010 (Met Office, 2020).

As a result of the reliance on surface waters by various sectors in Wales, as well as the impact of individual catchment characteristics on the response of a watershed to precipitation, understanding future changes in the timing, quantity and quality of streamflows at a catchment scale is crucial. Five catchments in Wales have been selected for study, The Clwyd, Conwy, Dyfi, Teifi, and Tywi (Figure 1.2). These five have specifically been chosen to reflect the wide variety of catchment characteristics displayed across Wales, allowing for comparisons of responses to different conditions to be made. The catchments differ in terms of topography, land use/land cover proportions, size, and location. All of these factors have the potential to influence how future climate change will impact of streamflows and water quality. Furthermore, these catchments provide water for a population in excess of 975,000 people, as well as agricultural, industrial, and commercial purposes, and more than 70 HEP schemes. The characteristics of each catchment are described in greater detail in the overall methodology (Chapter 3) and study chapters (Chapters 4, 5 and 6). The research presented in this thesis has therefore been undertaken in order to strengthen the knowledge base of future hydrological regime for the region, with the results being useful in future water resource allocation planning, as well as ensuring PWS security and efficient HEP generation.

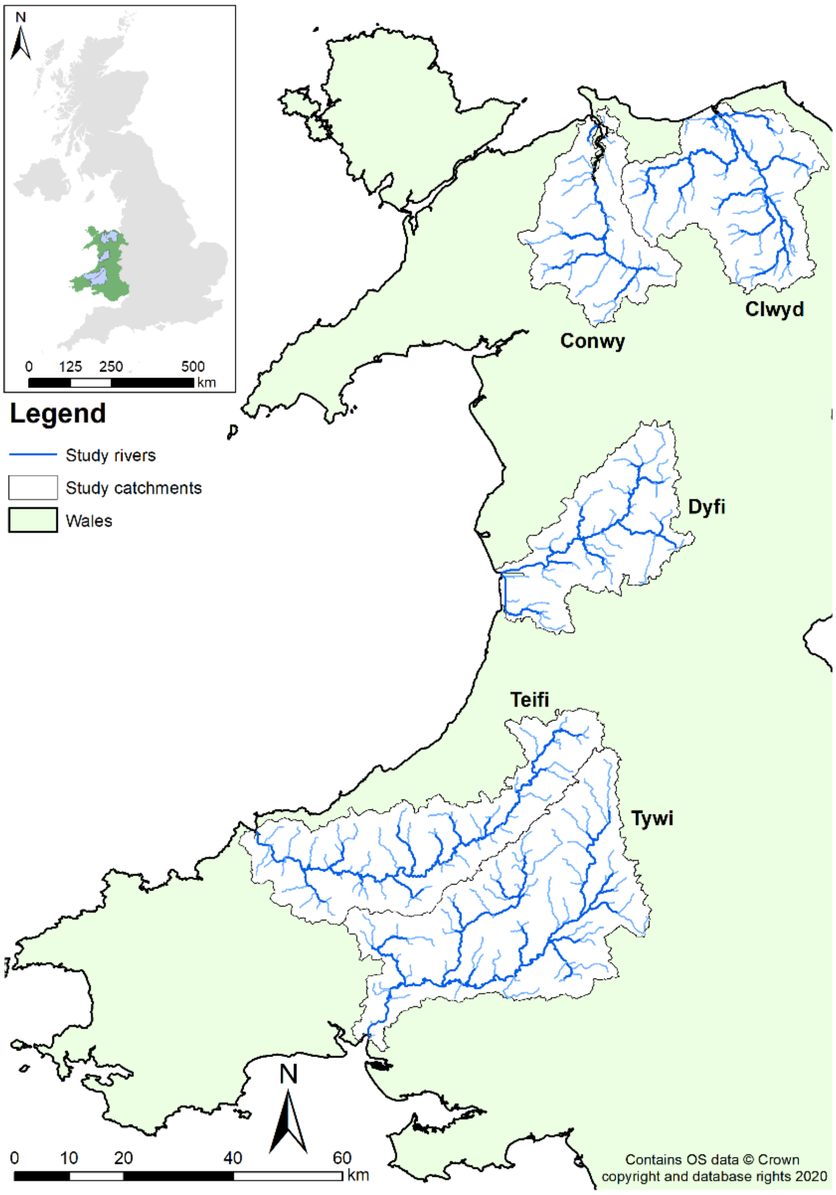

Figure 1.2. Study catchments; streams greater than second order shown, as defined by Strahler method.

1.3 Research aim and objectives

The overarching aim of this thesis is an assessment of the impact of future climate change on the streamflow characteristics of catchments in Wales and an evaluation of the effect of such changes on the abstractable water resource. To achieve this, the thesis will address the following research objectives:

I. Assess and analyse historical changes in hydroclimatic factors at a catchment-scale for Wales;
II. Quantify the relationship between weather conditions and total demand for water from surface sources in Wales;
III. Construct hydrological models for each study catchment and apply future weather data under a worst-case scenario for future climate change;
IV. Measure and analyse future hydrological regime and water quality changes, given future climate forcing;
V. Calculate catchment level change in water availability for public water supply and hydroelectric power generation.

1.4 Thesis structure

This thesis is comprised of eight chapters. The first (this chapter), provides context to the work, details the justification for the study, and provides a brief introduction to the chosen study area and catchments. The overarching aim and objectives are also stated.

Chapter 2 presents a review of literature relevant to the thesis. Firstly, context is given to the global climate change picture both historically and for the future. The latest report by the IPCC (AR5) is used as a basis for discussion of global change, with recent relevant peer-reviewed work being included to provide further scientific grounding. A review of the changes observed and projected for the UK and Wales is then undertaken. Projected changes in climate for both nations are discussed in the context or UK Climate Projections by the MET Office as well as peer-reviewed work. Literature detailing the impact of the discussed future climatic changes on hydrological regime and quality of surface waters in Wales are then introduced, before the potential implications for water resource use in Wales are conferred.

Chapter 3 details the data, analytical methods, and modelling processes used in the thesis, justifying the reason for their use and presenting the implications that arise from their use. Detailed descriptions of the five catchments studied, as well as an explanation for their use and discussion on the applicability of the results gained outside of Wales, are also provided.

Chapter 4 explores historical hydroclimatic change for the five study catchments, conducting trend analysis for 34 years of temperature, precipitation, and streamflow data. Daily actual abstraction volume data for PWS in each catchment is correlated with the hydroclimatic factors in order to explore the relationship between weather and total water demand.

Chapter 5 considers the impact of climate change on the hydrological regime and water quality of the study catchments, under a high future GHG emissions scenario (Representative Concentration Pathway 8.5), using the latest UK Climate Projections 2018 data. Future streamflow projections are generated using the Soil and Water Assessment Tool (SWAT) as well as projections for four water quality factors. Analysis of changes in average and extreme flows, as well as the average concentration of the water quality factors is presented for the period 2021-2079.

Chapter 6 uses the streamflow data generated in Chapter 5 to quantify the impact of climate change on the generation potential of HEP schemes in the Conwy and the Tywi. Furthermore, the temperature-water demand relationship established in Chapter 4 is implemented in order to project water demand under increasing future temperatures and relate this to available streamflow at a key PWS abstraction location. This chapter therefore provides an impact assessment of future climate change on two key streamflow-dependent sectors in Wales.

Chapter 7 provides an overall discussion of the findings of the thesis and places them in the context of previously published research. The chapter also provides the opportunity to discuss the implications of the results and conclusions of each study chapter upon each other, providing fresh insight into the implications of future climate change on a variety of sectors.

Chapter 8 addresses how the aims set out in Chapter 1 have been met, as well as delivers recommendations for future research to further advance knowledge in the field. Finally, an overall summary of the conclusions is drawn, highlighting the novel study areas and knowledge gaps addressed and detailing the implications of the findings.

A list of figures and a list of tables have been included after the contents page for navigational aid; a list of abbreviations follows this. Two appendices are included at the end of the thesis, presenting, for each catchment, (1) calibration charts comparing modelled and observed streamflow and, (2) ensemble projections of future seasonal and annual streamflow.

The study chapters of this thesis (Chapters 4, 5 and 6) have been submitted in full for publication with peer-reviewed journals. Chapter 4 has been published in Water (Dallison *et al.*, 2020), while Chapters 5 and 6 have been submitted to the *Hydrological Sciences Journal* and the *Journal of Hydrology: Regional Studies*, respectively. Conceptualisation of each of the studies has been the work of Richard Dallison and Sopan Patil. Implementation and investigation of each of the studies has been conducted by Richard Dallison, along with modelling, data analysis and curation, visualisation, and original draft writing and editing. Reviewing and editing of drafts, as well as supervision, has being undertaken by Sopan Patil and Prysor Williams for all studies, as well as Ian Harris for the second study (Chapter 5), who also assisted with resource procurement for this piece of research.

1.5 The Dŵr Uisce Project

The work contained within this thesis has been undertaken as part of the Dŵr Uisce Project, which has the overarching aim of improving the efficiency of water distribution in Ireland and Wales. In practice the project has four key themes, the first investigates new smart and low-carbon technologies, such as pumps-as-turbines, drain water heat recovery and smart network controls, to enable energy savings in future water distribution and end use. The second theme is policy support and guidance, work here encompasses benchmarking and energy auditing the water sector, as well as completing life cycle assessments on the technologies developed under the first theme, in order to improve efficiency in the sector. Third is dissemination and collaboration, through a smart specialisation cluster set up by the project, allowing the communication of the project outputs, as well as learning opportunities through four demonstration sites, using the technologies developed. Finally, climate change, this theme is over-arching to the whole project and is the area in which the research in this thesis has been undertaken. The aim of this section of the project is to assess the impacts of future climate change on (1) water supply and water users in the Dŵr Uisce region, and (2) the technologies developed in theme 1 of the project; this thesis has a focus on the former.

CHAPTER 2: LITERATURE REVIEW

2.1 Global warming and climatic change

2.1.1 Historical changes

The relationship between atmospheric greenhouse gases (GHGs) and global temperatures has been studied for well over a century, with Arrhenius (1896) first suggesting the idea of the Greenhouse Effect and the link between GHGs and temperature. The seminal work by Callendar (1938) then made the connection between rising carbon dioxide (CO_2) and increasing temperatures, due to absorption and re-emittance of 'sky-radiation'. It is now widely accepted by the scientific community (Cook *et al.*, 2013, 2016; Oreskes, 2018), that climate change is unequivocally occurring and has been/is being exacerbated substantially by the anthropogenic input of GHGs to the atmosphere (IPCC, 2013). The Fifth Assessment Report (AR5) published by the Intergovernmental Panel on Climate Change (IPCC) states that by 2011, atmospheric concentrations of CO_2, methane (CH_4) and nitrous oxide (N_2O) had increased by 40%, 150% and 20% respectively, compared to 1850 levels (Figure 2.1; IPCC, 2014a).

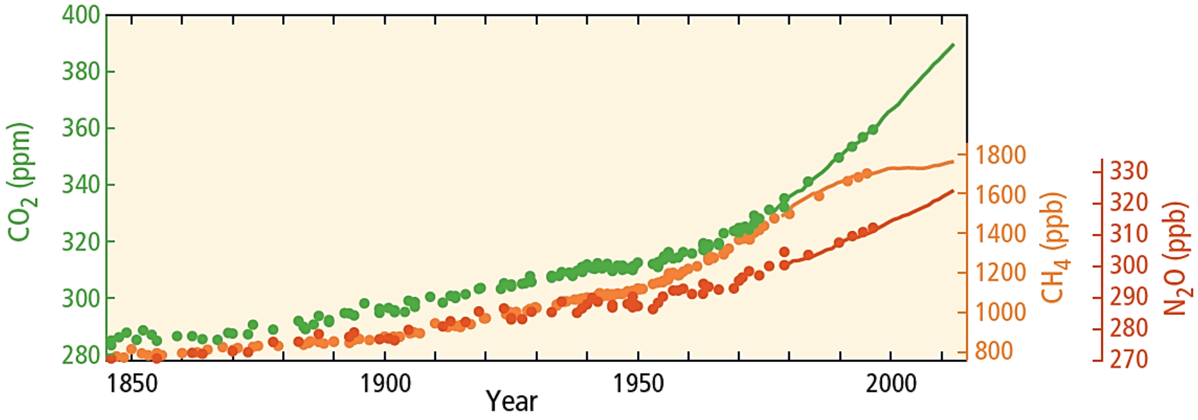

Figure 2.1. Atmospheric concentrations of CO_2, CH_4 and N_2O from both direct atmospheric measurement (lines) and indirect analysis of ice cores (dots; IPCC, 2013).

These GHG concentrations are higher than any seen in the last 800,000 years and roughly 40% of GHG emissions from 1750 to 2011 are estimated to have been released since 1970 (IPCC, 2013). Concurrently, warming of the global climate system has occurred at an unprecedented rate, with it being extremely likely to have been predominantly caused by GHG concentrations and other anthropogenic drivers (IPCC, 2014b). Global average temperatures reached approximately 1.0°C warmer, when compared to pre-industrial levels in 2017, with global warming likely to reach 1.5°C between 2030 and 2052 (Figure 2.2; IPCC, 2018).

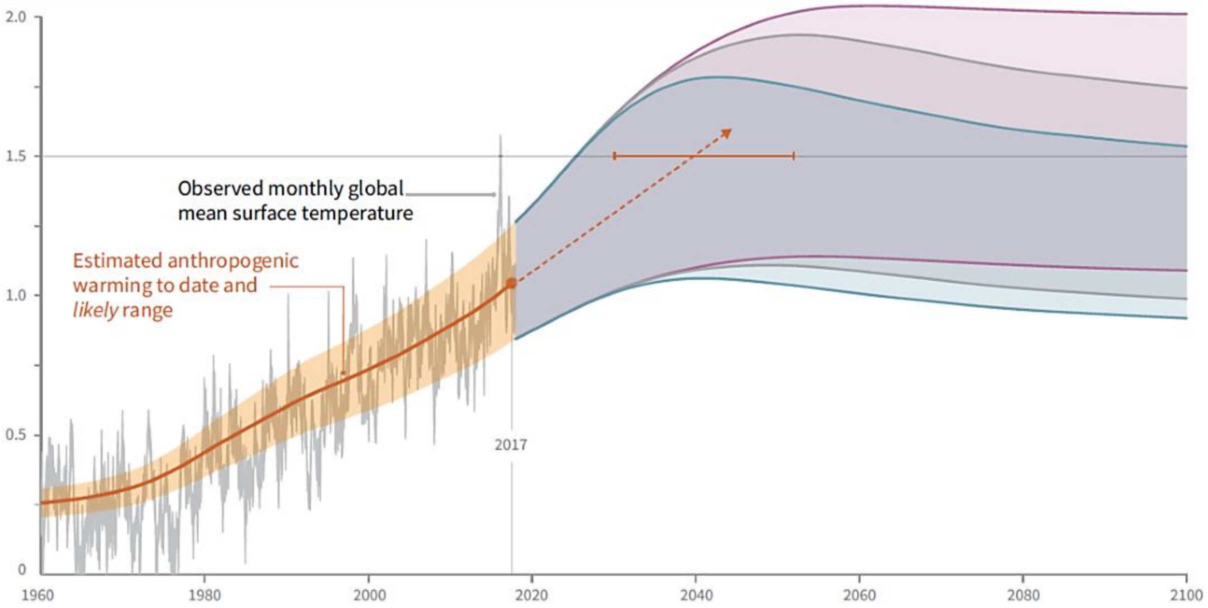

Figure 2.2. Observed (grey line to 2017) and projected (2017-2100) global mean surface temperature. Solid orange line represents estimated anthropogenic warming, dashed continuation and orange horizontal error bar represent central estimate of time range when 1.5°C increase is likely to be reached. Future projections are based on net zero global CO_2 emissions by 2055 (grey plume) and 2040 (blue plume), both with declining non-CO_2 radiative forcing after 2030. Purple plume represents net zero global CO_2 emissions by 2055 combined with no decline in net non-CO_2 forcing after 2030. Adapted from IPCC (2018).

With regard to global precipitation changes, AR5 states that there is low confidence in changes in average precipitation since 1901, with a small increase detected (IPCC, 2013). However, when studying latitudinal zones (Figure 2.3), it is clear that more defined regional-scale changes have occurred over the last century. The most substantial change is seen in the mid-latitudes of the Northern Hemisphere (30°N to 60°N), with a trend towards increasing precipitation observed from 1901 to 2008. Further analysis reveals that this increasing trend is most pronounced in the period pre-1951 (IPCC, 2013). In contrast, evidence for change in the mid-latitudes of the Southern Hemisphere (60°S to 30°S) is less clear, with a slight increase seen to the 1980s and a small decline after this. Precipitation over the tropics (30°N to 30°S) is largely stable, up to the 1980s, whereby a small decline is seen, peaking in the mid-1990s, before returning to levels in line with the rest of the dataset (IPCC, 2013).

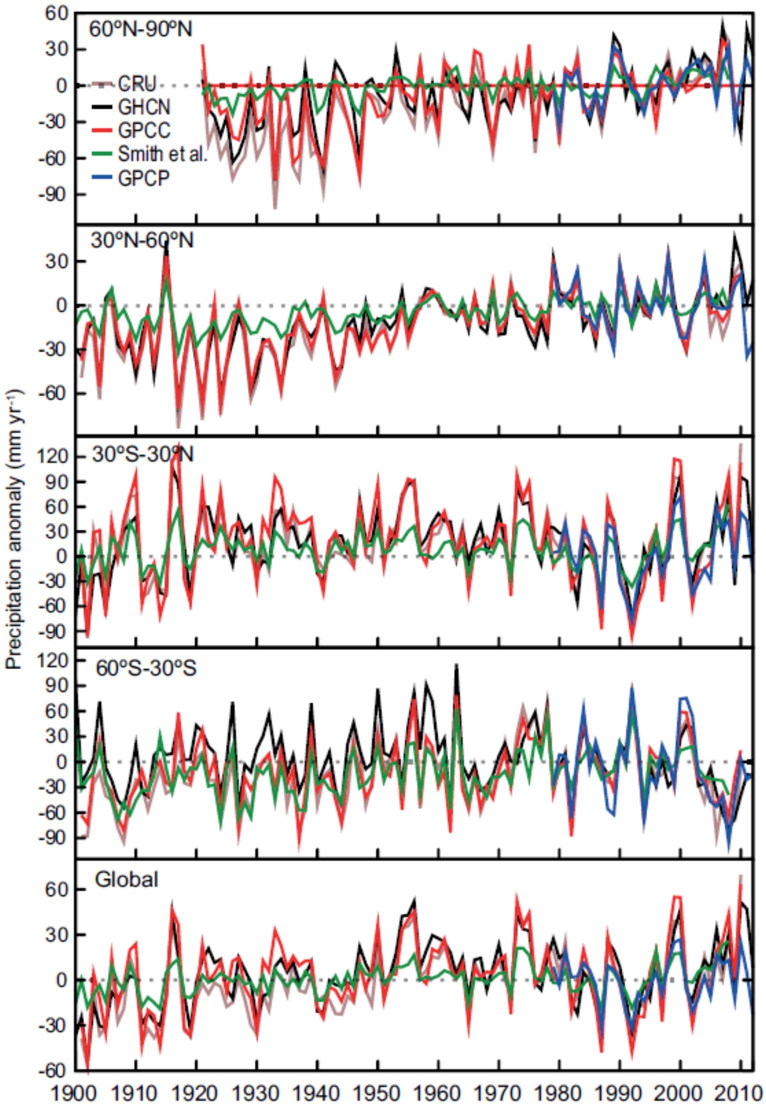

Figure 2.3. Historical over-land annual precipitation anomalies compared to the 1981-2000 mean, as detected by five global precipitation datasets. Timeseries for four latitudinal bands as well as globally shown (IPCC, 2013).

Trends in precipitation reported by the IPCC are consistent with those found in the literature prior to its publication; for example Dore (2005) reports that for the latitudinal zone 30°N to 85°N, an increase of between 7% and 12% has occurred over the 20th century. The change in the south (0°S to 55°S) is much less pronounced at around 2%, reflecting the difference in the distribution of landmasses for the two zones (Dore, 2005). Similarly, Trenberth (2011) identifies historical trends of dry areas (the sub-tropics) becoming drier, and wet areas (mid- to high-latitudes in the north) becoming wetter, with little change in the global average. Additionally, using fourteen climate models compared to observed changes which correspond with those suggested by the IPCC, Zhang *et al*. (2007) show that anthropogenic forcing has had a detectable impact on changes in precipitation between 1925-1999 and 1950-1999. Since the publication of AR5, further evidence has been published on historical global precipitation change, this also largely supports the reported trends. Gu & Adler (2015) for example, showed how global precipitation change occurred concurrently with surface warming, especially the increases observed between 1901-2010 over high latitudes of the northern hemisphere. Further regional variations are also described, with increases in annual precipitation seen in Australia and north America, while declines are observed for tropical Africa and the Indian-Tibetan region (Gu & Adler, 2015). Furthermore Adler *et al.* (2017) study precipitation trends during the 'satellite era' (1979-2014) using the Global Precipitation Climatology Project (GPCP) monthly dataset (Adler *et al.*, 2003; Huffman *et al.*, 2009). The results of this shorter-term study suggest a near-zero trend in global precipitation change, but do highlight the same regional trends seen in the longer-term studies (Adler *et al.*, 2017).

Examining change in extreme weather and climate events, AR5 reveals that at a high confidence level, globally there has been an increase in the value of both maximum and minimum temperatures (IPCC, 2013). The rate of change of increasing minimum temperatures is also shown to be greater than the rate of change in maximum temperatures. The Asia region is most effected by increasing minimum temperatures, while Africa is more greatly affected by increases in maximum temperature (IPCC, 2013). Similar regionality is displayed for changes in the frequency of heatwaves, with Europe, Asia and Australia all being subject to a great number of heatwaves through the 20th century. As with trends in precipitation, changes in extreme temperatures presented by the IPCC agree with studies published more recently. Horton *et al*. (2015) demonstrate for the northern hemisphere that during the satellite era, minimum temperature have increased for all regions except western North America, especially in summer and autumn; maximum temperature increases are more observed across Eurasia, in all seasons except winter. Work by Papalexiou *et al*. (2018) also speaks to an increase of global maximum temperatures over the period 1966-2015; Mishra *et al*. (2015) also demonstrate that the increase in extreme temperatures are pronounced for urban areas globally. Global increases in the number of heatwaves are also demonstrated in work by Liu *et al*. (2017), Chapman *et al*. (2019) and Perkins-Kirkpatrick & Lewis (2020), with general consensus also being for an increase in intensity. While changes in average precipitation volume were small across the 20th century, trends in extreme precipitation events have been more extensive, with heavy precipitation events increasing disproportionality compared to the mean (IPCC, 2013). This trend is seen globally, but regional and seasonal variation are detected, with the most consistent increases in heavy rain event severity observed in Europe and North America (IPCC, 2013). Once again, recent research by the likes of Asadieh & Krakauer (2015), Alexander (2016), and Papalexiou & Montanari (2019) supports these findings.

Regardless of location and regional differences in climate change impacts, all areas will see consequences due to future climate change. Indeed, all global regions have already experienced impacts, both on natural and human systems, such as agriculture and food production, poverty and livelihoods, ocean systems, and freshwater resources (IPCC, 2014a, 2014c). Freshwater systems are some the most effected however, due particularly to changing precipitation patterns as well as alterations in snowmelt characteristics which have had a major impact on the global hydrological cycle (IPCC, 2014a). Changes in hydrological regime have already caused important consequences in various regions for issues such as water resource allocation, fluvial ecosystems, and flood and drought management, as outlined in Chapter 1. The sustainability of water supply and increasing water scarcity are of particular concern, this is true not only for arid countries, but also more generally, especially in areas of dense population. England, for example, is not a country classed as arid, it does however have areas of water stress, in the south of the country in particular. This area already experiences water shortages (Cook, 2016), a situation which is likely to occur more frequently under future climate change. Dobson *et al*. (2020), for example, projects an increase in the probability of water use restriction implementation doubling by 2050 and quadrupling by 2100.

In recent years, changes in Earth’s climate have been particularly stark, with 2019 being the second warmest year on record, after 2016 (WMO, 2020) and July 2019 being the hottest month on record (Blunden & Arndt, 2020). Averaged across Europe, 2019 was the warmest year on record, with central Europe experiencing drought (European Commission, 2020). Globally, the hottest 5-year period on record was also set for 2015-2019, as was the hottest decade (2010-2019), with each decade since the 1980s being warmer than the last (WMO, 2020). Records were also set in 2019 for highest global mean sea level and ocean heat content, while May, June and July saw record low sea-ice extents (WMO, 2020). Additionally, the American Meteorological Society reported that global atmospheric CO_2 concentration reached a record high in 2019 of 409.8 ppm, while the CO_2 uptake of global oceans also increased to 33% higher than the 1997-2017 average (Blunden & Arndt, 2020). All of these changes point to an apparent worsening of the impacts of climate change in recent years.

2.1.2 Future projections

Projections for global climate in the future generally show a continuation of the trends already observed over the 20th century and first two decades of the 21st. However, the extent to which this change will continue is unknown, due to its dependence on future atmospheric GHG concentrations and the degree of climate forcing and global warming that this causes. Since 2010, the context of future climate change and its impacts has been based on four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), developed by the scientific community for the IPCC in advance of AR5 (Moss *et al.*, 2010; van Vuuren *et al.*, 2011). The RCPs represent a trajectory of atmospheric GHG concentrations under which a specific degree of radiative forcing would be reached. The designation of each RCP therefore relates to this degree of radiative forcing reached by 2100 (Table 2.1), with RCP2.6 for example, relating to 2.6 W m^{-2} by 2100 (this scenario peaking at 3 W m^{-2} before 2100 and then declining).

Table 2.1. Overview of the characteristics of the four Representative Concentration Pathways (RCPs), adapted from Moss *et al*. (2010).

RCP	Radiative forcing	CO_2 equivalent concentration (ppm)	Pathway
RCP2.6	Peak at 3 W m^{-2}, decline to 2.6 W m^{-2} by 2100	Peak at 490 before 2100, then declines	Peak and decline
RCP4.5	Rising to reach 4.5 W m^{-2} peak by 2100	650 at stabilisation in 2100	Stabilisation
RCP6.0	Rising to reach 6 W m^{-2} by 2100, peak soon after	850 at stabilisation after 2100	Stabilisation
RCP8.5	Rising to reach 8.5 W m^{-2} by 2100, peak in 2200s	>1,370 in 2100	Rising

While RCP2.6 denotes a peaking and declining pathway associated with early GHG mitigation, RCP4.5 and RCP6.0 describe stabilising pathways due to GHG emissions reduction after 2050 (Figure 2.4), with RCP4.5 peaking in terms of radiative forcing at 2100 and RCP6.0 before 2150 (van Vuuren *et al.*, 2011). RCP8.5 represents a worst-case scenario of future global emissions (Figure 2.4), the 90th percentile of the no-policy baseline scenarios, with increasing high levels of atmospheric GHG concentrations, leading to a scenario of radiative forcing still being in significant increase by 2100 (van Vuuren *et al.*, 2011).

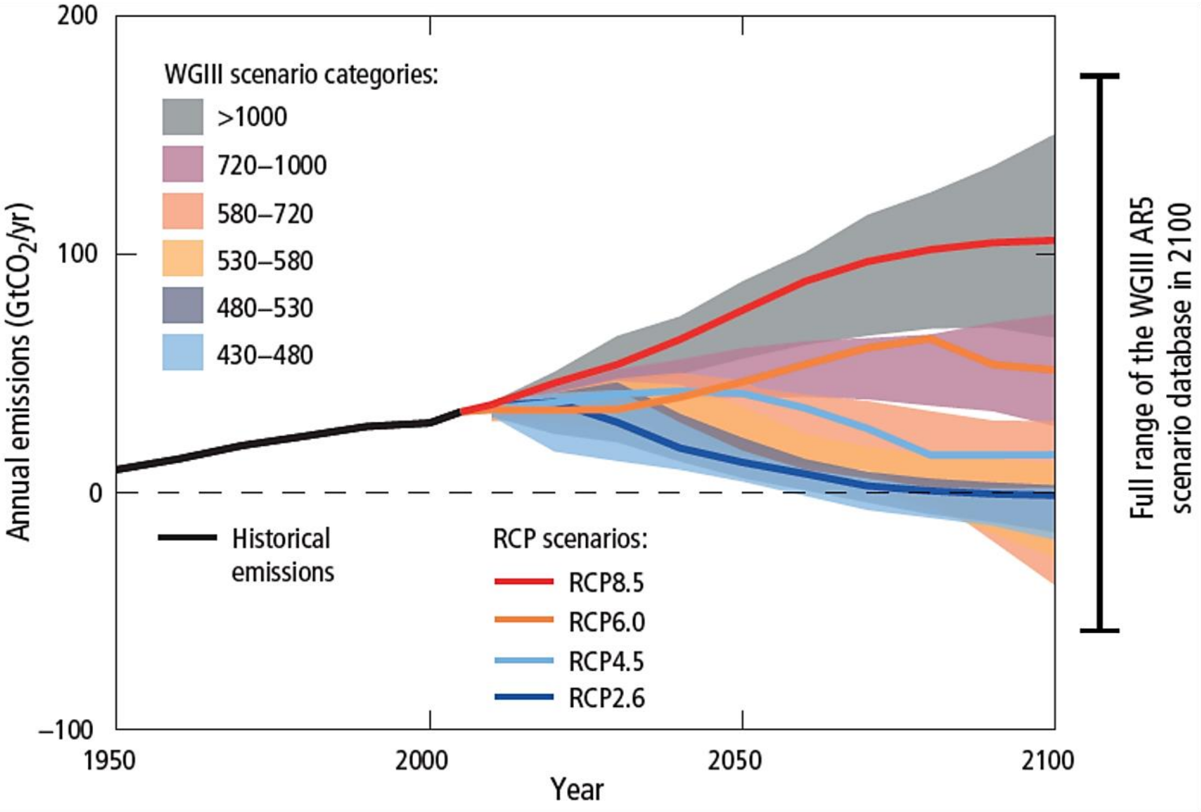

Figure 2.4. CO_2 emissions under each Representative Concentration Pathway (RCP; coloured lines) and historically (black line). Coloured plumes show range of scenarios relating to atmospheric CO_2 concentrations as described in the panel on the figure (ppm; 5% to 95% range shown for each category; IPCC, 2013).

The IPCC used the fifth phase of the Coupled Model Intercomparison Project (CMIP5) in AR5 for the analysis of future climate change under the forcing of each RCP (IPCC, 2013). The CMIP5 ensemble comprises 42 global climate models (GCMs) at different spatial resolutions (IPCC, 2013; Ahmed *et al.*, 2019) and is used to give both a multi-model mean, and range of model outcomes. Projections by the IPCC under all RCPs suggest a continuation of global warming, at least in the short-term, with temperatures stabilising under RCP2.6 before 2050 at 1°C (±0.4°C [1 standard deviation]) higher than the 1986-2005 mean (IPCC, 2013). Under RCP8.5, mean temperatures for 2081-2100 are projected to rise by 3.7°C (±0.7°C), when compared to the same mean, with projections for RCP4.5 and RCP6.0 being 1.8°C (±0.5°C) and 2.2°C (±0.5°C) respectively (Figure 2.5; IPCC, 2013). These results relate to an assessment of high confidence in likely exceedance of 1.5°C above 1850-1900 temperatures by 2081-2100 for RCP4.5, RCP6.0 and RCP8.5; this is also true for exceedance of 2°C by RCP6.0 and RCP8.5 (IPCC, 2013). It is also noted by the report that it is as likely as not (medium confidence) that global temperatures will exceed 4°C under RCP8.5, occurring in more than half of the CMIP5 ensemble models.

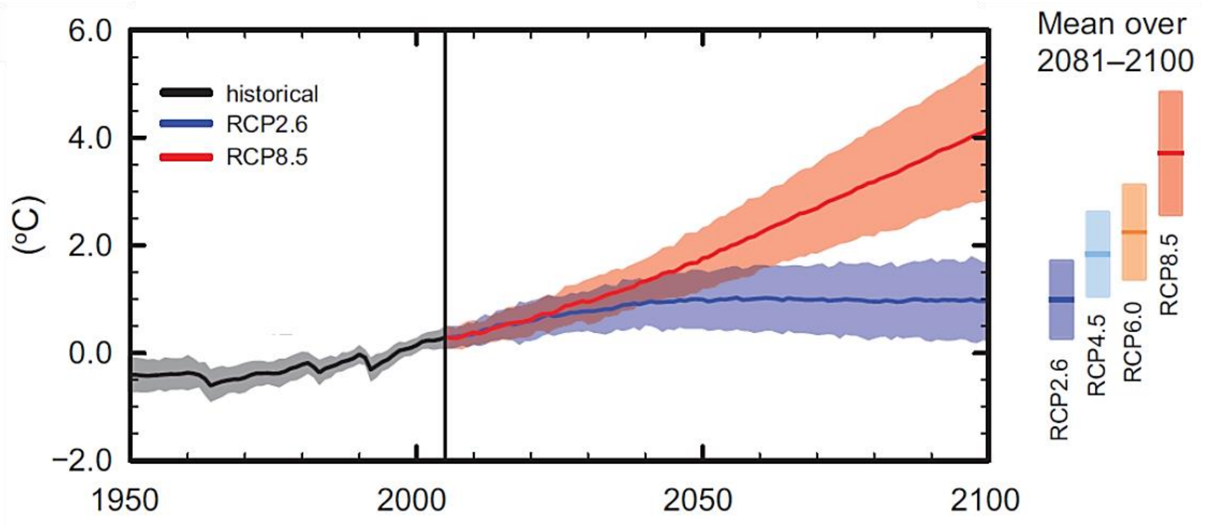

Figure 2.5. Global average surface temperature (relative to 1986-2005 mean) for 2006-2100 under Representative Concentration Pathways. Multi-model mean shown for RCP2.6 (blue line) and RCP8.5 (red line), 5% to 95% range of CMIP5 model outcomes shown by bands. Multi-model mean for mean 2081-2100 temperature for all RCPs also shown on right hand side, with model ranges (IPCC, 2013).

Global precipitation levels also display an increase to 2100, although much more gradual than global temperature change; a 2% to 5% increase over the period is observed under RCP2.6 and RCP8.5 respectively (IPCC, 2013). Interestingly, little relationship is seen between changes in total precipitation and extreme precipitation (IPCC, 2013), with the intensity of extreme precipitation events projected to increase. These increases are expected both for short-term events (individual storms) and longer periods, with a 5% (RCP4.5) to 20% (RCP8.5) increase in 5-day maximum precipitation accumulation (IPCC, 2013). Return periods of large precipitation events are also shown to be impacted, extreme precipitation events being very likely to become more severe and frequent, a 10% to 20% reduction in return period is observed per 1°C warming; for tropical regions this value is even higher (IPCC, 2013). With regards to temperature extremes, it is stated that it is virtually certain that fewer cold extremes will be experienced, but a greater number of hot extremes, in line with global warming. Warmest daily maximum temperature is shown to increase between 1.5°C (RCP2.6) and 5.5°C (RCP8.5) by 2100, with coldest daily minimum increasing by an even larger margin, between 2°C (RCP2.6) and 7°C (RCP8.5). Heatwaves are also projected to very likely occur more frequently and for longer; in the same manner as for precipitation, the magnitude of events with a 20-year return period is set to increase substantially for minimum and maximum temperatures (IPCC, 2013).

2.2 Climatic trends in the UK and Wales

2.2.1 Historical changes

The climate of Wales has altered in line with general trends seen globally and for the wider UK, that being over the course of the 20th century an increase in mean temperature, with daily temperatures increasing in all seasons, while annual precipitation has seen little change, but large seasonal variation. Estimations of the degree and nature of changes vary between studies, dependent on the time frame under review. Farrar & Vaze (2000), for example, report that for the period 1901 to 1998 annual temperatures warmed slightly, with more substantial change observed in autumn and winter, but little change in the summer. Similarly, the Welsh Government (2013) detailed how over the course of 1914-2006 mean annual temperature rose 0.7°C, with the greatest increase in autumn (0.99°C) and least in winter (0.47°C). While the two reports agree about increased seasonality of precipitation, decreases in summer and autumn, increases in winter and spring, there is a contrast in the annual observations. Farrar & Vaze (2000) report a ~3% increase in annual precipitation, while Welsh Government (2013) suggest a 0.9% decrease over their longer and more recent study period. These difference seem to be driven by different magnitudes or seasonal change reported, especially in summer, with Welsh Government (2013) reporting a 24% decrease, and Farrar & Vaze (2000) a smaller 15% decrease. The majority of works align with either the latter view, a small decline in annual precipitation historically, or suggest no trend at all (Perry, 2006; Jenkins *et al.*, 2008; ASC, 2016b; de Leeuw *et al.*, 2016).

In terms of extreme temperature and precipitation events, a report by the MET Office Hadley Centre (MOHC) on UK climate extremes states that for the period 1961-2017 annual maximum temperatures increased across the UK, including Wales specifically (MOHC, 2018a). The number of warm spell days (days associated with spells of six or greater consecutive days where temperatures exceed the daily climatology 90th percentile) also increased substantially, more than doubling for Wales when comparing the 1961-1990 and 2008-2017 averages (MOHC, 2018a). Extreme events associated with cold weather also display warming, with fewer icing days (days where maximum temperature is less than 0°C) and lowest minimum temperatures increasing (MOHC, 2018a). For Wales specifically, average lowest minimum temperature increases from -7.8°C for 1961-1990 to -6.6°C for 2008-2017; icing days reduce from 4.2 to 2.7 (MOHC, 2018a). This non-standard record period of 2008-2017 does have the potential to miss-represent long-term trends, as the time period is more likely to be influenced by decadal time-scale variation, nonetheless it does provide a useful comparison of the current state of change in the climate. Precipitation trends reported by MOHC (2018a) display an increase for highest 5-day precipitation total from 1960 to 2000, rising 4%, with this being more pronounced in the west of the UK. Additionally, 1-day extreme rainfall (greater than 99th percentile) totals also increases by 17% nationally, with the change being more pronounced for Wales than the national average (MOHC, 2018a). Little change in the length of wet spells (consecutive rainfall days) is observed.

Further literature (Perry, 2006; Jenkins *et al.*, 2008; Burt & Ferranti, 2012; Jones *et al.*, 2013) studying the nature of change in extreme temperature and precipitation events, agrees with the broad findings of the MOHC report. Perry (2006), for example, corroborates the findings relating to annual maximum temperature, with observations of a 0.59°C increase for north Wales ($p < 0.01$) and a 0.55°C increase for south Wales ($p < 0.05$), for the period of 1914-2004. An increase in summer and annual minimum temperature is also reported at a significance level of $p < 0.01$ for both north Wales (+0.88°C and +0.84°C respectively) and south Wales (+0.56°C and +0.55°C); once again in agreement with MOHC (2018a). Furthermore, Jones *et al.* (2013) brings agreement to the precipitation trends shown, reporting an increase between 1961-2009 in 1-, 5- and 10-day precipitation totals for north and south Wales, albeit only statistically significant for 5- and 10-day events. Within these trends, statistically significant increases in spring 2-, 5- and 10-day totals are observed, while the same is true for summer declines, this also being significant for 1-year events. Winter totals for all four event lengths rise significantly (Jones *et al.*, 2013). The literature also supports observations of increasing seasonality in extreme precipitation events, with a greater proportion of winter precipitation falling during intense events (Osborn & Hulme, 2002; Jenkins *et al.*, 2008; Burt & Ferranti, 2012; Jones *et al.*, 2013).

Studying the most recent complete year, 2019, in isolation, Kendon *et al*. (2020) report it to be the 12th warmest on record for the UK overall, with national records set for all time highest recorded temperature (38.7°C) and winter high (21.2°C). For Wales, annual average temperature was 0.5°C higher than the 1981-2010 average, mainly due to the winter average being 1.6°C higher, one of the top 10 on record (Kendon *et al.*, 2020). A below average number of frost days also occurred for the sixth straight year, while rainfall was above both the 1981-2010 and 1961-1990 averages, at 107% and 112% respectively (Kendon *et al.*, 2020). The work conducted in Chapter 4 further examines the changes seen in temperature and precipitation for Wales for the period 1982-2015, investigating changes in annual and seasonal averages and frequency of extreme events, as well as breakpoints of marked change during the period.

2.2.2 Future projections

For the UK the key point of reference on future climate is the MOHC's UK Climate Projections (UKCP). This climate analysis tool provides the most up-to-date assessments of future climate outlook for the nation, aiding with planning future risk management and adaptation plans. Recent projections were published in late 2018 (hereafter UKCP18), succeeding the 2009 iteration (UKCP09). The UKCP09 projections have been widely used in literature for impact assessments on various sectors, indeed 107 impact assessment studies using UKCP09 data are indexed by Web of Science at time of writing (6th October 2020). To date however, little peer-reviewed literature has yet been published using the UKCP18 projections, with only two impact study results appearing in Web of Science searches (6th October 2020) for these projections (Kay *et al.*, 2020; Mohammadi *et al.*, 2020). A further three studies have been published assessing the methods and performance of the projections (Murphy *et al.*, 2019; Fosser *et al.*, 2020; Rostron *et al.*, 2020). The research by Kay *et al*. (2020) in fact both assess the impact of climate change on river flows in ten UK catchments, and compares the UKCP09 and UKCP18 outputs, demonstrating that for the catchments studied, the results of both projections are similar and comparable. Therefore, the results of previous work using UKCP09 projections remain valid and relevant, allowing for future works to assess new research areas.

The UKCP18 data contain three 'strands', probabilistic (strand 1), global (strand 2) and regional (strand 3). Strand 1 provides probabilistic projections at a 25 km grid resolution derived from 350 climate model simulations, expressing a wide range of potential outcomes (Murphy *et al.*, 2018). This dataset is important for exploring uncertainty in future impact assessments, giving the most complete view of outcomes under all four RCP scenarios assessed in AR5 (Murphy *et al.*, 2018). Strand 2 uses 28 climate models; a 15-member perturbed parameter ensemble (PPE) from the MOHC's HadGEM3-GC3.05 (hereafter GC3.05) model, and a 13-member ensemble from the CMIP5 coupled ocean-atmosphere model.

These thirteen CMIP5 models were selected from the 42 used by the IPCC in AR5, based on their suitability in terms of data coverage and performance criteria (Gohar *et al.*, 2018). These globally based projections under RCP8.5 are particularly useful for exploring the impact of spatially large-scale drivers of change, for example global circulation, and are provided at 60 km grid spacing to the year 2100 (Murphy *et al.*, 2018). Finally, strand 3 projections use twelve of the fifteen GC3.05 PPE members used for strand 2, downscaled to a regional projection and driven by global simulations for the period 1980-2080 under RCP8.5 conditions (Murphy *et al.*, 2018). Projections are presented as a 12 km grid for the British Isles, therefore taking account of regional-scale features such as mountains, coastlines, and large waterbodies, allowing for local level analysis (Murphy *et al.*, 2018). It is these regional projections that have been used in this thesis for future streamflow estimation (Chapter 5) and subsequent impact assessment for hydroelectric power (HEP) and public water supply (PWS; Chapter 6).

The UKCP18 overview report describes projected future UK climate to 2100 using the strand 1 probabilistic projections detailed above. Under RCP2.6 conditions, the median annual average temperature for 2080-2099 is expected to reach 1.4°C higher than a 1981-2000 baseline, under RCP8.5 this figure is 3.9°C (Figure 2.6; Lowe *et al.*, 2018), further analysis suggest that temperature increases will be larger in summer than winter (MOHC, 2019a). For precipitation the same seasonal variation is seen, with reductions in median summer average (RCP2.6 -15%; RCP8.5 -29%) being much more pronounced than increases for winter (RCP2.6 +6%; RCP8.5 +18%; Figure 2.7; Lowe *et al.*, 2018). Additionally, regional variation is also present, with southern and central England seeing larger winter increases, and the south bigger summer reductions, than the UK average (MOHC, 2019b).

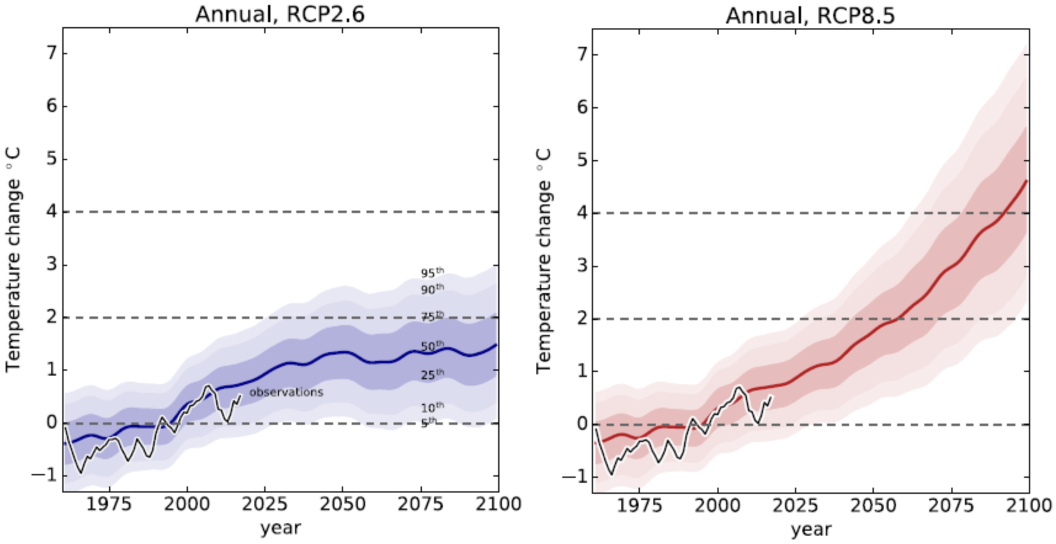

Figure 2.6. Change in UK average temperature compared to the 1981-2000 mean, under RCP2.6 (blue) and RCP8.5 (red). Shading shows percentile boundaries, with solid line indicating the median; black lines are observed temperatures made by the National Climate Information Centre (Lowe *et al.*, 2018).

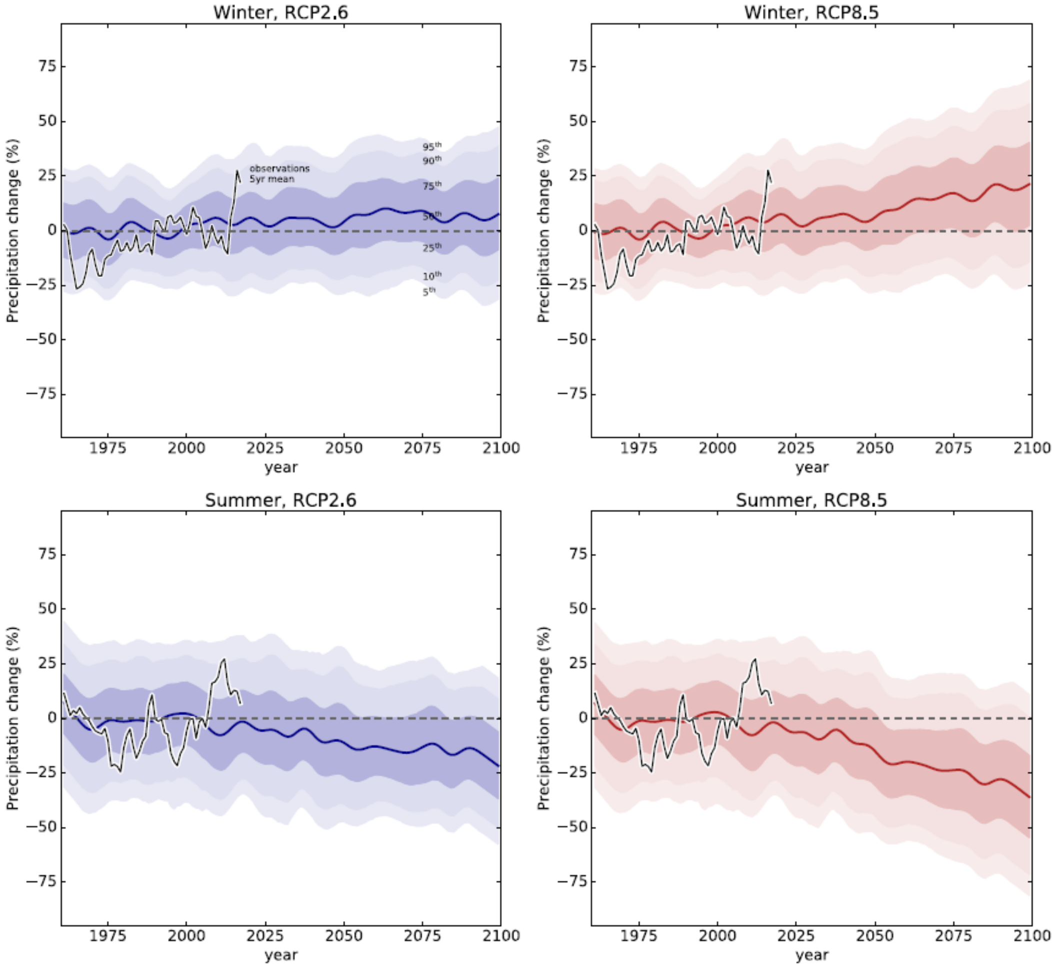

Figure 2.7. Percentage change in UK average precipitation compared to the 1981-2000 mean, under RCP2.6 (blue) and RCP8.5 (red) for winter (top) and summer (bottom). Shading shows percentile boundaries, with solid line indicating the median; black lines are 5-year mean of observed precipitation made by the National Climate Information Centre (Lowe *et al.*, 2018).

With respect to trends in future climate projected for Wales specifically, the UK Climate Change Risk Assessment for Wales, by the Adaptation Sub Committee (ASC) of the Committee on Climate Change, is the most recent publication to report (ASC, 2016b). This report was published prior to the release of UKCP18 datasets, so assesses trends under the former UKCP09 projections, with an update using the new projections expected by the end of 2020 (Welsh Government, 2019a). As aforementioned, these results are still valid, being shown by Kay *et al*. (2020) to be similar and comparable to the most recent projections. With that in mind, Murphy *et al*. (2009) present trends for Wales, based on a high-medium future GHG emissions scenario (SRES A1B, equivalent to between RCP6.0 and RCP8.5). In Wales, climate is set to follow general UK trends of warmer wetter winters and hotter drier summers, with an increase in occurrence of extreme events (Murphy *et al.*, 2009). Mean winter temperature for example is projected to increase by 2°C (median probability; range of 1.1°C to 3.1°C; representing 10% and 90% probability level) for Wales by 2080 (compared to 1961-1990 levels); mean summer temperatures increase by a greater amount 2.5°C (1.2°C to 4.1°C; Murphy *et al.*, 2009). Summer maximum and minimum temperatures are both expected to increase, maximum by 3.4°C (1.3°C to 6.1°C) and minimum by 2.6°C (1.1°C to 4.6°C; Murphy *et al.*, 2009). Annual precipitation is projected to be stable at a median probability level under SRES A1B to 2080, with the 10% to 90% probability range being -4% to +5%. This masks seasonal variation however, with winter precipitation expected to increase by 14% (+2% to +30%) and summer to decrease by 16% (-36% to +6%; Murphy *et al.*, 2009).

Work conducted in Chapter 5 characterises alterations observed under future UKCP18 climate projections for Wales, investigating changes in annual and seasonal averages up to 2080, representing an update on the UKCP09 trends presented by the ASC (2016b) and Murphy *et al*. (2009) and discussed above for Wales.

2.3 Changing hydrology in the UK and Wales

2.3.1 Historical hydrological trends

As previously discussed, hydrological systems have been some of the worst effected systems globally by climate change historically (IPCC, 2014a), with notable variation in impact dependent on regional characteristics. The UK is no exception, with Harrigan *et al*. (2018)

demonstrating a 6.8% (interquartile range: 0.1% to 13.8%) increase in annual mean flow between 1965-2014 when studying 146 near natural catchments across the UK. The same study also analysed seasonal trends over the same period, with winter, summer and autumn mean flows increasing by 12.7% (4.1% to 26.2%), 1.4% (-11.2% to 18.5%), and 16.7% (5.5% to 25.5%) respectively; spring flow is shown to have declined by 10.7% (-19.0% to 1.6%; Harrigan *et al.*, 2018). Interestingly, mapped results for the UK reveal that annual mean streamflow trends display regionality in Wales, with catchments in the north of the country having generally positive trends, and those in the south being negative (Harrigan *et al.*, 2018). Variations in trend characteristics (magnitude and significance) are also observed across the UK, with a northwest-southeast divide being particularly prominent. For example, seasonal analysis conducted by Hannaford & Buys (2012) found that for the period 1969 to 2008, all seasons showed predominantly upwards trends for mean streamflow in catchments in Scotland and the northwest. In the south and east however, the picture was much more varied, with downward trends dominating for spring, upwards for autumn, and mixed changes seen in winter and summer (Hannaford & Buys, 2012).

With regards to extreme hydrological events, Harrigan *et al*. (2018), for the same study conditions as above, demonstrate a 13.5% (7.9% to 23.8%) increase in Q_5 volume (flow volume exceeded 5% of the time), with agreement of trend direction in 88.4% of catchments. The same level of agreement is not achieved for low flows, with 52.4% of catchments displaying an increase in volume for this metric, and 47.6% showing a decline (Harrigan *et al.*, 2018). Additionally, work by Hannaford & Marsh (2008), was some of the first to identify the northwest-southeast divide in large streamflow event trends. Results of the work demonstrate an increase in annual flow maxima across all of the UK, but with a marked increase in magnitude in Wales and northwest England (generally upland areas with a maritime climate) compared to the east and south. For trends in 10- and 30-day maximum flows, the frequency of large flows, and flood magnitudes, significant increases are seen again for the west and north, but little evidence is seen in the south and east (Hannaford & Marsh, 2008). The increasing trends seen for the westerly catchments are supported by the results of Dixon *et al*. (2006), who studied 56 gauging stages in Wales and the Midlands of England for the period 1962-2001. Even here, the vast majority of trends display an east-west gradient in terms of both statistical significance and magnitude of change, being true for increases in annual maximum flow, high flows (Q_{10}), Q_{mean}, low flows (Q_{90}), and annual minimum flows (Dixon *et al.*, 2006). Furthermore, Hannaford and Buys (2012) identify that for low flows, the northwest-southeast divide only occurs in summer (northwest increasing, southwest decreasing), although different regional variations are still seen in other seasons. In winter for example, low flows show a decline in Scotland, Northern Ireland and northeast England, while the midlands and the south are mainly positive. The divide is still present in the high flow analysis, albeit generally less defined. In winter for example, strong positive trends are seen for Scotland, Northern Ireland and the northwest; while positive trends are also seen in the south, but are substantially weaker and generally confined to only smaller catchments (Hannaford & Buys, 2012). Furthermore, in both spring and summer a positive trend in high flows is seen in the northwest, while results are more mixed in the southeast; for autumn rises are seen across the country (Hannaford & Buys, 2012). Work by Laizé & Hannah (2010), to further characterise the spatial variation of seasonal streamflow, suggests that spatial patterns show inter-season variability, meaning the divide is not clear cut. More generally the paper suggests that it is the physical characteristics of basins which drive differences, with elevation and permeability being particularly important. In the UK, this corresponds to the characteristics of the areas in the southeast and northwest, as well as to the greater exposure to prevailing westerly winds that the northwest receives (Laizé & Hannah, 2010).

Evidence reviews completed by Hannaford (2015), Watts *et al*. (2015a) and Garner *et al*. (2017), using published literature on historical UK hydrological change, all identify similar key trends for average and extreme flows, in line with those detailed above. The overarching agreement in the literature being for little change in summer flows, with small declines seen in some areas, an increase in annual and winter flows, and an increase annually in high and low flow event frequency and magnitude.

2.3.2 Future projections under climate change

With regard to future impacts for the hydrology of the UK and Wales, continued changes in the timing, quantity and quality of streamflow are likely. Several studies in recent years have sought to suggest future UK streamflow scenarios for both average (Christierson *et al.*, 2012; Prudhomme *et al.*, 2012; Sanderson *et al.*, 2012; Kay *et al.*, 2020) and extreme flows (Prudhomme *et al.*, 2013a, 2013c; Kay *et al.*, 2014a, 2014b, 2020). Several more have studied smaller areas, Charlton & Arnell (2014) for example for England only; Remesan *et al.* (2014) for the River Derwent; Cloke *et al*. (2013) for the upper Severn; and Bell *et al*. (2012) for the Thames. General consensus among these studies is for a largely stable annual average streamflow, but with large variations seasonally, in particular increases in winter and decrease in summer. These changes are in line with a continuation of historical trends discussed above, and with future climate projections for the nation.

The seasonal average picture for future streamflows is for greater winter and spring flow, with reductions in summer and autumn; as with historical flows, this is particularly applicable to north-western impermeable upland catchments. This trend was demonstrated for the near-future (end of 2020s) by Christierson *et al.* (2012), who reported, using UKCP09 data, a reduction in summer flows across the country. Furthermore, a small increase in winter flows was observed for western areas, with annual mean flow decreasing for all of the UK. Longer-term research by Prudhomme *et al*. (2012) to 2050 explored national level changes under each of the eleven ensemble members that form the HadRM3-PPE-UK model that drives UKCP09 (Murphy *et al.*, 2007). Comparing mean seasonal flows for 2040-2069 with those for the baseline 1961-1990 period highlights a decrease in summer mean flow that is particularly pronounced in the west; autumn flows are more variable with a larger proportion of the 11 models showing a decline, more so for England and Wales than Scotland (Prudhomme *et al.*, 2012). Winter is characterised by increasing flows, showing spatial variability between the 11 models for areas of greatest magnitude of change; generally, however, England and Wales are more effected than Scotland. Spring flows are the most variable, with little agreement in magnitude or trend direction displayed (Prudhomme *et al.*, 2012). Sanderson *et al*. (2012) project future streamflow even further, to the 2080s, in their study of the UK using the same 11-member ensemble, under the SRES A1B future emissions scenario. Once again winter streamflows display an increase across the country by the 2080s, with agreement for almost the whole country on this direction of change. Coastal regions of west Wales are projected to see a particularly large increase, between 15% and 25%, with all 11 models in agreement. For spring flows all but the north of Scotland is reported to see no change or a small decrease, however there is little agreement on this between the models (Sanderson *et al.*, 2012). Summer and autumn flows show a greater degree of agreement for trend direction between the models, with decreases for the whole of the UK in summer and all but the northwest of

Scotland in autumn. In summer, similar to winter, coastal regions in the north, west and south of Wales are projected to see large (-15% to -25%) decreases in mean flow, with agreement in all 11 models; autumn mean flow shows a more moderate decline (-5% to -15%; Sanderson *et al.*, 2012). Finally, median annual flow for the period 2040-2069 was shown by Kay *et al*. (2020) to decrease for 10 catchments studied throughout the UK, under both RCP4.5 and RCP8.5 conditions; the magnitude of this reduction only being marginally greater under RCP8.5, but with greater uncertainty.

Kay *et al*. (2020) also analysed changes in high (Q_5) and low (Q_{95}) flows under the same conditions as for average flows above. Trends in Q_5 displayed variation in line with the east-west divide aforementioned; those catchments in the west exhibiting small increases in future high flows, and those in the east presenting little or no change. Low flows were much more consistent, all catchments' Q_{95} projected to decline under both RCP4.5 and RCP8.5 (Kay *et al.*, 2020). The majority of research on future extreme streamflows is framed within the context of changing flood and drought risk. This is true of Collet *et al*. (2018) who's findings concur with those of Kay *et al*. (2020). The study used the Future Flows Hydrology (FFH) dataset (Prudhomme *et al.*, 2013b) to compare 2080s hydrological hazards with the 1970s. The median trend of the FFH, is for increases in frequency, magnitude and duration of both floods and droughts almost exclusively in the west of the UK only, especially concentrated in the south west of England and Wales (Collet *et al.*, 2018). The magnitude and duration of droughts is projected to show a larger percentage change than the magnitude of floods, but changes in frequency are broadly the same (Collet *et al.*, 2018). Interestingly, the paper also assess the change in seasonality of events, showing that floods are much more likely to occur in winter in the future, while droughts are less seasonally bound, but still more likely to occur in the autumn, and to a lesser extent, the summer (Collet *et al.*, 2018).

A considerable amount of work has been completed in the last decade for the whole of the UK and regions/catchments thereof, in characterising future high flow and flood regimes under changing climate (e.g. Cloke *et al.*, 2013; Lavers *et al.*, 2013; Kay *et al.*, 2014a, 2014b; Sayers *et al.*, 2016; Jenkins *et al.*, 2017). Kay *et al*. (2014a, 2014b) comprehensively reviewed probabilistic impacts on flood magnitude in particular, for England, Wales and Scotland. Using the UKCP09 projections, it is shown for England and Wales that under the SRES A1B emissions scenario, peak flows in 20-year return period floods will increase by between 20% to 25% in the east and by 25% to 35% in the west (Kay *et al.*, 2014a). Under a high A1F1 SRES emissions scenario (equivalent to RCP8.5), this trend remains, with magnitudes of change becoming larger, the east rising to between 25% to 35%, and the west to between 35% to 45% (Kay *et al.*, 2014a). For Scotland a similar trend is observed in terms of spatial distribution, the west being more greatly affected than the east, but the magnitude of change is larger; the very north west for example, seeing a 45% to 60% increase under SRES A1F1 scenario by the 2080s (Kay *et al.*, 2014b). Sayers *et al*. (2015) also suggest a 13% increase by 2080 under a 2°C warming scenario, for peak streamflows in Wales, increasing to 42% in east Wales, and 36% in west Wales under 4°C scenario. These results have large implications for return period changes; for example, under the 2°C scenario, the return period for an event currently at 100 years, would reduce to ~40 years; under the 4°C scenario this would be reduced to less than 11 years in east Wales, and ~13 years in the west of the country (Sayers *et al.*, 2015).

While future hydrological drought trends have not received the same level of attention as flood events in the literature, a few studies have characterised projected changes through the 21st century. As is common with many of the studies presented in this section, the HadRM3-PPE-UK 11-model ensemble has been used by Rahiz & New (2013) to comprehensively assess the severity of future droughts in the 2020s, 2050s and 2080s; the results for the 2080s are discussed here. The intensity of modest droughts is to increase substantially for England and Wales, while the increase in intensity of the most severe droughts is set to be less, although the most pronounced area in the UK is shown to be Wales (Rahiz & New, 2013). Additionally, the frequency of drought occurrence shows the same spatial pattern for the UK as intensity, but the rate of change for severe and moderate events is broadly the same, both increasing in England and Wales (Rahiz & New, 2013). Average drought length however is shown to decrease, with little change in the number of 12- and 10-month droughts projected, but an increase in 6- and 3-month events, especially the latter and for both severe and moderate events (Rahiz & New, 2013). Overall for Wales, therefore, the study projects increased intensity and frequency events, which will very likely be shorter in length than at present. The results of Rudd *et al.* (2019) are broadly in agreement with Rahiz & New (2013), with similar spatial patterns for intensity and drought duration shown for the 2080s. Studying low flow characteristic changes, Kay *et al*. (2018) compared low flow frequency curves, to quantify the percentage change in 2- and 20-year return period events between the 1975-2004 average and the 2070-2099 average. As with the previous worked based on drought, results show a decrease in the volume of 2- and 20-year low flows, suggesting an increase in drought severity; again this is especially pronounced across England and Wales (Kay *et al.*, 2018).

In addition to changes in precipitation and temperature projected up to 2080, Chapter 5 also analyses trends seen in annual and seasonal average streamflow, as well as the intensity and frequency of extreme high and low streamflow events.

2.4 Water quality implications of hydroclimatic change

Changes in precipitation patterns and hydrological regime will impact and influence the in-stream environment. One of the key change areas will be river water quality, with key processes such as run-off, overland flow, stream power, dilution potential and carrying capacity all likely to be altered. Globally, the effect of changing precipitation extremes and streamflow patterns on water quality factors has been well studied, often at a regional or catchment-scale (e.g. Johnson *et al.*, 2009, 2015; Tu, 2009; Whitehead *et al.*, 2009b; Rehana & Mujumdar, 2012; Crossman *et al.*, 2013; Michalak, 2016; Wang *et al.*, 2018; Guo *et al.*, 2019). General consensus is that increasing extreme precipitation events will likely lead to larger overland flows with greater capacity for eroding and flushing of non-point-source pollutants from the land surface into river systems (Nilsson & Malm Renöfält, 2008; Whitehead *et al.*, 2008; Guo *et al.*, 2019). In addition, large discharge events are likely to cause greater in-stream erosion of bed and banks, causing increased turbidity (Nilsson & Malm Renöfält, 2008; Bussi *et al.*, 2016). Paradoxically, an increased likelihood of low flow events is also expected to decrease water quality, with less water available for dilution, this is clearly a larger issue downstream of point-sources of pollution, for example industrial and wastewater treatment outfalls (Nilsson & Malm Renöfält, 2008; Whitehead *et al.*, 2008, 2009b). Work by Gau *et al*. (2019) for 102 water quality monitoring stations in southeast Australia identifies that same day streamflows are the largest driver of declining water quality, also suggesting that reduced flow and lack of dilution is less important; this is of course highly location dependent however.

In light of this body of research, the previously discussed projected increases in magnitude and frequency of larger streamflow and precipitation events, as well as decreasing summer flow and increased magnitude, frequency and duration of droughts is invariably expected to impact negatively on water quality in the UK and Wales. In terms of water quality changes, less work has been published in the UK on this topic than for hydroclimatic changes, with even fewer publications focusing on or featuring Wales specifically. Nonetheless a consensus in the literature is for a general decrease in surface water quality under future climate change in the UK (Johnson *et al.*, 2009; Whitehead *et al.*, 2009b; Ritson *et al.*, 2014; Watts *et al.*, 2015a; Hutchins *et al.*, 2016). The nature of that change is not likely to be uniform, with catchment characteristics such as basin permeability, soil types, land cover proportions, topography, and pollution sources all contributing to variation (Whitehead *et al.*, 2009a). Key fundamental process will remain largely similar across the UK however, and the implications of climate change on these key processes is discussed below.

Natural Resources Wales (NRW), in its latest assessment of the ecological status of rivers for the Water Framework Directive (WFD), identified a total 1,352 reasons why sections of river in Wales were not achieving good ecological status under the WFD classifications (NRW, 2019a). When investigating the causes behind these failures, it has been found that 47.6% of reasons for not achieving a good status is due to diffuse pollution sources, with 30.3% being due to point sources (NRW, 2019a). Looking at the west Wales river basin district, which encompasses all of the catchments studied in this thesis, 733 reasons are listed for river sections not achieving good ecological status. Both diffuse and point sources of pollution cause a greater proportion of total failure reasoning for this region than the full Wales dataset, at 48.7% and 34.1% respectively (NRW, 2019a). Changes to flow regime (e.g. water impoundment or abstraction) have a similar proportion of impact for both regions, as do natural causes, such as natural barriers to fish migration or natural streamflow conditions. Physical stream modification, for the purpose of river navigation, for example, or due to construction, has a larger impact when looking at the whole of Wales, than for the west Wales region, potentially reflecting the greater level of urbanisation represented in the all Wales dataset. Table 2.2 provides an overview for all of Wales and the west Wales river basin district on the breakdown of reason for stream sections not achieving good ecological status.

Table 2.2. Categorisation of reasons for stream sections not achieving good ecological status in the Water Framework Directive classifcations, for all of Wales, and the west Wales river basin district (NRW, 2019a).

Reason	All of Wales		West Wales	
	Number	Percent	Number	Percent
Diffuse source	644	47.6%	357	48.7%
Point source	409	30.3%	250	34.1%
Physical modification	176	13.0%	57	7.8%
Flow	52	3.8%	22	3.0%
Natural	32	2.4%	18	2.5%
Other	39	2.9%	29	3.9%

Jin *et al*. (2012) found that for the River Thames, nitrate concentrations increased considerably in the winter months when modelling the period 2070-2099 compared to observations for 1961-1990, with a decrease shown in summer. This is commensurate with previous research that suggests larger winter flows will cause greater flushing of nitrate from land to river systems (Whitehead *et al.*, 2009a). Furthermore, there is evidence to suggests that longer residency times and high water temperature will cause greater loss of nitrate through de-nitrification in rivers (Whitehead & Williams, 1982), explaining the lower summer concentrations. A similar trend was found by Conlan *et al*. (2007) for nitrate and ammonia in the River Wharfe catchment, with levels falling under drier summer conditions. There is the risk, however, that after prolonged periods of drought (greater than a year), the effect of the return of rainfall could result in exceptionally high peaks of nitrogen in rivers systems, as projected for the River Kennet by Wilby *et al*. (2006). Hutchins *et al*. (2016) review changes in river quality for the UK also, they suggest that the use of combined sewer overflow systems, which are common in the UK and especially in Wales, with over 3,000 (DCWW, 2015), are likely to cause an increase in particulate phosphorus, especially during times of high flow, as well as increases in sediment transport. Increases in the concentration of future suspended sediments is supported by Bussi *et al*. (2016), who showed that under extreme precipitation events, suspended sediment yields in the River Thames increased substantially, due to greater splash erosion, greater overland flow, and larger channel flow. Additionally, Jennings *et al*. (2009) showed for the River Flesk (Ireland), independent of factors such as combined sewer overflows, that phosphorous levels are to substantially increase in the winter months, linked to higher precipitation levels causing greater delivery of contaminants to the river system. These trends fit with international literature such as Crossman *et al*. (2013), who found for the Black River in Canada, that total phosphorous loads in winter were greatly increased under future climate projections, caused by larger precipitation volumes enabling greater transfer into streams. Nilawar & Waiker (2019) found that for the large Purna river basin in India, under future RCP8.5 conditions, sediment concentrations were set to increase fivefold when comparing 2054-2075 with a baseline period of 1980-2005; 50% of this rise was attributed to greater stream power causing riverbank erosion.

In general, increased SS loads have implications for other water quality factors, as pollutants such as phosphorous and bacteria adsorb to the grains, meaning that projected increases in SS concentrations will likely lead to higher levels of other pollutants (Dearmont *et al.*, 1998; Loperfido, 2014). However, when looking at faecal indicator bacteria, such as coliforms, as an indicator of pathogen organism presence in freshwater, work has shown that the situation may be more nuanced. Dakhlalla & Parajuli (2020) show for the Big Sunflower River, that while increased rainfall causes greater washing of bacteria into rivers, increases in temperature cause faster die-off rates. These results are in agreement with other established research, such as Cho *et al*. (2010), Hofstra (2011), and Wilkes *et al*. (2011), which have investigated this relationship in various regions and catchment types globally. In addition, Bussi *et al*. (2017) show for the Conwy (also studied in this thesis) a decline in future faecal indicator bacteria even under an intensified agricultural scenario. Their research compares observed 1960-1990 bacteria levels with modelled data for 2060-2090 using the INCA-Pathogens model, under the SRES A1B scenario. The declines observed are also attributed to combined temperature increases, causing faster bacterial die-off, and precipitation declines, especially in summer, causing a reduction in runoff and therefore contaminant routing (Bussi *et al.*, 2017). It should be noted however, that Bussi *et al*. (2017) assess monthly average changes, and therefore projected increases in the magnitude and frequency of large streamflow events (Kay *et al.*, 2014a), which could cause a greater number of spikes in bacterial concentrations, are not accounted for. None of the studies mentioned explicitly account for combined sewer overflows either, these could be especially important for the study region of this thesis, when considering the large number in operation, and the potentially contribution to contamination from bacteria in times of high flows (Astaraie-Imani *et al.*, 2012; Abdellatif *et al.*, 2015). Therefore, while average pathogen concentrations are likely to decline under future climate change, it is also likely that larger spike will be seen, this could prove problematic for water treatment works, as well as in-stream ecology, and sectors such as the shellfish industry.

A further consideration for future water quality is the impact of changing (mainly increasing) air temperatures on stream water temperature and associated effects on water quality factors such as dissolved oxygen (DO). The relationship between air and river water temperature is well established and has been studied globally (Crisp & Howson, 1982; Preud'homme & Stefan, 1992; Erickson & Stefan, 2000; Morrill *et al.*, 2005; Harvey *et al.*, 2011). Morrill *et al*. (2005) estimated a 0.6°C to 0.8°C rise in water temperature for every 1°C rise in air temperature when studying 43 rivers in 13 countries, they did however note that an S-shaped relationship better captures changes at air temperatures close to zero and above 25°C. This S-shaped relationship is also suggested as the best fit by Harvey *et al*. (2011) who studied four sample sites in Newfoundland. Erickosn & Stefan (2000) also concluded that the relationship between the two factors depart from linearity after 25°C, for two catchments in the US; the relationship is also closer when studied as a weekly or monthly average, rather than daily (Erickson & Stefan, 2000; Webb *et al.*, 2003; Morrill *et al.*, 2005). The effect of water temperature on DO has also been well researched, with increased temperature causing a decrease in DO concentrations (Morrill *et al.*, 2005; Nilsson & Malm Renöfält, 2008; Cox & Whitehead, 2009; Harvey *et al.*, 2011). Future warming of summer temperatures in particular could therefore cause DO concentration to fall to critically low levels, potentially impacting in-stream ecology, threatening various aquatic life (Morrill *et al.*, 2005; Cox & Whitehead, 2009; Harvey *et al.*, 2011). Eutrophication also has the potential to be altered, especially when combined with increasing nutrient supply, as is expected due to increased overland flow and associated flushing of nutrients from soils into river systems (Nilsson & Malm Renöfält, 2008; Watts & Anderson, 2016). With increased nutrient supply, and chemical reactions running more quickly at warmer temperatures, there is the potential for a large increase in the size and development speed of algal blooms in the UK (Whitehead *et al.*, 2008, 2009a, 2009b; Cox & Whitehead, 2009; Watts & Anderson, 2016). This increase in nutrient supply, temperature, and algal volume is likely to increase the biological oxygen demand of river systems, putting yet further pressure on DO levels (Whitehead *et al.*, 2008). These problems could be further exacerbated by the potential for long periods without rain in the summer in future, followed by intense precipitation events, further increasing spikes in poor water quality (Delpla *et al.*, 2009; Whitehead *et al.*, 2009a; Watts & Anderson, 2016).

It is therefore likely that river systems in Wales will see marked changes in water quality under future hydroclimatic change. It is crucial to understand the nature of this change in order to plan for and mitigate its effects. Therefore, Chapter 5 assesses future seasonal changes in the concentrations of four water quality parameters: suspended sediment, total phosphorous, total nitrogen, and dissolved oxygen.

2.5 Future water resource use implications for Wales

Water resources in Wales are overseen and regulated by NRW on behalf of the Welsh Government. NRW manages and monitors abstraction, impoundment and discharge licences for water use in the country as well as being tasked with monitoring aspects such as water quality and pollution (NRW, 2020a). The largest exploitation of natural water resource in Wales is for PWS, which for Wales is mainly under the jurisdiction of Dŵr Cymru Welsh Water (DCWW). In the past two decades the amount of water supplied by DCWW has reduced by about a fifth, to ~800 million litres per day, down from ~1000; approximately half of this reduction is due to a lowering in the amount of leakage in the system; the rest because of falling demand from heavy industry (DCWW, 2019a). This reduction is despite an increase in average consumption per capita from 110 litres per day in the 1970s to 157 litres per day in 2016 (DCWW, 2016b). Wales is highly reliant on surface waters for PWS, in fact roughly 95% of supply sources used by DCWW are taken from surface waters (DCWW, 2016c), mostly from 65 impounding reservoirs owned and operated by the company in Wales (DCWW, 2019a). While only 3% of water falling as rain is abstracted for PWS in Wales, compared to figures nearer 50% in south and east of England, the country still faces potential water supply issues. This heavy reliance on surface waters and lack of back-up ground water supplies, makes Wales more vulnerable in times of prolonged severe drought. Indeed, there are already regions at risk of water deficit in Wales during dry summer months, a situation compounded by a relative lack of transfer capabilities between water supply zones (DCWW, 2019b).

Currently the industry regulator for England and Wales, Ofwat, and the Water Act 2003, require water companies to develop a water resources management plan, in which companies plan the supply of water into the future (HM Government, 2017). The most recent for DCWW covers the period 2020-2045, but it should be noted that this is a snapshot of thinking at the time, and that actual planning is continuous (DCWW, 2019a). The latest water resources management plan for DCWW states an expected drop in the amount of water available for abstraction, both due to reductions in abstraction license amounts by NRW and climate change. In addition, total water demand is predicted to fall by DCWW, based on targets for reductions in leakage; individual large customer usage predictions and development forecasts for Wales (DCWW, 2019a). With the majority of water being taken from large storage reservoirs for the most of Wales, and given the trends previously mentioned of increasing winter precipitation and declining summer precipitation, combined with longer and more intense droughts, means that the water supply systems could still come under strain. Increasing precipitation in winter, for example, will do little to combat shortages in the summer and autumn due to reduced filling, if reservoirs are already at maximum capacity in the proceeding winter.

Climate change not only has the ability to impact on the supply of water, but also water demand. Despite projections for an overall decline in demand by DCWW, it is likely that, as is true for precipitation, demand patterns will become more exacerbated. Domestically, increasing summer temperatures are likely to lead to a greater amount of water usage for personal bathing and gardening, with Downing *et al*. (2003) showing, under 2.3°C warming to 2050, a 7% (winter) to 21% (summer) increase in domestic demand. Goodchild (2003) demonstrated a 3.3 litre per person increase (range 1.3-5.7) in summer domestic water demand, equating to 2.1% increase, when studying the Essex water supply zone under future increased temperatures. It was also noted by Goodchild (2003) that peak water demand also increases, with a 7-day domestic water demand average of 183 litres per person occurring 10% of the time under future scenarios, compared to 5% at the time of study. Xenochristou *et al*. (2020) found that sunshine duration and air temperature are the two most important weather based controls on domestic water demand. During week days, a one hour increase in daily sunshine duration related to a 6 litre per person increase in water use; for daily air temperature, a rise of between 2.5 and 7.5 litres per person was seen per 1°C warming after 15°C, depending on the affluence of the water user (more affluent increasing the greatest; Xenochristou *et al.*, 2020). Furthermore, likely increases in temperature and decreases in rainfall have the potential to generate much greater demand for water from the agricultural sector in the UK, for irrigation of crops and water supply for animals. Downing *et al*. (2003) for example showed an average 84% increase in water demand for potato production in the

UK between by 2050 under a high future emissions scenario, or 74% under a medium scenario; with potatoes being one of the most water intensive crops to grow.

Looking more widely at general water use and abstraction by all sectors, it is clear that here too there are substantial implications in terms of water availability, especially in summer months. Although very much a worst-case scenario, Figure 2.8 highlights two potential future problems for catchments and water users in Wales when looking at total abstraction demand. The scenario presented is set during low flow conditions under RCP8.5 levels of future emissions, with an increased population (ASC, 2016b). First, future demand is set to outpace supply significantly in this scenario, with substantially less water available than is needed across the UK but especially so in Wales. Second, and more important environmentally, is the lack of adequate streamflow to satisfy even minimum environmental flows. These flow levels are often assigned to water abstractors, to ensure a sufficient flow is maintained to protect the ecological and morphological status of the river. Insufficient flow to maintain these levels could have serious implications for the health of the river and its ecology.

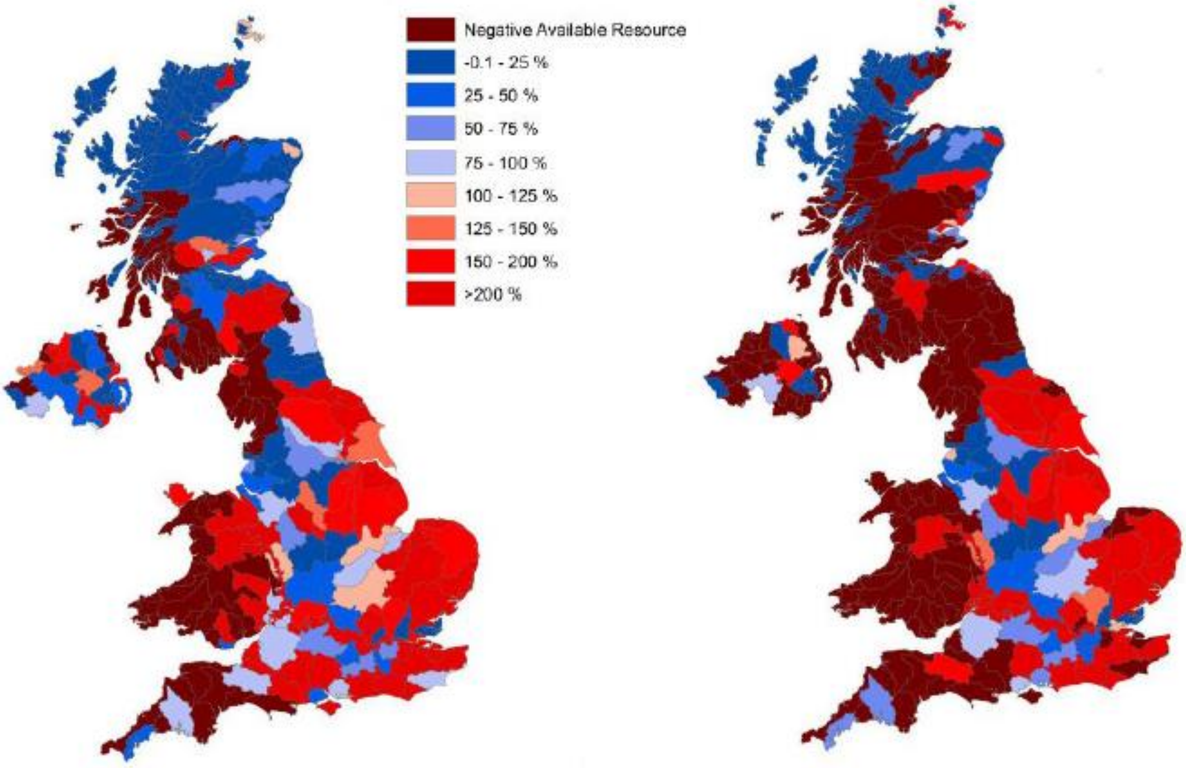

Figure 2.8. UK abstraction demand in the 2050s (left) and 2080s (right) as a percentage of available discharge during low flow conditions, under high population growth and RCP8.5 equivalent future scenario. Maroon colour denotes areas of negative available resource, i.e. those areas where the available flow is not sufficient to satisfy required environmental flow, meaning no abstraction is possible (ASC, 2016b).

Additional pressure is also potentially faced by public water supplies in the form of changing water quality, as previously discussed. Nitrate peaks as projected by Wilby *et al.* (2006) for the River Kennet, for example, would be greater than the legal limit acceptable by the UK for drinking water supply, so would require additional treatment methods to be in place. This is a trend likely to be seen across the country; with decreasing water quality there is an increased environmental and financial cost in order to maintain drinking water standards. If higher levels of water pollution were seen consistently, such changes may even require the introduction of new technologies or drinking water treatment plant upgrades, once again this would be potentially highly costly.

Planning of future PWS resources has been under consideration for some time in the UK, Arnell (2004b) for example, assessed that, given a projected 30-50% reduction in Q_{95} by 2050 and higher pressures on the supply-demand balance due to both higher consumer demand, and reduced supply availability (lowered abstraction license levels due to Water Framework Directive), a significant difficulty could be posed for the industry. In addition, Arnell and Delaney (2006) suggested that a potential 20% increase in water demand for irrigation could have the most severe knock on effects for supply sustainability; Downing *et al*. (2003), however, suggests peak domestic demand has the potential to be the most important factor in future water supply planning. However, work is still ongoing and needed, with ensuring future water supply often touted as one of the key challenges facing Wales and the UK under a changing climate. The Adaptation Sub-Committee (ASC) of the Committee on Climate Change, for example states that 'more action is needed' to tackle and understand the risks to public water supplies in Wales, the highest level of urgency it gives (ASC, 2016b). Furthermore, the Welsh Government's climate change adaptation plan (Welsh Government, 2019a) states that risks to public water supplies from drought and low flows is one of four key risk areas in relation to climate change. Finally, DCWW in their 2050 plan (DCWW, 2018) state that reduction in available water and water quality change are two key future trends that require planning and adaptation, to safeguard clean drinking water for all.

Work reported in Chapter 5 of this thesis addresses potential changes in streamflow and water quality, which could be important for all water users in the future. Furthermore, Chapter 6 address future water resource availability in Wales for both PWS and HEP, analysing trends in unmet demand for PWS and generation potential for HEP.

2.6 Summary

As can be seen by the research presented, changes in the quantity and timing of water supply historically and for the future have been relatively well studied for the UK as a whole, but less well for Wales specifically. Wales is however an important area to study, with evidence in many of the papers cited in this section detailing how the west of the UK and Wales is more likely to see a greater impact of future changes in both average and extreme hydroclimatic conditions. Furthermore, the impacts of projected climate change on water quality parameters for Wales has seen even less research, as has future water resource availability. In the light of this, as well as global, UK and Welsh level policy, and the heavy reliance on water resources in Wales, as outlined in Chapter 1, it is important to have a good understanding of how climate in Wales will change and the impacts that such changes will have on hydrology. Furthermore, given the dependence on surface waters, greater knowledge of how industries that are heavily reliant on water will be affected is crucial. While water resource management plans published by DCWW do provide important insight into the impacts on water supply, there is scope for further research assessing the influence of changing climate on water supply and demand relationships, the bearing of extreme events, and the impact of changing water quality. Likewise, the impact on other large water users has seen limited research, especially considering the consequences that changes in the seasonality and quantity of streamflow could cause. It is these knowledge gaps that this thesis aims to address, as laid out in the aim and objectives section in Chapter 1. It is hoped that by addressing the gaps relating to (1) water demand links to prevailing weather conditions, (2) future streamflow and water quality characteristics, and (3) the impacts on water abstraction locations, that more informed future planning decisions may be made.

CHAPTER 3: METHODOLOGICAL OVERVIEW

3.1 Overarching methodology

The research conducted in this thesis is based on a process of results, with the findings of the earlier studies informing the research direction and methods of latter studies. While the objectives of the research were established at the project outset (Chapter 1), the overarching and individual study methodologies have been continuously developed based on the findings. This approach has been taken in order to ensure that the most appropriate methods are used given the output data, and that the results are therefore meaningful, reliable, and useful. The same study area and five catchments (details in Section 3.2) have been maintained throughout the thesis, allowing a full picture of change within each to be established.

The first study investigates historical trends in temperature, precipitation, and streamflow for each catchment, in order to establish the current direction and magnitude of change in the variables. In addition, the relationship between the variables and total water demand, using total public water supply (PWS) abstraction volume as a proxy, is also completed. This study was undertaken in order to characterise for the first time the historical trends in both average and extreme streamflow, precipitation, and temperature for several of the catchments. This characterisation is also then used to inform the methodology of the future hydrological modelling completed in Study 2, as well as to provide context and comparison with the future observed trends. In addition, the establishment of the relationship between weather and total PWS demand has not been made for Wales previously, with little work of this kind being published for the UK more widely. This work is important for the assessment of potential future PWS demand generally, with the results, for temperature in particular, also important for the future water resource availability analysis completed in Study 3.

Study 2 analyses the impact of future climate change on the streamflow regime and water quality of the five catchments. Projected future climate input is based on a worst-case scenario of future global greenhouse gas (GHG) emissions, in the form of Representative Concentration Pathway 8.5 (RCP8.5) from the Intergovernmental Panel on Climate Change (IPCC). RCP8.5 represents one of the worst emissions outcomes of a no-policy scenario, with high population growth, continued coal use, and no downturn in global GHG emissions (Riahi *et al.*, 2011; van Vuuren *et al.*, 2011), leading to a scenario of radiative forcing still rising by 2100, and not peaking until the 2200s (Moss *et al.*, 2010; van Vuuren *et al.*, 2011). This is an extreme future scenario, in the 90th percentile of future modelled outcomes of no climate change mitigation (van Vuuren *et al.*, 2011) and has been used in this thesis despite the higher levels of uncertainty associated with it, due to the critical nature of the study subject, in particular PWS. To ensure an uninterrupted future PWS it is vital to take account of such a scenario, to allow for robust planning. Furthermore, the use of this scenario is important for all potential water users, hydroelectric power (HEP), for example. In a future society where renewable energy is likely to make up a larger part of the overall energy mix, understanding the potential fluctuation in HEP generation caused by alteration in streamflows under climate change is highly important. The same is also true for purposes such as abstraction for agricultural irrigation, also likely to become more important under a warmer and drier future summer climate in the Wales. The results of Study 2 not only inform Study 3, but also, as aforementioned, have significance to any abstractors or users of, surface waters in Wales. Changes in streamflow and water quality will impact on all water users, as well as aquatic life, the results of this work therefore have wide reaching consequences, providing context to the decision and policy making of various organisations.

The third and final study uses the daily future streamflow output modelled in Study 2 to investigate the impact of climate change on available water resource for two of the key water abstracting sectors in Wales, HEP and PWS. These two sectors were chosen based on their year-round water use, streamflow allowing (as opposed to the more seasonal nature of agricultural demand, for example), as well as their importance to society, for water supply and energy generation. The study was undertaken in order to provide a degree of quantification of the potential societal, environmental, and economic impacts of climate change induced hydrological regime change in the future, as well as to provide context to future decision making in terms of preparation and adaptation.

3.2 Study catchments

Five catchments in Wales have been chosen for study, the Clwyd, Conwy, Dyfi, Teifi and Tywi (Figure 3.1); with each exhibiting varied characteristics such as topography, hydrometry, land cover, and climate. They are all also used extensively for water abstraction for a variety of sectors, such as PWS, HEP, agriculture and industry. The rationale behind the selection of Wales as the study area, as well as these five particular catchments, is provided in Section 1.2.

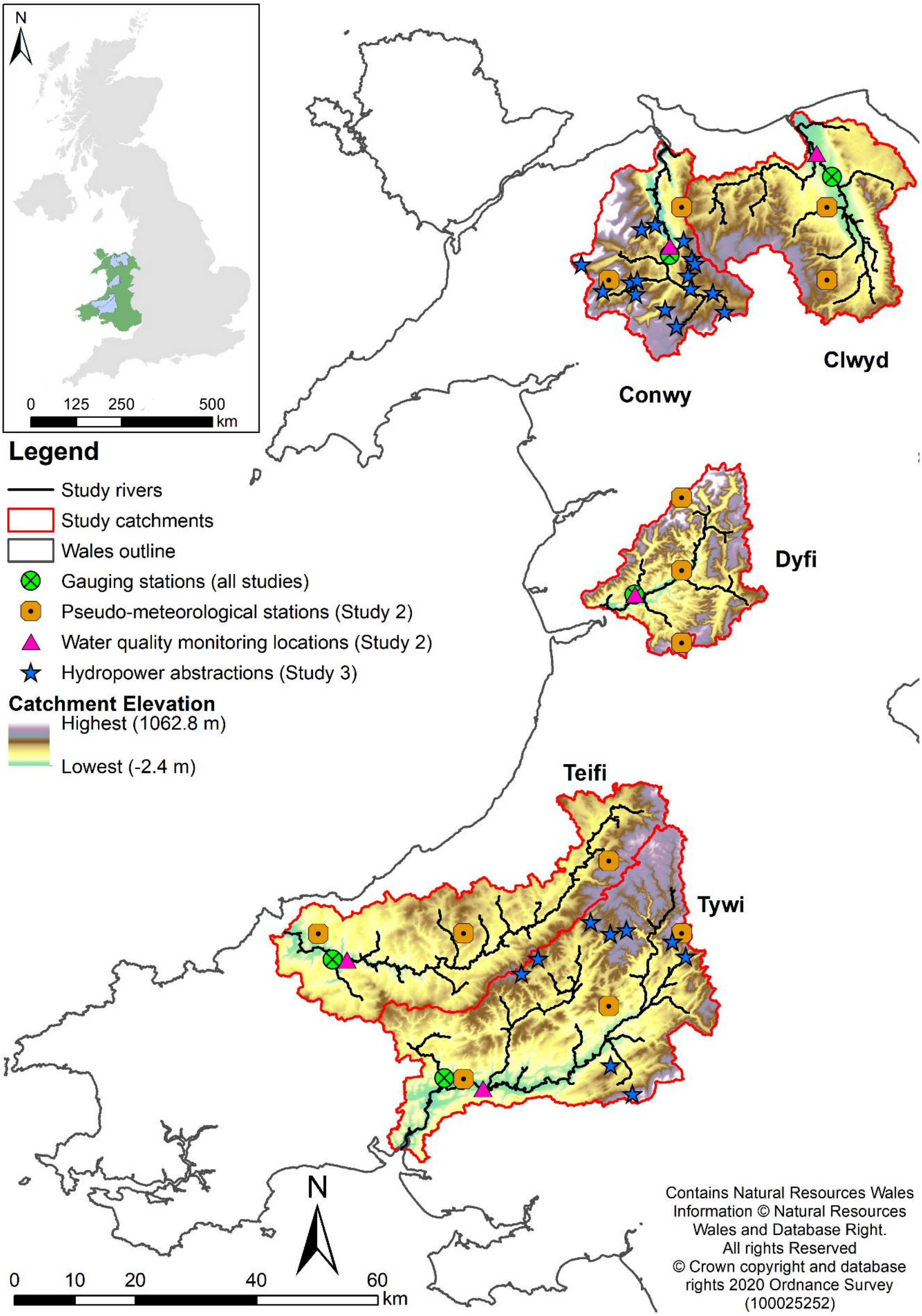

Figure 3.1. Study catchments displaying streams larger than third order and catchment elevation. The location of streamflow gauges used in all three studies are shown (green circles), as well as the location of pseudo-meteorological stations (orange octagons) and water quality monitoring locations (pink triangles) used in Study 2. The 25 hydroelectric power abstractions locations examined in Study 3 are also shown (blue stars).

The following section provides detailed descriptions of each catchment and a comparison of characteristics between catchments. Reported details and figures are based on the catchment areas as modelled for Study 2. Morphometric calculations are based on data derived from the OS Terrain 5 digital elevation model (DEM) from Ordnance Survey (Ordnance Survey, 2020); land use/land cover (LULC) proportions are calculated from 2012 CORINE Land Cover data from the European Environment Agency (EEA, 2012). Gauged streamflow data (NRFA, 2020), and precipitation data from the Climate, Hydrology and Ecology research Support System (CHESS) dataset (Robinson *et al.*, 2017), for the hydrological years 1982 to 2015, has been used in the calculation of hydrometric signatures and precipitation statistics. In relation to hydrometric signatures, mean streamflow (Q) and precipitation (P) for the period 1982-2015 have been used to calculate runoff ratio (R_{QP}), as per Equation 3.1. Values closer to 1 denote a streamflow dominated catchment, and nearer to 0 signals evapotranspiration is foremost:

$$R_{QP} = \frac{Q}{P} \tag{Eq. 3.1}$$

Baseflow index was calculated by the digital filter method (Sawicz *et al.*, 2011) to give an indication of the long-term contribution of baseflow to total streamflow. Direct runoff at a given time-step (Q_{Dt}) is first computed, as per Equation 3.2:

$$Q_{Dt} = cQ_{Dt-1} + \frac{1+c}{2}(Q_t - Q_{t-1}) \tag{Eq. 3.2}$$

where c is a constant with value 0.925, Q_{Dt-1} is direct runoff at the previous time-step (at $t = 0$, Q_D is assumed to be 0) and Q_t and Q_{t-1} are streamflow at this and the previous time-step respectively. Baseflow (Q_{Bt}) for the time-step is then calculated using Equation 3.3:

$$Q_{Bt} = Q_t - Q_{Dt} \tag{Eq. 3.3}$$

Baseflow index (I_{BF}) can then be computed by Equation 3.4, summing all time-step values, where I_{BF} values closer to 1 infer catchments with higher baseflow contribution:

$$I_{BF} = \sum \frac{Q_B}{Q} \tag{Eq. 3.4}$$

Finally, streamflow elasticity (E_{QP}) has been calculated as a measure of the sensitivity of each catchment to precipitation, as established by Schaake (1990) and Dooge (1992), and modified by Sankarasubramanian *et al*. (2001), which compares the percentage change in precipitation to the percentage change in streamflow, normalised by the runoff ratio, as in Equation 3.5:

$$E_{QP} = median\left(\frac{dQ}{dP} \times \frac{P}{Q}\right) \qquad \textbf{(Eq. 3.5)}$$

where dQ and dP represent the difference between the previous year's and current year's mean annual streamflow and precipitation respectively, and P and Q are as above. Values greater than 1 represent elastic catchments which are sensitive to precipitation changes, with values less than 1 denoting the opposite, inelastic catchments. A summary of catchment characteristics is made in Table 3.1, with detailed descriptions for each catchment after.

Table 3.1. Summary of comparative study catchment details based on the catchments as delineated in Study 2. Morphometric parameters derived from the 5 m resolution OS Terrain 5 DEM from Ordnance Survey (Ordnance Survey, 2020) with hydrometric signatures based on streamflow for the hydrological years 1982-2015 (NRFA, 2020). Precipitation statistics calculated from CHESS data (Robinson et al., 2017); land use/land cover derived from 2012 CORINE Land Cover data (EEA, 2012).

		Clwyd	**Conwy**	**Dyfi**	**Teifi**	**Tywi**
Morphometric and hydrometric parameters	Catchment area (km^2)	750.1	541.8	507.2	995.3	1364.6
	Mean elevation (m)	210.4	309.8	271.4	198.1	212.5
	Maximum elevation (m)	557	1062	903	591	801
	Mean slope (%)	12.5	19.7	25.3	11.6	16.6
	Runoff ratio	0.52	0.93	0.89	0.76	0.80
	Baseflow index	0.59	0.28	0.38	0.54	0.48
	Streamflow elasticity	1.28	1.21	1.06	1.09	1.17
Precipitation	Mean annual rainfall (mm)	977	1968	1803	1398	1596
	Winter proportion (%)	28.4	32.1	31.2	30.2	30.8
	Spring proportion (%)	20.1	19.2	18.8	18.8	19.1
	Summer proportion (%)	21.0	18.2	20.1	19.8	19.7
	Autumn proportion (%)	30.5	30.5	29.9	31.2	30.4
	Mean rain free days per year	48.3	44.1	52.1	55.7	49.5
Catchment land use/ land cover (%)	Urban	2.4	0.7	0.3	0.8	0.7
	Agriculture	80.9	30.6	30.0	83.0	64.6
	Arable	9.3	0.1	0.4	1.8	0.7
	Pasture	71.6	30.5	29.6	81.2	63.9
	Forest	7.3	13.7	21.5	5.5	16.0
	Broadleaf	1.6	2.7	1.8	1.2	1.0
	Coniferous	4.5	5.5	18.9	3.2	10.1
	Mixed	1.2	5.5	0.8	1.1	4.9
	Scrub	9.4	42.1	45.3	9.7	17.1
	Natural grassland	2.3	16.6	30.4	7.2	8.4
	Moors and heathland	6.6	23.6	11.3	1.2	6.5
	Transitional woodland scrub	0.5	1.9	3.6	1.3	2.2
	Peat bog	0.0	8.4	2.6	0.9	1.3
	Sparsely vegetated areas	0.0	4.1	0.2	0.0	0.0

The mostly easterly of the catchments, the Clwyd, is the third largest in terms of overall catchment area, with its headwaters in the Clocaenog forest and outlet to the Irish Sea at Liverpool Bay. It is largely agriculturally dominated (80.9%), with the majority of this being pasture (as is common in all catchments) at 71.6%; the largest proportion of land classed as urban (2.4%) is also found here. The Clwyd has the lowest maximum elevation of all of the catchments at 557 m, this is almost half the height of the same measurement in the neighbouring Conwy catchment; and is also the second least sloping on average, at 12.5%. In terms of hydrometric signatures, out of all of the catchments, the Clwyd has the lowest runoff ration (0.52), and conversely the highest baseflow index (0.59) and streamflow elasticity (1.28). These results show that the Clwyd is the most baseflow dominated of the catchments and has the largest proportion of total incoming precipitation exiting by evapotranspiration. The catchment is, however, still sensitive to changes in precipitation, of which it receives the least of all the catchments, the annual average being 977 mm. This precipitation has the most even split between seasons of all catchments, with autumn seeing the most (30.5%) and spring the least (20.1%).

The Conwy also flows into the Irish Sea on the north Wales coast, from its source in Snowdonia; indeed, the Snowdonia National Park area covers some 70% of the catchment. This mountainous terrain gives the Conwy the second largest mean slope value at 19.7% and the highest maximum catchment elevation, at 1062 m. This is also one of the highest rainfall areas in Wales, with the catchment receiving 1968 mm of precipitation per year on average, with only 44.1 rain free days per year, the lowest of those studied. The Conwy has the largest divergence in seasonal rainfall distribution, with 32.1% occurring in winter, compared to 18.2% in summer. Both the Conwy and the Dyfi differ from the other three catchments in that the main LULC is not agriculture. For the Conwy, scrub is the largest category (42.1%), with this being mainly moors and heathland (23.6%), and to a lesser extent, natural grasslands (16.6%). The Conwy also features the largest area of peat bog (8.4%), and, due to the mountainous terrain, 4.1% of land is sparsely vegetated. When looking at the catchment hydrometrics, it can be seen that these correspond with the morphometric, LULC and precipitation characteristics, giving the Conwy a flashy response. Runoff ratio is the highest of all catchments (0.93) and baseflow index the lowest (0.28), with streamflow elasticity the second highest, at 1.21, meaning the catchment is sensitive to changes in precipitation.

The Dyfi is the smallest catchment to be studied (507 km^2) and is situated in west Wales, flowing from the Aran Mountains in the east, to the Irish Sea. It is similar to the Conwy in many regards, especially in terms of LULC proportions, precipitation volume and regime, and morphometric parameters. In terms of LULC, the Dyfi has the lowest amount of urban (0.3%) and agricultural (30.0%) land of any of the study catchments, but the highest amount of forested land, at 21.5% (1.8% broadleaf, 18.9% coniferous, 0.8% mixed). Scrub land is the largest proportion (45.3%), but in contrast to the Conwy, a larger part of this is natural grassland (30.4%) than moors and heathland (11.3%). The Dyfi has the second highest single catchment elevation point in its headwaters, at 903 m as well as the steepest average slope (25.3%). Runoff ration is second only to the Conwy, at 0.89, with baseflow index being second lowest (0.38), the streamflow elasticity score is the lowest of all catchments (1.06), but is still greater than 1, suggesting that for a given change in precipitation, a greater change is seen in streamflow. This gives the catchment a flashy nature, with little baseflow contribution, little loss to evapotranspiration, and being small and steeply sloping. Annual mean precipitation total is 1803 mm, the second largest, with 61.1% of this falling in winter and autumn; the Dyfi also has the second largest number of rain free days per year, 52.1.

The Teifi, in south Wales, flows into Cardigan Bay from its source at Llyn Teifi, in the Cambrian Mountains. The catchment is the second largest of those studied (995 km^2), but also has the lowest maximum elevation, at 591 m, as well as the least steep mean catchment slope angle, 11.6%. The Teifi has the highest proportion of land classified as agricultural (83.0%) and conversely the lowest proportion of forest cover (5.5%) and scrub land (9.7%). These characteristics are similar to those seen in the Clwyd; it therefore follows that the hydrometric signatures of the Teifi are also similar to those seen in the Clwyd. Runoff ratio is 0.76 and streamflow elasticity is 1.09, both the second lowest of all five catchments; baseflow index is 0.54, the second highest in the study. As with the Clwyd, the characteristics of the catchment lead it to being less flashy in nature, in particular than the Conwy and Dyfi, but with streamflow still sensitive to changes in precipitation. The Teifi has the most rain free days of all catchments annually on average (55.7), with largest proportion of rainfall falling in autumn (31.2%) and least in spring (18.8%).

The Tywi, with its source roughly 15 km south of the Teifi's, is the largest catchment to be studied (1365 km^2); flowing from its source in the Cambrian Mountains to Carmarthen Bay, roughly 80 km of its length is designated as a special area of conservation. The river enters Llyn Brianne reservoir 10 km from its source; constructed in the 1970s the reservoir regulates the river in times of low flow, to ensure sufficient water for abstraction for PWS downstream. The majority of the Tywi is used as pasture (63.9%), with scrub and forested land being the next largest proportion of LULC (17.1% and 16.0% respectively). The catchment receives 1596 mm of rainfall annually on average, with 30.8% of this being in winter and 19.1% in spring; a mean 49.5 rain free days are experienced per year. The highest elevation in the catchment is 801 m, while the average slope is 16.6%, making it both the third highest and steepest catchment studied. Runoff ratio (0.80), baseflow index (0.48), and streamflow elasticity (1.17) values are all also mid-range when comparing the five catchments.

The bedrock geology of the catchments has been analysed using the British Geological Survey (BGS) Geology 625k (DiGMapGB-625) data set (BGS, 2019), with the majority in all catchments found to be mudstone, siltstone and sandstone in nature, ranging from 60% and 64% in the Clwyd and Conwy, to 87% in the Dyfi and Teifi, and 73% in the Tywi. The remaining bedrock in the Teifi and Tywi is made up of interbedded sandstone and conglomerate (13% and 27% respectively); this also makes up the second largest proportion of remaining bedrock in the other three catchments (Clwyd, 18%; Conwy, 17%; Dyfi, 12%). The majority of that remaining in the Dyfi and Conwy catchments is Felsic Tuff, at 1% and 12% respectively, while that remaining in the Clwyd is limestone with subordinate sandstone and argillaceous rock (16%), and siltstone and sandstone with subordinate mudstone (6%). While the bedrock of the Conwy, Dyfi, Teifi and Tywi has a low permeability, the limestone and sandstone deposits found under the Clwyd catchment are much more permeable (BGS, 2019).

As can be seen, the five catchments studied offer a variety of different catchment characteristics (morphometric parameters, hydrometric signature, LULC) which influence their hydrological regime, water quality, and response to precipitation. These characteristics and individual catchment response profiles could be important when considering future changes in climate and weather events, and the potential knock impacts this may have for catchments and water abstractors. As previously mentioned, each catchment is abstracted from for a variety of uses, these abstractions, except PWS, are shown in Figure 3.2 (PWS not shown due to data licence conditions prohibiting the identification of individual abstractions); with a breakdown in numbers by sector provided in Table 3.2.

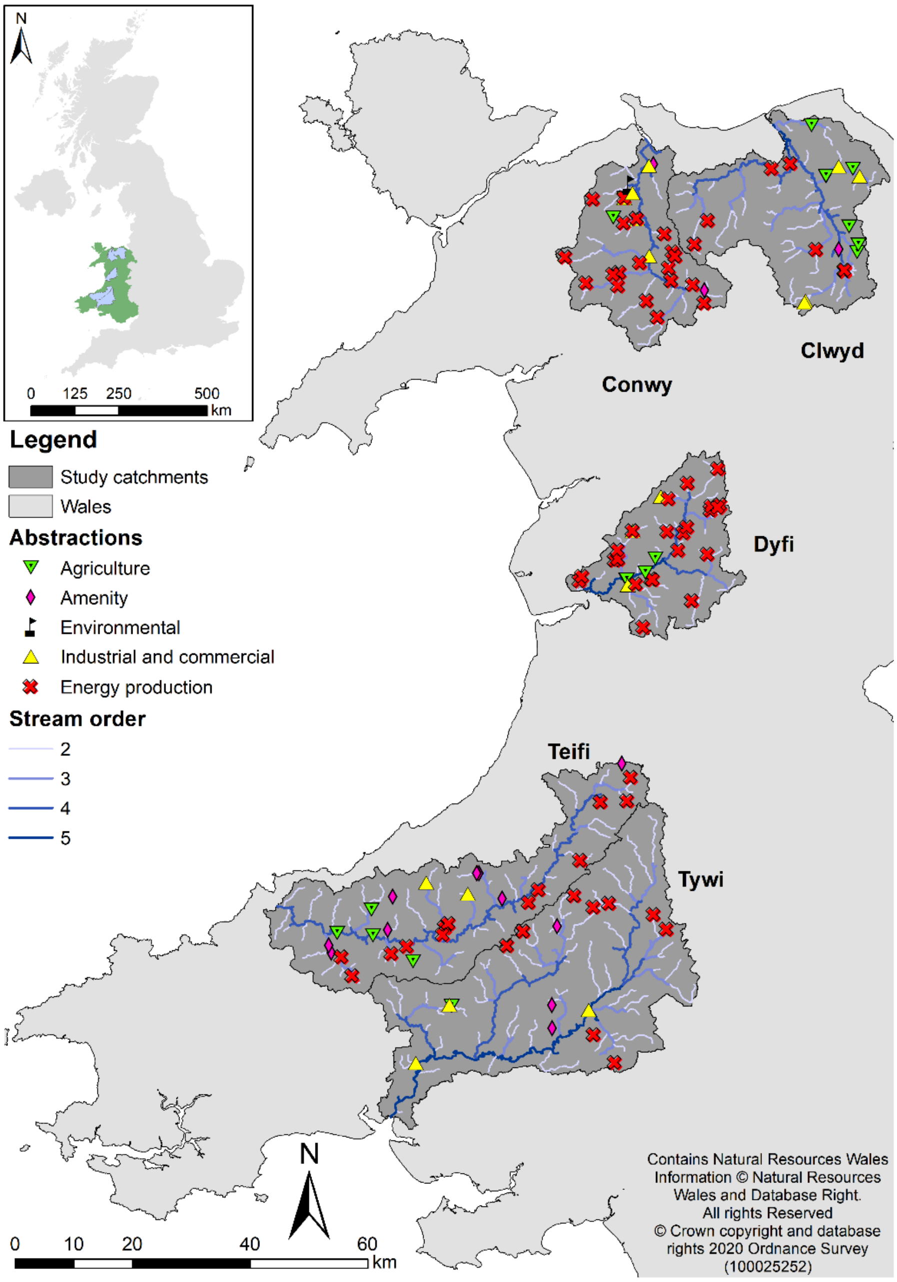

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Figure 3.2. Abstraction locations for the purposes of agriculture, amenity (e.g. land and pond throughflow), environment (e.g. wetland support), industrial/commercial, and energy production. Public water supply abstractions not shown due to dataset licence restrictions.

Table 3.2. Number of abstraction locations per sector for each catchment; 'water supply' includes both public and private water undertakings; 'energy production' accounts for both hydroelectric power and water used in other energy generation processes.

Catchment	Agriculture	Amenity	Environment	Industry/ commercial	Energy production	Water supply	Total
Clwyd	7	1		4	7	5	**24**
Conwy	2	2	1	5	20	5	**35**
Dyfi	4			4	23	11	**42**
Teifi	4	9		2	14	3	**32**
Tywi	2	3		4	10	3	**22**

3.3 Trend analysis

Long-term trend analysis of annual and seasonal datasets is a common thread throughout this thesis. In each of the three study chapters Mann-Kendall (MK) trend analysis (Mann, 1945; Kendall, 1975) has been used to detect the direction and statistical significance of trends in the meteorological, hydrological, water quality and water abstraction capability datasets studied. MK analysis is nonparametric and tests for a positive or negative monotonic trend in a time series based on the ranks of individual observations (Helsel & Hirsch, 2002). For a time series $X = [x_1, x_2, \dots, x_n]$, MK is calculated following Equations 3.6 to 3.10. Firstly, the test statistic, S, is calculated by Equation 3.6:

$$S = \sum_{i<j} a_{ij} \qquad \textbf{(Eq. 3.6)}$$

where a_{ij} is calculated as per Equation 3.7:

$$a_{ij} = sgn(x_j - x_i) = sgn(R_j - R_i) = \begin{cases} 1 & if\ x_i < x_j \\ 0 & if\ x_i = x_j \\ -1 & if\ x_i > x_j \end{cases} \qquad \textbf{(Eq. 3.7)}$$

where R_j and R_i are the ranks of observations x_j and x_i. Under the assumption that the dataset is independent and randomly ordered, Mann (1945) showed that S tends towards normality when $n \geq 8$, with the mean and variance of S being calculated as per Equations 3.8 and 3.9 respectively (Kendall, 1975):

$$E(S) = 0 \qquad \textbf{(Eq. 3.8)}$$

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \qquad \textbf{(Eq. 3.9)}$$

where n is the length of the time series. By comparing the standardised variable u with the standard normal variate at signficnace α, it is possible to test the significance of the trends, as in Equation 3.10:

$$u = \begin{cases} (S-1)/\sqrt{Var(S)} & for\ S > 0 \\ 0 & for\ S = 0 \\ (S+1)/\sqrt{Var(S)} & for\ S < 0 \end{cases} \qquad \textbf{(Eq. 3.10)}$$

However, the original MK test is vulnerable to false trend detection when dealing with autocorrelated data; that being data which displays a correlation with a lagged version of itself over a given time period (Hamed & Rao, 1998). This is common in hydrological and meteorological data due to the seasonality of the datasets. A modified MK test has therefore been performed, as per the Hamed and Rao autocorrelation correction method, the calculations for which are show in Equations 3.11 to 3.14 (Hamed & Rao, 1998). The variance of S is first recalculated as $V^*(S)$, as shown in Equation 3.11:

$$V^*(S) = Var(S) \times \frac{n}{n^*} = \frac{n(n-1)(2n+5)}{18} \times \frac{n}{n^*} \qquad \textbf{(Eq. 3.11)}$$

where n/n^* is a correction to $Var(S)$ (Equation 3.9) accounting for autocorrelations in the data and is calculated using Equation 3.12:

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i) \qquad \textbf{(Eq. 3.12)}$$

where $\rho_s(i)$ is the autocorrelation coefficient of the ranked data, expressed in Equation 3.13:

$$\rho_s(i) = \frac{\sum_{i=1}^{N-j}\left[(x_i - \overline{X})(x_{i+j} - \overline{X})\right]}{\sum_{i=1}^{N}(x_i - \overline{X})^2} \qquad \textbf{(Eq. 3.13)}$$

where N is the number of ranks of observations and $\overline{X}$ is the dataset mean. The result of Equation 3.11 allows for a modification of Equation 3.10, enabling significance testing which reflects the autocorrelation correction (Equation 3.14):

$$u^* = \begin{cases} (S-1)/\sqrt{V^*(S)} & for\, S > 0 \\ 0 & for\, S = 0 \\ (S+1)/\sqrt{V^*(S)} & for\, S < 0 \end{cases} \qquad \textbf{(Eq. 3.14)}$$

In addition, in order to better quantify the magnitude of the detected trends, Sen’s nonparametric slope estimator (Sen, 1968) has also been applied. This procedure estimates the slope of a linear trend in a sample of n pairs of data. Firstly, the slopes of the entire time series of data points, Q_i, are calculated using Equation 3.15:

$$Q_i = \frac{X_j - X_k}{j - k}\; for\; i = 1,2,\ldots,n \qquad \textbf{(Eq. 3.15)}$$

where X_j and X_k are data values at time-steps j and k. All Q_i values are then ranked smallest to largest, with median slope, Q_{med}, then being calculated as Equation 3.16:

$$Q_{med} = \begin{cases} Q_{[(n+1)/2]} & if\ n\ is\ odd \\ \left(Q_{[n/2]} + Q_{[(n+2)/2]}\right)/2 & if\ n\ is\ even \end{cases} \qquad \textbf{(Eq. 3.16)}$$

A negative Q_{med} result indicates a negative trend, with the opposite true for a positive trend; the value of the result indicates the steepness of the trend, the median absolute value change per time-step. To calculate if the median slope is statistically significantly different from zero, Equation 3.17 is used:

$$C_\alpha = Z_{1-\alpha/2}\sqrt{V^*(S)} \qquad \textbf{(Eq. 3.17)}$$

where $Z_{1-\alpha/2}$ is obtained from a standard normal distribution table and $V^*(S)$ is as defined in Equation 3.11.

These methods for trend analysis and slope detection were chosen because of their nonparametric nature, allowing for the detection of trends in datasets which are non-normally distributed and that display seasonality, unlike trend analysis methods such as linear regression (Jaiswal *et al.*, 2015). This is important when dealing with hydrological and meteorological data which often displays the characteristics aforementioned (Kundzewics & Robson, 2004). This combination of modified MK trend analysis alongside Sen's slope estimator, is a method that has been used extensively for similar studies as well as more generally for the analysis of trends in hydrological, meteorological and water resources data globally (Gocic & Trajkovic, 2013; Murphy *et al.*, 2013; da Silva *et al.*, 2015; Atta & Dawood, 2017); it was therefore deemed suitable for use in this work.

For all three studies, trend analysis has been conducted on mean values based on hydrological years (1st October to 30th September) and each individual season. Results for any given year, 2021 for example, therefore are based on data from the following time periods; annual: October 2020 to September 2021; winter: December 2020 to February 2021; spring: March to May 2021; summer: June to August 2021; and autumn: September to November 2021. As can be observed, due to the nature of hydrological years ending in the middle of autumn, there is a mismatch between seasons and annual data, this has no impact however on the measurement and detection of trends seasonally or annually.

3.4 Study 1: Historical analysis

3.4.1 Hydroclimatic data

For the first study (Chapter 4), a 34-year period (1982-2015) of daily air temperature, total precipitation, and streamflow volume data has been analysed for each of the five study catchments. This time frame corresponds with the most recent period of complete and reliable data available for all three datasets across all catchments, at the time of analysis. Thirty years is classically considered as the minimum required dataset length in order to carry out climatic analysis (IPCC, 2007), not allowing smaller timeframe variations and cycles to impact on observed trends. This is also the period suggested for use by the World Meteorological Organisation (WMO) in the assessment of climate norms (WMO, 2017). Given this, the parity of study period timing for each catchment was prioritised over additional study period length for any given catchment or dataset. This decision was made to ensure cross-comparability of results for all catchments, enabling interpretation of the impact of catchment location and characteristics on the observed trends.

Daily climatic data studied (air temperature and total precipitation) was obtained from the CHESS dataset (Robinson *et al.*, 2017) from the UK Centre for Ecology and Hydrology (CEH). This gridded dataset was chosen due to its complete coverage across Wales, especially when compared to data from individual meteorological stations, of which there are few with long, complete, and consistent records in the study region, leaving some catchments underrepresented. CHESS precipitation data is based on the CEH 1 km Gridded Estimates of Areal Rainfall (GEAR) dataset, which is an interpolated dataset based on meteorological station rainfall observations adjusted for topography, to provide full UK coverage (Keller *et al.*, 2015). Temperature data for CHESS is downscaled to a 1 km grid, also taking account of topographical data, from the 0.5 degree gridded Climate Research Unit Time Series, version 3.21 dataset (CRU TS3.21), which is also based on meteorological station observations (Harris *et al.*, 2014). In order to provide a single dataset of each climatic variable for each catchment, the mean value of all grid cells contained with a catchment was calculated for each day of the study period; it is this value, after inspection for anomalies, that has been used in the analysis described in the following section.

Daily streamflow data has been obtained from the UK National River Flow Archive (NRFA) for a single velocity-area gauging station in each catchment, as shown in Figure 3.1 (NRFA, 2020). The stations used were those with as close to a natural flow regime as possible, as well as a long record length, to allow for a more robust attribution of streamflow changes to external factors, as opposed to regulation or abstraction. For each station, a review of the station information, hydrometric description, and flow record and regime descriptions was undertaken, to ensure the record was appropriate and check for any required correction to the data. This investigation showed that no correction or action was needed for any of the flow records used, details of each gauging station are provided in Table 3.3.

Table 3.3. Details of gauging stations used throughout the thesis (NRFA, 2020).

	Station ID	Upstream area (km^2)	Station elevation (m)	Station opened	NRFA brief flow regime description
Clwyd	66001	404	15.3	1959	Low flows augmented by groundwater
Conwy	66011	345	11.6	1964	Largely natural
Dyfi	64001	471	5.9	1962	Natural to within 10% at Q_{95}
Teifi	62001	894	5.2	1959	Largely natural
Tywi	60006	130	7.5	1968	Natural to within 10% at Q_{95}

3.4.2 Hydroclimatic analysis

In order to best characterise any changes in the climatic and streamflow data, analysis was performed annually and seasonally (as described in Section 3.3) for both average and extreme temperatures, precipitation volumes and flows. Analysed time series are based on the WMO standard methods for annual, seasonal and multi-month calculations (WMO, 2017). For each season and year, mean flow, temperature and precipitation has been calculated for the analysis of averages. For the extreme analysis, 1-day maximum and minimum flow and temperature, as well as maximum precipitation total, for each season and year has been extracted; this characteristic was chosen to give an indication of the change in magnitude of extremes during the study period. Additionally, the number of days above and below the dataset 95th and 5th percentiles respectively has been calculated for streamflow and temperature, with analysis of precipitation only taking account of the former. This analytical method was chosen to give an understanding of the change in frequency of extremes.

The above extracted time series were first analysed using the aforementioned MK analysis methods. Subsequently, a breakpoint analysis has been performed on each of the historical average and extreme hydroclimatic times series, once again both seasonally and annually, to detect any abrupt changes during the study period. This analysis was performed in order to assist in the attribution of changes to known events that may have occurred in one or more catchments (e.g. damn construction or major LULC change or climate driver alteration). Two nonparametric methods of breakpoint analysis have been employed, Pettitt's test (Pettitt, 1979) and the Standard Normal Homogeneity Test (SNHT) method (Alexandersson, 1986; Alexandersson & Moberg, 1997). Pettitt's test has been shown to perform better at detecting changes in the middle of a time series, whereas SNHT performs more favourable at the start and end of a time series (Hawkins, 1977; Jaiswal *et al.*, 2015; Hänsel *et al.*, 2016). It was therefore decided to perform both tests to ensure the best coverage of potential breakpoints. Both methods detect changes in the value of the dataset mean and are location specific, therefore identifying the point of change within the time series, (Hänsel *et al.*, 2016).

Pettitt's test, for a time series $x_1, x_2, \ldots, x_n$, calculates the distribution function for time series data both before ($F_1(x)$) and after ($F_2(x)$) a breakpoint, t. The nonparametric test statistic, U_t, is calculated as per Equation 3.18:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} sgn(x_t - x_j) \qquad \textbf{(Eq. 3.18)}$$

Where n is the time series length and $sgn(x_t - x_j)$ is calculated by Equation 3.19:

$$sgn(x_t - x_j) = \begin{cases} 1 & if\ x_i < x_j \\ 0 & if\ x_i = x_j \\ -1 & if\ x_i > x_j \end{cases} \qquad \textbf{(Eq. 3.19)}$$

Equation 3.20 calculates the test statistic K, which is subsequently used in the calculation of the confidence level (ρ) for the given n, as in Equation 3.21, itself a term in the calculation of the approximate significance probability (p) of a breakpoint, in Equation 3.22:

$$K = Max|U_t| \qquad \textbf{(Eq. 3.20)}$$

$$\rho = exp\left(\frac{-K}{n^2 + n^3}\right) \qquad \textbf{(Eq. 3.21)}$$

$$p = 1 - \rho \qquad \textbf{(Eq. 3.22)}$$

The value of K is compared to a critical value based on the time series length, to determine whether the change is statistically significant (Jaiswal *et al.*, 2015).

SNHT compares the mean of the first n observations with the mean of the remaining observations $(n-k)$, in the calculation of the test statistic T_k, as shown in Equation 3.23:

$$T_k = kZ_1{}^2 + (n-k)Z_2{}^2 \tag{Eq. 3.23}$$

where Z_1 and Z_2 are calculated by Equations 3.24 and 3.25 respectively:

$$Z_1 = \frac{1}{k}\sum_{i=1}^{k}\frac{(x_i - \overline{x})}{\sigma x} \tag{Eq. 3.24}$$

$$Z_2 = \frac{1}{n-k}\sum_{i=k+1}^{n}\frac{(x_i - \overline{x})}{\sigma x} \tag{Eq. 3.25}$$

where $\overline{x}$ is the mean and σx is the standard deviation, of the series. T_k is the point at which there is maximum difference in value of the means of the proceeding and succeeding time series points. The value of the test statistic is compared to a critical value based on the time series length, to determine whether the change is statistically significant (Jaiswal *et al.*, 2015).

3.4.3 Water abstraction relationships

In addition to the analysis performed on the three hydroclimatic factors, an investigation of the relationship between these factors and total water demand has also been performed. The water demand data to enable this analysis has been obtained from Dŵr Cymru Welsh Water (DCWW) in the form of total daily abstraction for 22 abstraction points within the five study catchments. This daily total has been used as a proxy for overall PWS demand across all sectors and also takes account of leakage. The data was provided for just under five calendar years, from 1st January 2012 to 30th September 2016, however, due to the length of record available for the hydroclimatic data, analysis was only completed up to the 30th September 2015. The relationship between the three hydroclimatic factors and total abstraction has been characterised by both Pearson's & Spearman's rank correlation coefficients. This analysis has been conducted for both daily data, as well as monthly mean. Pearson's coefficient value (*r*) was computed using Equation 3.26:

$$r = \frac{\sum_{i=1}^{n}\left(hc_i - \overline{hc}\right)\left(abs_i - \overline{abs}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(hc_i - \overline{hc}\right)^2\right)\left(\sum_{i=1}^{n}\left(abs_i - \overline{abs}\right)^2\right)}} \qquad \textbf{(Eq. 3.26)}$$

where hc_i refers to the daily/monthly average hydroclimatic variables studied, abs_i refers to daily/monthly total abstraction volume, and $\overline{hc}$ & $\overline{abs}$ represent the mean of the entire respective datasets. The nonparametric Spearman's correlation coefficient (ρ) was calculated using Equation 3.27, a modified version of Pearson's correlation coefficient which calculates correlation between ranks, as opposed to raw data:

$$\rho = \frac{\sum_{i=1}^{n}\left(R(hc_i) - \overline{R(hc)}\right)\left(R(abs_i) - \overline{R(abs)}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(R(hc_i) - \overline{R(hc)}\right)^2\right)\left(\sum_{i=1}^{n}\left(R(abs_i) - \overline{R(abs)}\right)^2\right)}} \qquad \textbf{(Eq. 3.27)}$$

where $R(hc_i)$ refers to the rank of the daily/monthly average hydroclimatic variables studied, $R(abs_i)$ refers to the rank of the daily/monthly total abstraction volume, and $\overline{R(hc)}$ & $\overline{R(abs)}$ represent the mean rank of the entire respective datasets. These two complementary methods have been used to test for a linear trend, in the case of Pearson's, and a monotonic trend in the case of Spearman's rank. It was important to characterise the trend between abstraction and temperature in particular at this stage, in order for the relationship to be used in the research conducted in Study 3 (Chapter 6) which required the projection of future water demand based on climatic conditions.

3.5 Study 2: Hydrological modelling

3.5.1 Model selection

For the second study, future hydrological modelling of streamflow regime and water quality is the key focus. When selecting the hydrological model used for the study, several factors were taken into consideration while comparing multiple options. First, due to the size of the catchments to be studied, it was decided that a semi-distributed model was required, balancing greater computational efficiency, when compared to fully distributed models, with maintained representation of catchment characteristics, when compared with a lumped model (Suliman *et al.*, 2015). Second, the model needed to be operable at a continuous daily time-step in order to make use of the future climate input data, as well as enable analysis of extreme streamflows and events. It was also important for the model to be physically based, with both land and in-stream processes being modelled, and the ability to handle both water quantity and quality data. Several well-established hydrological models were considered, including, but not limited to, APEX (Williams & Izaurralde, 2010), MIKE-SHE (Refsgaard & Storm, 1995), SWAT (Arnold *et al.*, 1998), TOPMODEL (Beven, 1997), and VIC (Liang *et al.*, 1994). The decision was made to proceed with the Soil and Water Assessment Tool (SWAT) model, using the interface with QGIS for catchment delineation and model setup. SWAT was chosen after a review of several studies comparing the performance of different hydrological models (Yang *et al.*, 2000; El-Nasr *et al.*, 2005; Golmohammadi *et al.*, 2014; Suliman *et al.*, 2015; Kauffeldt *et al.*, 2016), with SWAT performing favourably in these, especially for low flows which are important to the latter stages of the research, where future water availability is assessed. Additionally, SWAT is well supported by the model development team, offering trouble-shooting support as well as training workshops. This, coupled with the user-friendly nature of the model interface which eliminates the need for high level computer coding, was important, as the research was not being undertaken by an experienced modeller.

As was required by the model selection process, SWAT is a physically based, semi-distributed, continuous time-step model, which operates at a catchment scale. The model makes use of sub-basins, which are further sub-divided into hydrological response units (HRUs), these are lumped areas of unique LULC, soil, and slope configuration. The output from each HRU is routed to the corresponding sub-basin, and eventually the reach outlet (Neitsch *et al.*, 2011). Hydrological processes modelled by SWAT are precipitation, evapotranspiration, infiltration, plant uptake, soil moisture redistribution, surface runoff, lateral flow, percolation to and revap from the shallow aquifer, return flow and recharge of the deep aquifer, these are shown in Figure 3.3 (Neitsch *et al.*, 2011). In terms of in-stream processes related to water quality, the model allows for point sources of pollution to be added, as well modelling diffuse sources based on the LULC data provided. In addition, dissolved and particle transport is modelled, along with bed/bank erosion, sorption of pollutants onto sediments, biogradation and transformation, and dilution, diffusion, deposition, accumulation and resuspension of pollutants, as shown in Figure 3.4 (Neitsch *et al.*, 2011). Owing to the extensive number of modelled processes, the continued development of the model over more than two decades, and its ability to operate in ungagged basins, SWAT has been used extensively for the assessment of climate change impacts on water quantity (Qiao *et al.*, 2014; Coffey *et al.*, 2016; Perra *et al.*, 2018; Sultana & Choi, 2018; Yuan *et al.*, 2019) and quality (Nerantzaki *et al.*, 2016; Yang *et al.*, 2017; Pesce *et al.*, 2018; Jilo *et al.*, 2019) globally.

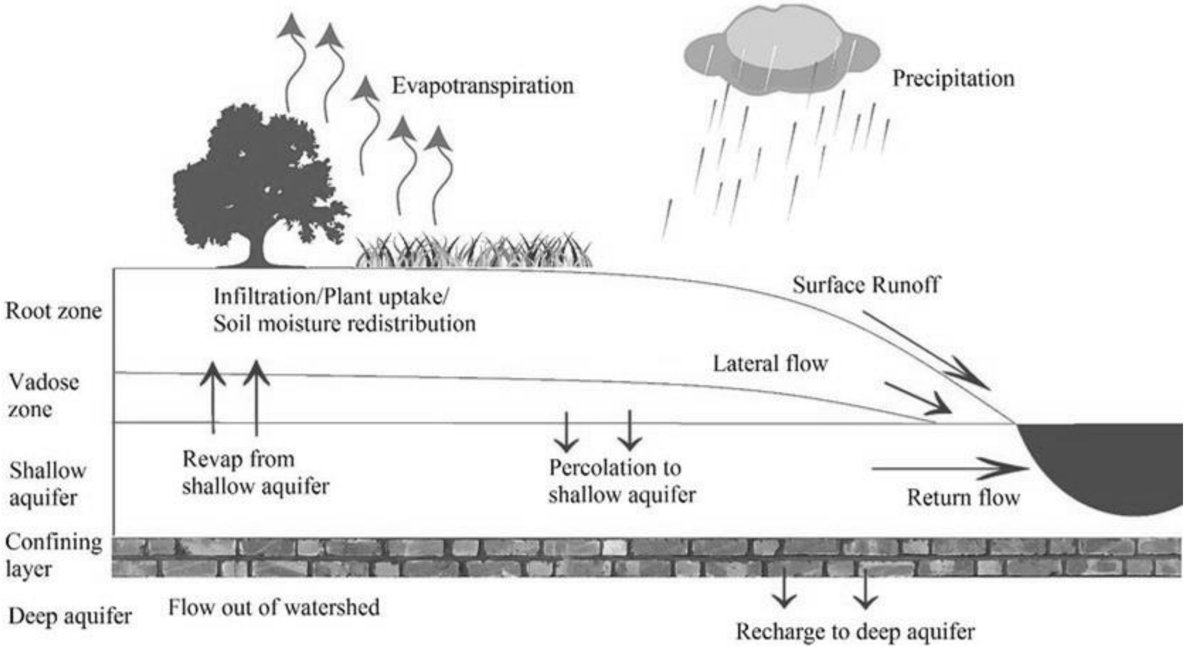

Figure 3.3. Representation of the processes modelled in the land phase of SWAT (Neitsch *et al.*, 2011).

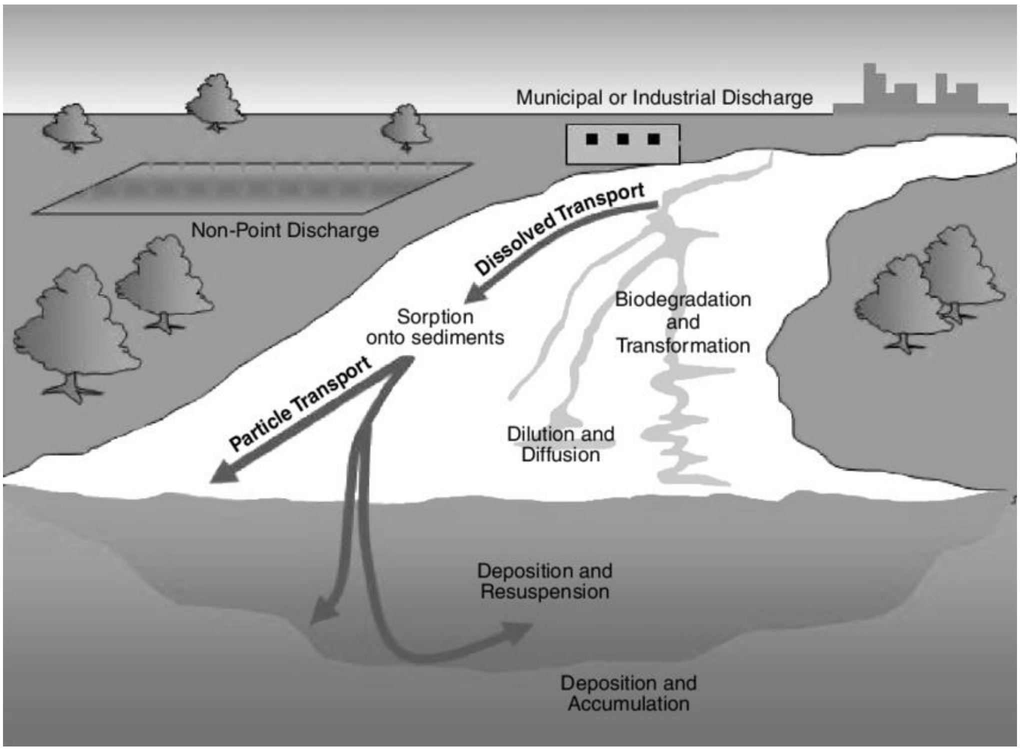

Figure 3.4. Representation of the processes modelled in the in-stream phase of SWAT (Neitsch *et al.*, 2011).

3.5.2 Model setup, calibration and validation

SWAT requires three key data inputs for initial model setup, these being elevation, LULC, and soil. In terms of elevation data, the OS Terrain 5 DEM from Ordnance Survey (Ordnance Survey, 2020) has been used. This high-resolution raster dataset, with a 5-metre post spacing (Ordnance Survey, 2017), was chosen in order to provide the most accurate catchment delineation and water routing as possible, as well as maintaining computational efficiency for the size of catchments studied. In terms of LULC, data from the CORINE Land Cover 2012 dataset (Copernicus Land Monitoring Data; EEA, 2012) was chosen due to the close match of LULC categories between it and the pre-exiting SWAT LULC categories, allowing for easy input to, and interpretation by, the model. The CORINE dataset is accurate spatially to within 25 metres, with a minimum mapping unit of 25 hectares for areal features and width of 100 metres for linear features; the accuracy of identified LULC type is greater than 85% (EEA, 2017). The dataset is generated by computer assisted photointerpretation of IRS P6 LISS III and RapidEye satellite data (EEA, 2017). Soil data was obtained from the EU soil database version 2.0, specifically the Soil Geographical Database of Eurasia, a 1:1,000,000 scale vector dataset (European Commission, 2004). The calculation of SWAT soil parameters was completed using the Pedo Transfer Function developed by Saxton & Rawls (2006), based on the characteristics associated with the given World Reference Base for Soil Resources (FAO, 1998) classification of each soil type. This dataset was used based on research and the suggestion of the SWAT model developers, having accurate and full coverage for the study area, being in a format that is easily transferable to SWAT, and having been used in the model successfully previously.

Initial setup of the SWAT model starts with catchment delineation from a DEM, this process first develops the stream network, based on the standard procedure (Martz & Garbrecht, 1992) of filling sinks in the DEM, calculation of flow direction using the D8 algorithm for each pixel, and calculation of flow accumulation; a stream formation threshold of 1 km^2 was used at this stage. The user then adds any additional inputs of water, reservoirs, pollution point sources and watershed outlets. For the purposes of this research, reservoirs have been ignored, partly due to the gauging stations used for model calibration being located on streams that are largely unaffected by upstream regulation, and partly due to the complex nature of reservoir operation in SWAT, for which insufficient data was available to properly model. Outlets can operate as water abstraction locations, aside from the furthest outlet downstream, which is classified as the final watershed outlet, for this reason, outlets were added at all PWS abstraction and HEP inlet locations in each catchment, to later enable analysis of future water abstraction potential at each location. Watershed boundaries are then delineated by SWAT, followed by subbasins, and then by HRUs therewithin, which are defined based on homogenous areas of LULC, soil and slope.

Historical weather data was added to the model to enable an initial SWAT run, this was then followed by calibration. The historical daily temperature and precipitation data used was the same as that for Study 1, from CHESS, here used for the period 1982 to 1998, with a 3-year model warm-up period. Weather data input for the model was based on single daily values of temperature and precipitation for each catchment, based on the mean of the gridded data, as before. Calibration was completed for each catchment individually, for streamflow only, using NRFA historical daily streamflow, also as in Study 1. The particle swarm optimisation (PSO) method was used to perform a multi-parameter calibration in the SWAT calibration and uncertainty programme 2012 (SWAT-CUP). A total of 17 parameters (Table 3.4) were calibrated simultaneously, these were selected based on a literature review of studies operating in similar catchment types, as well as on the advice of SWAT model developers.

Table 3.4. SWAT parameters calibrated through SWAT-CUP using the particle swarm optimisation method.

Parameter	Description	Input file location
ESCO	Soil evaporation compensation factor	.bsn
EPCO	Plant uptake compensation factor	.bsn
SURLAG	Surface runoff lag time	.bsn
GW_Delay	Groundwater delay	.gw
Alpha_BF	Baseflow alpha factor	.gw
GWQMIN	Threshold depth of water in shallow aquifer for return flow to occur	.gw
RCHRG_DP	Deep aquifer percolation fraction	.gw
REVAPMN	Threshold depth of water in shallow aquifer for "revap" to occur	.gw
GW_REVAP	Groundwater "revap" coefficient	.gw
ALPHA_BF_D	Baseflow alpha factor for deep aquifer	.gw
CANMX	Maximum canopy storage	.hru
CN2	SCS runoff curve number for moisture condition 2	.mgt
CH_N2	Manning's "n" value for the main channel	.rte
CH_K2	Effective hydraulic conductivity in main channel alluvium	.rte
SOL_AWC	Available water capacity of the soil layer	.sol
SOL_K	Saturated hydraulic conductivity	.sol
SOL_Z	Depth from soil surface to bottom of layer	.sol

PSO is a complex but highly efficient method of calibration, capitalising on swarm intelligence which takes inspiration from flocking birds (Kennedy & Eberhart, 1995). In this example, a flock of birds is searching a set area for a single food source, while no bird knows the exact location of the food, they are all aware of their individual distance from it, as well as the closest themselves and the group as a whole has come to it. The optimal solution for efficient identification of the food source is to learn from the group, travelling in the direction of the location identified as closest to the food (Lee *et al.*, 2008; Abbaspour, 2014). This theory can be applied to parameter calibration, with birds being substituted for particles searching for the optimal parameter value within a given range (search space), to satisfy a goodness-of-fit metric (Qi *et al.*, 2015). The group is initialised with each particle in the swarm randomly assigned a position and velocity, the initial locations are evaluated for model fit, and these automatically become each particles' current best solution. The group's best solution is set at the value of the particle with the best fit of all particles. The individual particles then iteratively work towards, with a random function, a combination of their own and the groups best known position (Qi *et al.*, 2015). For example, for a given particle, a, at a given iteration, i, the velocity (v) for the next iteration v_a^{i+1} is updated by Equation 3.28 (Lee *et al.*, 2008):

$$v_a^{i+1} = wv_a^i + c_1 r_1 \left(p_a^i - x_a^i\right) + c_2 r_2 \left(p_g^i - x_a^i\right) \qquad \textbf{(Eq. 3.28)}$$

where w is an inertia factor for control of movement; c_1 and c_2 are acceleration coefficients which attract the particle in the direction of the local and global best positions respectively; and r_1 and r_2 are randomly generated, uniformly distributed variables between 0 and 1. The current velocity and position of particle a is represented by v_a^i and x_a^i, with p_a^i and p_g^i representing the location of the current best found position of a and the group (g), respectively. The position of a is then updated by Equation 3.29 (Lee *et al.*, 2008):

$$x_a^{i+1} = x_a^i + v_a^{i+1} \qquad \textbf{(Eq. 3.29)}$$

This cycle continues until either the objective function value is met, or the maximum number of iterations is reached. The method is highly efficient due to swarm intelligence, which enables a complex search to take place, with individual particles undertaking only simple search patterns (Xia *et al.*, 2018). This approach allows for faster centring upon the optimal solution, when compared with other calibration methods (Abbaspour, 2014) this was one of the key reasons for selecting this method. A total of 100 model runs were undertaken per catchment for this research, with ten particles undergoing ten iterations; in all cases a satisfactory objective function value had been reached at this point. The objective function used in this work was the Kling-Gupta efficiency (KGE; Gupta *et al.*, 2009), with the parameter values from the PSO iteration with the highest KGE being taken forward for implementation into SWAT. Equation 3.30 details the calculation of KGE:

$$KGE = 1 - \sqrt{(r-1)^2 + (a-1)^2 + (\beta-1)^2} \qquad \textbf{(Eq. 3.30)}$$

where r is the linear correlation between observations and simulations; α refers to the ratio between the standard deviation in the simulated flow and the standard deviation in the observed flow; and β is the ratio between the mean simulated and mean observed flow. Once calibrated parameter values had been finalised, these were checked to ensure that they were still within a range of what would be expected and acceptable for the catchment, so as to ensure that no over-parametrisation had occurred. These values were then updated within the SWAT databases and the newly calibrated model was validated against observed daily streamflow for the period 1999 to 2014, again with a 3-year model warm-up period. Calibration and validation KGE results for each catchment are shown in Table 3.5.

Table 3.5. Kling-Gupta efficiency (KGE) calibration and validation values for comparison of gauged and modelled daily mean streamflow for each catchment.

Catchment	Calibration KGE	Validation KGE
Clwyd	0.810	0.788
Conwy	0.770	0.718
Dyfi	0.788	0.728
Teifi	0.851	0.723
Tywi	0.841	0.717

In terms of water quality, four factors have been studied, suspended sediment, total nitrogen, total phosphorous and dissolved oxygen. These factors were chosen based on the available and reliable outputs achievable in SWAT, observation data availability for output validation, as well as their importance to overall stream water quality, aquatic life, and water abstractors. While the inclusion of other factors, such as coliforms, persistent bacteria, and dissolved organic carbon, was considered, these ultimately fell short of one or more of the selection criteria, so were deemed unsuitable. Due to a lack of sufficient historical data for any of the four factors, it was not possible to calibrate the model for water quality. A validation has been carried out however, with model output being compared with data taken from the Natural Resources Wales (NRW) water quality data archive held in WISKI (NRW, 2019b). This dataset provides occasional, and often temporally randomly distributed, data points on each of the four factors, for the period 2000-2010. Sampling frequency varies from monthly to as infrequently as once per year, with sampling rate generally increasing towards the end of the time period in all catchments, Table 3.6 summaries the number of samples available for each factor and catchment. The samples were mostly collected by NRW to check compliance with EU directives, so there is a high confidence in the dataset reliability and consistency; for this reason, and following an inspection of data for obvious outliers, no correction or alteration was made to the data. A single sampling location for each catchment was chosen (shown in Figure 3.1), with the aim of maximising the number of data points and, where possible, ensuring coverage for all four factors. Unfortunately, the latter aim was only fully achievable in three of the five catchments, with no observations recorded for total nitrogen at the Conwy or Dyfi sampling locations. Validation, where possible, took the form of the calculation of Person's correlation coefficient values between simulated and observed data points, to give an indication of the agreement in the datasets.

Table 3.6. Total samples used in the validation of studied water quality factors in SWAT.

Catchment	Number of samples			
	Suspended sediment	Total phosphorous	Total nitrogen	Dissolved oxygen
Clwyd	85	63	63	84
Conwy	118	83	0	106
Dyfi	105	85	0	104
Teifi	82	74	75	82
Tywi	23	19	79	22

3.5.3 Future model runs

With calibration and validation successfully completed, future daily weather data could be implemented into the catchment models. Section 3.1 details the rationale behind the selection of RCP8.5 as the future global GHG emissions scenario under which the future streamflow and water quality assessment was conducted. Future daily temperature and precipitation data, generated under RCP8.5 conditions, was obtained from the Met Office Hadley Centre's (MOHC) UK Climate Projections 2018 (UKCP18) dataset, specifically the

'Regional Projections on a 12 km grid over the UK for 1980-2080' (MOHC, 2018b). UKCP18 data was selected for use as the latest and most comprehensive projections for the UK. The regional projections in particular were chosen as the dataset with the finest spatial scale, at the time of implementation into SWAT, which takes account of regional-scale landscape features, allowing for a local level analysis (Murphy *et al.*, 2018). This dataset is an update to the previous version (UKCP09), which incorporates improved representation of extreme events as well as greater spatial resolution (MOHC, 2018b), both important to the analysis in Studies 2 and 3. The dataset consists of an ensemble of twelve member models, each of which has been dynamically downscaled from the 60 km gridded HadGEM3-GC3.05 global coupled model perturbed parameter ensemble (Murphy *et al.*, 2018). Each of the ensemble members differs due to natural climate variability as well as uncertainty in the projections (Kendon *et al.*, 2019). Input weather data was inspected for obvious outliers or anomalous entries before use in SWAT, with no other corrections or alterations undertaken on the data.

To enable the implementation of the UKCP18 data into SWAT, it was necessary to convert the gridded data to points, with a point at the centre of each 12 km grid being assigned that grid's daily climate variable values, and termed a pseudo-meteorological station. A total of 28 grid squares for which the central point lay within one of the five catchments were identified; a subset of thirteen of these were taken forward to be used as pseudo-meteorological stations (Figure 3.5). This selection was required because of the substantial time and computational requirement of extracting daily weather data values from the supplied NetCDF format, to allow for implementation in SWAT. Station selection was completed with the aim of ensuring a good coverage both spatially, as well as in terms of elevation, which is particularly important in SWAT for temperature and precipitation variation based on elevation and topography. While narrowing down the number of stations may limit the representation of variability due to elevation, this was mitigated in four of five catchments, those which share a boundary (Clwyd with Conwy, and Teifi with Tywi), as pseudo-meteorological station data from both catchments was made available to each individual model, increasing data coverage while maintaining computer resource efficiency. As the Dyfi has no neighbouring catchments that have been modelled in this study, this catchment has the highest density of stations, to ensure the best coverage possible (Figure 3.5).

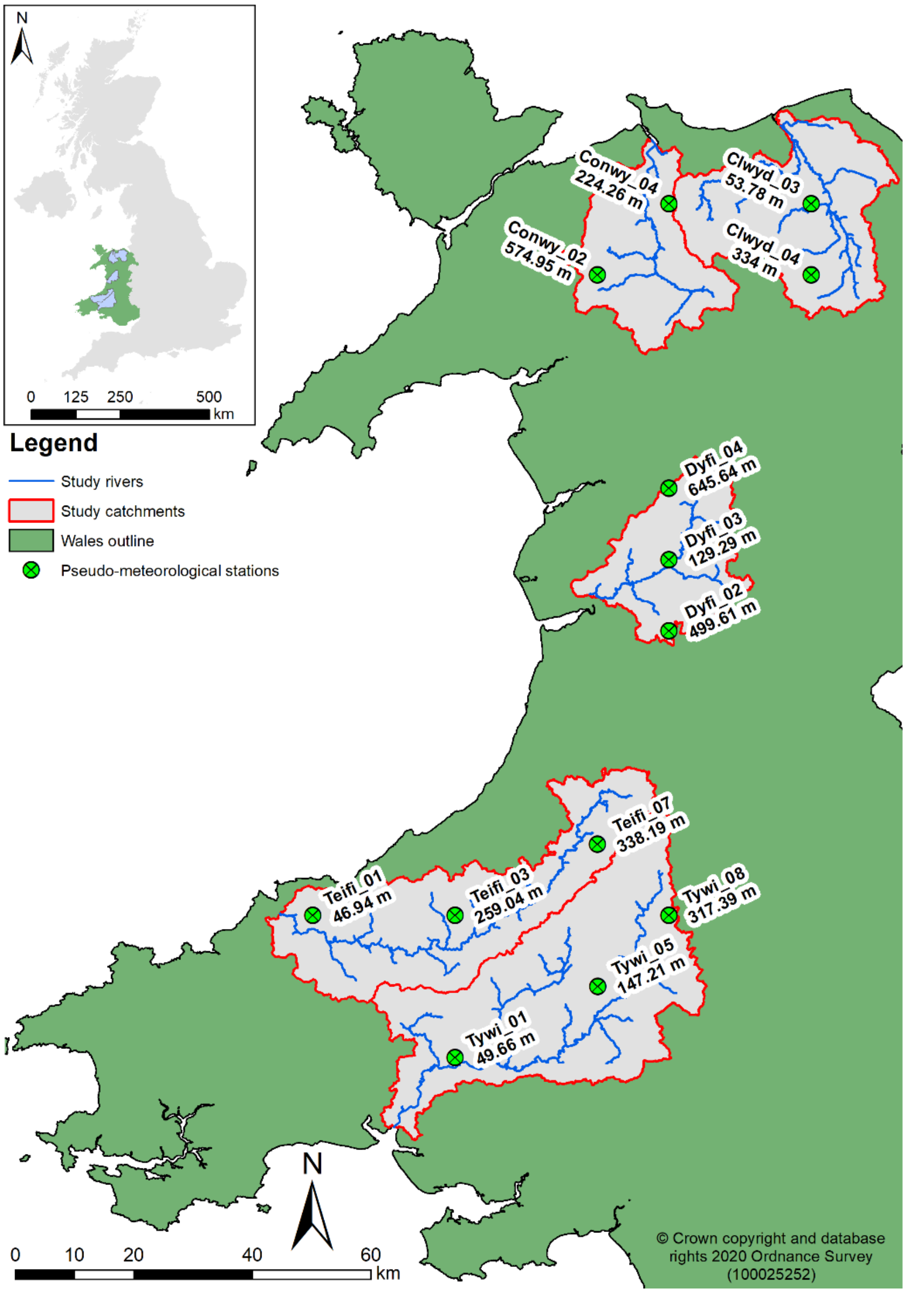

Figure 3.5. Pseudo-meteorological stations used in the implementation of UKCP18 future weather data into SWAT, elevation in metres shown below station name.

Future modelling at a daily time-step was completed for the hydrological years 2021-2080, with each of the five catchments being modelled for each of the twelve ensemble members. This approach has been taken to account for some of the uncertainty in the projections, allowing for an envelope of potential future streamflow and water quality changes under RCP8.5 conditions to be established, as well as an ensemble mean. Due to the size of the catchments studied, and limits set upon the size of Microsoft Access databases, which are used to store the model output, model runs for the 60-year period had to be split in to multiple periods; as many as four, 15-year periods for the largest catchments (Table 3.7). To counteract as far as possible any discontinuity in the output at these breaks, a 7-year model warm up period was used before the start of each period. In order to further mitigate disjointedness in model outputs, as few breaks as possible were used in each catchment, therefore smaller catchments are split into fewer, longer periods (Table 3.7), in this way individual dataset continuity was prioritised above overall approach consistency.

Table 3.7. Catchment SWAT model characteristics and run period information.

Catchment	Total sub-basins	Total HRUs	Number of model periods	Model period length	Model period break points
Clwyd	302	697	3	20 years	2041, 2061
Conwy	202	770	2	30 years	2051
Dyfi	227	662	2	30 years	2051
Teifi	425	1333	4	15 years	2036, 2051 2066
Tywi	496	1697	4	15 years	2036, 2051 2066

3.5.4 Data analysis

Trend analysis has been conducted for seasonal and annual average streamflow and water quality factor output, using the mean of the outputs of all 12 model runs. The method used for analysis is the same as for Study 1, MK trend analysis, as detailed in Section 3.3. The method used to characterise low flows also remains as conducted in Study 1; the analysis of high flows, however, has been modified. The characterisation of extreme high flows for Study 2 takes account of discrete high flow events, to give a better understanding of how such events are changing in magnitude and frequency, as well as duration. In the previous analysis, change in the number of days per year/season when streamflow exceeded the dataset 95th percentile was analysed. In this study, it is the number of events per year/season with at least one day of flow above the 60-year 95th percentile, which are analysed, where a single event could have several days above the 95th percentile. This method helps to mitigate the impact that multi-day high flow events could have on the analysis, which could potentially give the impression that high flow events are becoming more frequent, as opposed to longer in duration and magnitude. By identifying individual events, the analysis of individual event duration and frequency is also therefore possible. Individual events were classified as starting and ending when streamflow was equal to baseflow; this method was selected as it enabled multi-peak events to be easily identified. Baseflow was calculated by the digital filter method as defined by Sawicz *et al*. (2011) and presented in Equations 3.2 and 3.3 in Section 3.2.

3.6 Study 3: Future water availability analysis

3.6.1 Study area and analysis framework

The third study uses the Conwy and Tywi only, in the analysis of the impact of modelled streamflow changes from Study 2 on PWS and HEP. These two catchments were chosen due to their contrasting physical characteristics (Section 3.2, Table 3.1), especially in terms of LULC, slope, and catchment area, enabling investigation of the impact of these differences on catchment water resources. In addition, both catchments host several non-impoundment run-of-river HEP schemes, suitable for the analysis undertaken in this study, sixteen in the Conwy and nine in the Tywi (NRW, 2019c). Furthermore, the Tywi also contains the single largest river-based PWS abstraction location found in any of the five catchments. Indeed, it supplies the largest water treatment works in all of DCWW's network, producing water for over 400,000 consumers, therefore a highly important strategic asset (DCWW, 2019a).

Daily streamflow data for the analysis has been taken from Study 2, with the mean of all 12 model runs dataset for each catchment being used. The mean dataset has been used for computational efficiency, especially considering the scenario analysis conducted for PWS (details below) and the number of HEP locations studied. While this method does remove the ability to give a range of potential future outcomes, the results are still able to provide a sufficient picture of the future situation and the challenges likely to be faced.

For both HEP and PWS, MK trend analysis of the studied characteristics (described below) was undertaken for both a medium-term and long-term scenario. The medium-term scenario spanned the years 2021-2054, a useful study period for both industries. For HEP, this is the regular life span of small-scale systems, such as those studied here, that have been installed recently or are to be installed in the near future (Hatata *et al.*, 2019; Killingtveit, 2019). For PWS, the timeframe covers the period of focus of DCWW's most recently published water resource management plan (DCWW, 2019a), as well as their vision document to 2050 (DCWW, 2018). The long-term scenario (2021-2079) gives an indication of the far-future challenges faced by both industries and the potential future adaptation needs.

3.6.2 Hydroelectric power

Calculation of the ability of future streamflows to power run-of-river HEP installations in the Conwy and Tywi was undertaken manually, using new methods developed for this study. Abstraction conditions for the total 25 schemes identified from a dataset of licensed abstractions, provided by NRW (NRW, 2019c), were first set as per the general licensing guidelines for HEP schemes, set out by NRW (NRW, 2020b). These guidelines were used due to a lack details pertaining to the actual abstraction conditions placed on the individual schemes studied. They are, however, a good proxy, as these are commonly applied, aside from in situations where specific environmental, ecological or other concerns require more stringent abstraction conditions (NRW, 2020b).

The guidelines set out several conditions relevant to the analysis of this study, these being the hands-off-flow (HoF; streamflow volume below which abstraction is not permitted), maximum daily abstraction volume (A_{max}), and percentage take (Q_{take}; proportion of flow between HoF and A_{max} permitted for abstraction). Two parallel sets of guidelines exist, depending on the gradient of the stream section between which water is abstracted, and returned (NRW, 2020b). While HoF volume is the same for both (set at Q_{95}; streamflow volume exceeded 95% of the time), A_{max} and Q_{take} differ. Schemes with a depleted reach where the slope is less than 10% are classed as 'Zone 2' (Z2), while those with a depleted reach slope greater than 10% are classed as 'Zone 3' (Z3). Z2 schemes have an A_{max} volume of 1.3 times mean annual streamflow, whereas for Z3 schemes, this is less, being set at the mean annual streamflow. Conversely, Q_{take} is lower in Z2 schemes than Z3, being 50% and 70% respectively (NRW, 2020b). Due to the fact that individual characteristics of the schemes studied were not known, the depleted reach slope has been estimated for each scheme, based on the slope of the subbasin immediately downstream of the abstraction location. While not a perfect approximation, this method does give a good indication of the situation of each scheme, allowing for the best decision to be made upon zone classification.

With the scheme classification and associated abstraction conditions of each scheme in mind, the calculation of daily abstraction (A_{daily}) for each scheme was executed by Equations 3.31 and 3.32, develop for this study. These calculations operate under the assumption that each HEP scheme abstracts the maximum amount of flow allowable:

$$Q_{surplus} = Q - HoF \quad \textbf{(Eq. 3.31)}$$

where $Q_{surplus}$ is the amount of water available for abstraction, Q is daily streamflow, and HoF represents the hands-off-flow; the result is used in the calculation of A_{daily}:

$$A_{daily} = \; Q_{surplus} \times Q_{take} \begin{cases} 0, & if\ A_{daily} < A_{start} \\ A_{max,} & if\ A_{daily} > A_{max} \\ A_{daily,} & if\ A_{start} < A_{daily} > A_{max} \end{cases} \quad \textbf{(Eq. 3.32)}$$

where Q_{take} is the proportion of flow available for abstraction as per the zone conditions, A_{start} refers to the minimum abstraction volume required to start, and for efficient operation of, the turbine, and A_{max} represents the maximum permitted abstraction volume. It has been assumed that an impulse turbine is in use at each site, as is common with small-scale HEP schemes in upper catchment reaches, such as those analysed in this study (Lilienthal *et al.*, 2004; Cobb & Sharp, 2013; Židonis *et al.*, 2015). Impulse turbines have largely high and stable efficiency after approximately 10% of designed flow is achieved (Paish, 2002; Novara & McNabola, 2018; Chitrakar *et al.*, 2020), making them ideal for settings with variable daily abstraction (Cobb & Sharp, 2013). For this reason, A_{start} was set at 10% of A_{max} for each scheme, which has been assumed as the designed flow volume.

Four factors have been studied in the analysis of the impact of future streamflow changes on HEP operations, these being, the number of days A_{start} is achieved, the number of days A_{max} is reached, mean daily abstraction on days A_{start} is achieved, and total abstraction. These factors have been calculated annually and seasonally for each scheme. The mean of all combined Z2 and Z3 schemes in each catchment has then been calculated separately, with MK analysis conducted on these mean datasets, allowing for a comparison of the response both between catchments, as well as between scheme classifications. The four factors chosen for analysis were selected in order to provide as complete a picture as possible in terms of the potential change in future HEP scheme operation and power generation.

3.6.3 Public water supply

Assessment of the ability of future streamflows to satisfy PWS demand at the previously referenced abstraction location in the Tywi has been undertaken using the Water Evaluation And Planning (WEAP) system (Yates *et al.*, 2005). This programme was chosen due to its ability to easily implement different scenarios and compare the results; this was important as the assessment of three future water demand scenarios was being undertaken. The three scenarios studied are based on an increasing, static, and decreasing future PWS demand, with demand data being derived from the 5-year PWS abstraction dataset provided by DCWW and used in Study 1. This data has been taken as a proxy for total water demand and leakage.

Future daily water demand under the increasing demand scenario was based on the linear relationship established in Study 1 between daily temperature and daily total abstraction from the abstraction location studied on the Teifi. This relationship has then been extrapolated and applied to the mean daily temperature of the three pseudo-meteorological stations positioned within the Tywi for the SWAT modelling. The daily temperature relationship was chosen as the predictor of future demand because of the difficulty that would be encountered if using the daily precipitation relationship, due to the presence of days without rainfall, which is likely to skew the data. This scenario represents a worst-case in terms of future demand, with no effort made to reduce demand or combat leakage. The static scenario represents a control dataset and presumes abstraction rates stay constant at present levels. Present levels were established by calculating mean demand on each day of the year from the 5-year dataset provided by DCWW. This year of mean daily demand was then repeated yearly for the full period of study. Finally, the decreasing demand scenario is based on a projection by DCWW for a 20% decline in total water demand from the Tywi catchment by the end of the study period, due to a decline in domestic demand and reduction of network leakage (DCWW, 2019a). The decreased demand scenario starts with the same base year as is used and repeated in the static scenario, with the 20% decline being applied linearly across the full 60-year study period and represents an optimistic scenario of substantial demand reduction and therefore abstraction requirement. The three scenarios chosen represent a wide range of future demand levels, enabling a broad assessment of future climate change impacts on abstraction capability.

The daily ability of future streamflow to satisfy the volume of demand set out in the three scenarios, has been assessed based on the abstraction license conditions under which the abstraction operates. The main condition in the license is a compensatory HoF, set at 681.91 million litres per day (SWWRA, 1965); this volume was incorporated into WEAP and total daily unmet demand (D_{unmet}) was then calculated for each scenario, using Equation 3.33:

$$D_{unmet} = Q - HoF - D \qquad \textbf{(Eq. 3.33)}$$

where D is daily total water demand; and Q and HoF are defined as Equation 3.31. At times of low flow, the abstraction licence allows for releases to be made from Llyn Brianne reservoir, in the upper reaches of the catchment, which can subsequently be abstracted downstream, up to a given limit. Due to this mechanism, D_{unmet} is therefore also assumed to be equal to the total daily required reservoir release. MK trend analysis for PWS has been undertaken seasonally and annually on three characterises of D_{unmet} for each future demand scenario and for the medium- and long-term. Total volume of unmet demand per season/year, number of days per season/year when demand is unmet, and mean annual/seasonal unmet demand have all been calculated. These three characteristics have been chosen as they provide a good overview of the changes and challenges faced in the future supply of water, in the catchment. They indicate, amongst others, the potential future volumes of water required to be released from Llyn Brianne, the frequency with which release may be required, and the mean volume of release per day when compensation of flows is needed. All of these have important implications for water resource and reservoir management.

CHAPTER 4: STUDY I

Influence of historical climate patterns on streamflow and water demand in Wales, UK

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Prysor Williams: writing – review & editing, supervision

4.1 Abstract

Ensuring reliable drinking water supplies is anticipated to be a key future challenge facing water service providers due to fluctuations in rainfall patterns and water demand caused by climate change. This study investigates historical trends and relationships between precipitation, air temperature and streamflow in five catchments in Wales, before correlating these with actual total abstraction data provided by the water company, to give insight into the supply-demand balance. Changes in seasonal and annual averages, as well as extreme events, are assessed for a 34-year period (1982-2015) and a breakpoint analysis is performed to better understand how climate has already changed and what this might mean for the future of water supply. Results show a north-south divide in changes in extreme temperature and streamflow; a strong warming trend in autumn average temperatures across Wales (Sen's slope range: 0.38-0.41, p <0.05), but little change in precipitation. Abstraction, as a proxy for overall water demand, is shown to be positively correlated to temperature (Spearman's ρ value range: 0.094-0.403, p <0.01; Pearson's r value range 0.073-0.369, p <0.01) in four of five catchments. Our study provides new insight into the relationship between abstraction volume and hydroclimatic factors and highlights the need for catchment-scale water resource planning that accounts for hydroclimatic variations over small spatial distances, as these nuances can be vital.

Keywords: Abstraction; Breakpoint analysis; Climate change; Hydroclimatic change; Trend analysis; Water demand

4.2 Introduction

Water service providers (WSPs) face a vast array of challenges and uncertainties when planning their future operations and services. Brown *et al*. (2010) compiled a list of 94 priority research questions for the UK water sector, in which the impact of climate change on water quantity was ranked as the second most important question. Their work also highlighted the need to better understand the drivers of water demand, both domestic and commercial, in order to improve future demand forecasting. Previous work on the characterisation of hydroclimatic trends in the UK suggests that precipitation and streamflows have become more seasonal, a pattern that is expected to continue (Whitehead *et al.*, 2009b; Suggitt *et al.*, 2015; Garner *et al.*, 2017). A study by Christiersen *et al.* (2012) showed, using UK Climate Predictions 2009 (UKCP09) data, that by the late 2020s, increases in winter precipitation levels are likely to be more prominent in northern and western parts of the UK, while decreases in summer flows will be seen more generally across the whole country. Similarly, a hydrological modelling study by Prudhomme *et al*. (2012) showed that summer precipitation and streamflows will decrease across the UK by varying amounts for the period 2040-2069; whereas future winter precipitation and streamflows showed an upward trend, especially for Wales. Extreme precipitation events are also projected to become more seasonal in the UK, with longer duration and more intense rainfall events in winter becoming more common (Suggitt *et al.*, 2015). Mayes (2000) suggested that these anticipated changes will not be uniform across the UK, and current rainfall gradients are likely to be accentuated, i.e., the south getting drier in summer and the north getting wetter in winter.

Regional-scale understanding of water resource provision in the UK is particularly important because water supply is under the control of individual water companies that serve separate regions of varying sizes, populations, and physical characteristics. For instance, in south-east England, which is already a water stressed area, studies on future hydroclimatic trends suggest that summer streamflow levels will continue longer into autumn, with overall summer flow levels declining also. Furthermore, winter streamflows will increase and continue longer into spring, leading to accentuated seasonality in terms of season longevity and flow volumes (Diaz-Nieto & Wilby, 2005; Wilby & Harris, 2006; Wilby *et al.*, 2006; Cloke *et al.*, 2010; Arnell, 2011). However, an increase in winter precipitation will do little to combat summer shortages if no further storage capacity is developed soon (Whitehead *et al.*, 2013).

Borgomeo *et al*. (2014) suggested that, due to the combined effect of climate change and significant predicted population growth, the London water supply zone urgently required both supply and demand-side interventions if the current standard of water provision is to continue. In Scotland, although winter precipitation is predicted to increase in the future, a lower percentage of it will fall as snow (Capell *et al.*, 2013, 2014). This will make catchments more responsive to winter precipitation and increase the pressure on water managers to deal with larger discharge events (Baggaley *et al.*, 2009). For summer precipitation and streamflows, Blenkinsop & Fowler (2007) noted that Scotland has a limited amount of groundwater storage capacity, which heightens the drought risk from any reduction in non-winter precipitation. In Wales, studies suggest that winter and summer season characteristics, e.g. wet winters and dry summers, will be exacerbated, especially in winter (Dixon *et al.*, 2006; Fowler & Wilby, 2010; Thompson *et al.*, 2017).

In this study, we use Wales as a case study region, a country often viewed as abundant in water resources, receiving some of the highest average annual rainfall totals in the UK (Met Office, 2020), but which in reality has zones of water deficit (DCWW, 2016a). Wales is also important due to its role as an exporter of water to major metropolitan areas in England. Dŵr Cymru Welsh Water (DCWW), the major WSP for Wales, has over 20 bulk water trades, the largest of which supplies 360 million litres per year to Severn Trent Water for distribution around Birmingham (Warren & Holman, 2012; DCWW, 2016a).

Past studies on water resources in Wales have predominantly been conducted either as part of UK-wide research (Prudhomme *et al.*, 2003; Whitehead *et al.*, 2009b; Fowler & Wilby, 2010; Hannaford, 2015; Suggitt *et al.*, 2015; Watts *et al.*, 2015a; Burt *et al.*, 2016), or with a focus on the combined England and Wales region (Arnell, 2011; Henriques *et al.*, 2015). When focusing specifically on the area covering Wales, Fowler & Wilby (2010) projected a much larger magnitude of increase in winter flows from the 1960-1990 average to 30-year averages centred on 2025, 2055 and 2085, than the corresponding decreases in summer precipitation. Dixon *et al*. (2006) showed a significant upward trend across 56 Welsh and West Midlands catchments between 1962-2001 for winter high flow values, but no significant changes in the mean annual values. Conflictingly, Macdonald *et al*. (2010), demonstrated that during the period 1973-2002, there was no significant change in the seasonality of rainfall across 30 catchments in Wales, which they proved to have a significant link to streamflows; however, they did show that the frequency of occurrence of extreme precipitation events in Wales had increased during the study period. These contrasting results highlight the need for careful consideration when selecting study period length and timeframe due to the potential impact on trend analysis results and projections.

Up until recently, supply-side measures to tackle water scarcity and to manage water resources have traditionally been the main path towards a reliable sustainable future water network. However, it has increasingly been recognised over the past decade that demand-side interventions should also play a role as an adaptation measure (NIC, 2018). For this to be a viable option, further work is needed to understand the relationship between prevailing and antecedent weather conditions, and demand for water in the UK. Several studies have looked at the general interplay between the two in the UK (Herrington, 1996; Downing *et al.*, 2003; Butler & Memon, 2006; Browne *et al.*, 2013), and abroad (Gutzler & Nims, 2005; Balling & Gober, 2007; Chang *et al.*, 2014). This interplay has been investigated since at least as far back as the 1990s, with Herrington (1996) stating at the time, that up to 40% of total consumption in summer can be due to garden watering, which is obviously highly affected by the prevailing weather conditions. Goodchild (2003) used summer daily domestic water demand data (55% of UK piped water supply at the time) from 41 domestic properties and daily meteorological data to develop a demand prediction model. The model included ten weather variables to account for current and antecedent conditions; evapotranspiration, days since rain, and temperature were all important functions. This modelling work projected a 2.1% increase in average summer 7-day household demand by the 2020s. More recently, Parker & Wilby (2013) reviewed domestic water demand in the UK and noted the lack of studies on weather and climate. It is also important to look not only at domestic demand, but also industrial, agricultural and non-revenue water use (e.g. leakage), as they all influence the long-term sustainability of water supply.

In this study, we look at the implications of past trends in hydroclimatic data on two of the problems identified by Brown *et al*. (2010): (1) impact of climate variations on water availability and (2) understanding the factors affecting water demand. The first problem has been addressed by assessing trends in seasonal and annual average climate and streamflow data as well extreme event frequency and magnitude, using Mann-Kendall trend analysis and breakpoint analysis. We have addressed the second problem by investigating the historical links between hydroclimatic factors and total water demand, using actual abstraction data provided by DCWW as a proxy for demand. To our knowledge, this is one of the first studies conducted independently of a WSP to use actual abstraction data provided by a WSP in this manner in the United Kingdom. The reliance on Wales for water supply in other regions, combined with a potentially inaccurate assumption of national water abundance in Wales, makes the region a crucial area of study in terms of water management and water supply availability. Our research has therefore been undertaken in order to provide information for future water resource planning and policy decisions, as well as future research. It is hoped that this will be achieved by providing evidence of the long-term trends and links between prevailing weather and flow conditions, as well as total demand for water in Wales.

4.3 Data and methods

4.3.1 Study catchments

Our study focusses on the rivers Clwyd and Conwy in the north, the Dyfi in the west, and the Teifi and Tywi in the south of Wales (Figure 4.1). We selected these catchments as a result of them being among the largest systems within the region, encompassing a range of land use/land cover (LULC), and exhibiting a variety of different catchment characteristics. Furthermore, the catchments are also mostly encompassed within DCWW's water supply zone (Figure 4.1), and all have multiple surface water abstraction locations licensed to DCWW for use for public water supply. Brief catchments descriptions have been provided below and key comparative details about each are given in Table 4.1[1]. Figures for LULC in the catchments were calculated from 2012 CORINE Land Cover data (Copernicus Land Monitoring Data), while the catchment size, longest stream length, elevation and slope values were calculated using a 5 m digital elevation model provided by Ordnance Survey.

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[1] Stated catchment details/characteristics, such as land cover proportions and catchment area, differ for this study from those shown in Chapters 3, 5 and 6 due to variations in delineated catchment area for this study. Catchment areas defined in this study have been delineated manually in ArcMap using the Hydrology toolset of the Spatial Analyst toolbox; other chapters use the area delineated during catchment setup for SWAT modelling.

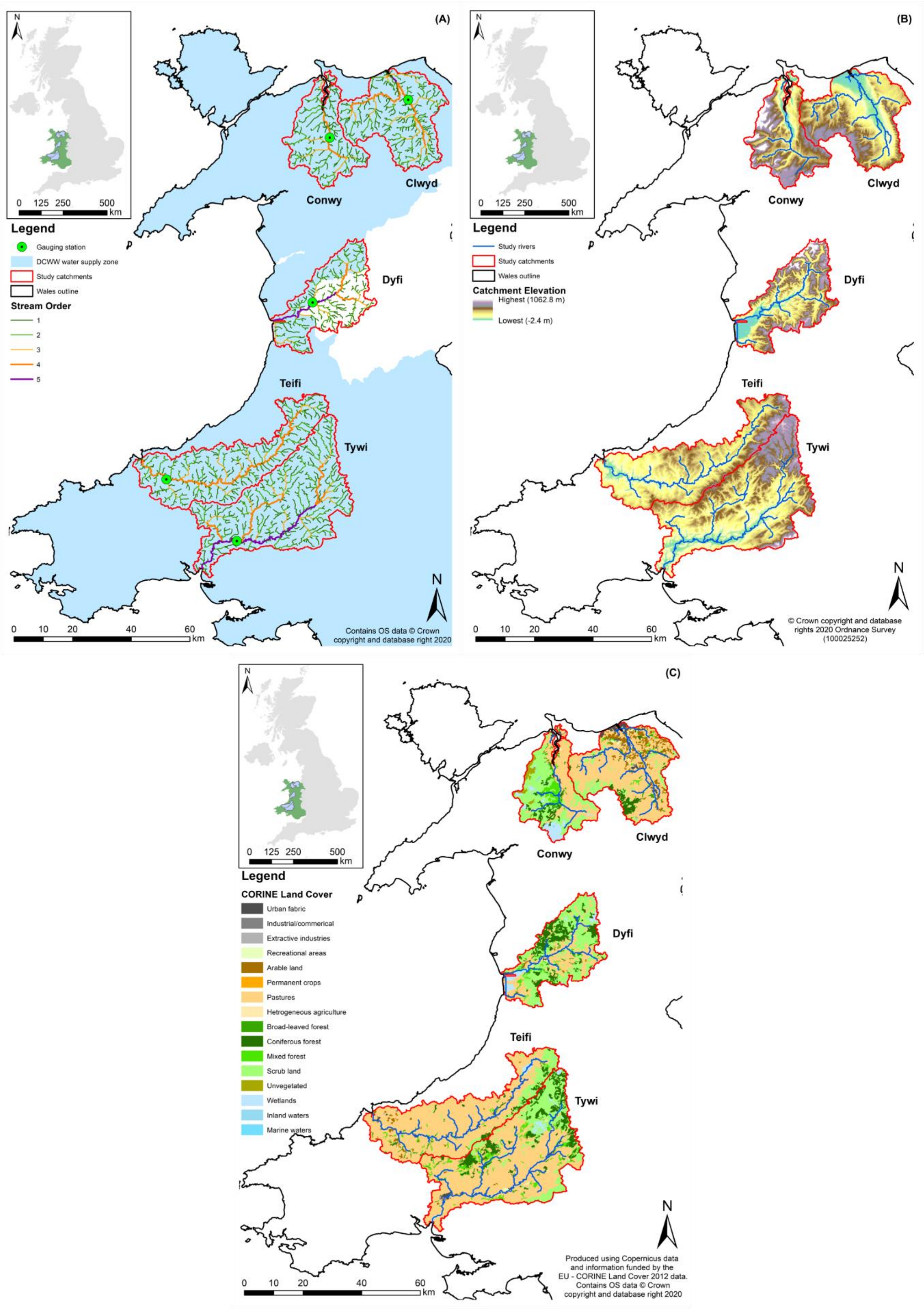

Figure 4.1. (**A**) Catchments; streams (formation threshold of 1 km^2); stream order (derived by Strahler method); and gauging station locations. (**B**) Catchment elevation. (**C**) Catchment land use/land cover derived from CORINE Land Cover data.

Table 4.1. Key study catchments details. Catchment area, main channel length, and slope data derived from Ordnance Survey provided 5 m digital elevation model; land use/land cover data derived from 2012 CORINE Land Cover data.

River	Catchment area (km^2)	Main channel length (km)	Mean catchment slope (degrees)	Catchment land use/land cover (%)				
				Urban	Agricultural	Forest	Scrub*	Wetland
Clwyd	803	35	7.1	3.7	80.3	7.2	8.8	0.0
Conwy	564	43	10.7	1.6	32.3	13.2	40.7	7.9
Dyfi	676	42	14.2	0.4	30.6	20.1	43.2	5.1
Teifi	1011	80	6.6	0.9	83.1	5.5	9.5	1.1
Tywi	1363	109	9.2	0.7	64.6	16.0	17.1	1.3

* Scrub-designated land includes land cover such as natural grasslands, transitional woodland-shrub, moors, and heathlands.

In terms of LULC, the Clwyd, Teifi, and Tywi are dominated by agricultural land use (Figure 4.1); while the largest proportion of LULC in Conwy and Dyfi is scrubland (mainly in the form of moors and heathland in Conwy, and natural grasslands in Dyfi). Agricultural land in all study catchments is mostly pastureland, however, Clwyd does have a larger proportion of its total LULC as arable land (10.4%). Forested land in all catchments is mainly coniferous, except in Conwy where there is an equal proportion of coniferous and mixed forest (5.1% LULC each) and 3% broadleaf forest. The bedrock geology is predominantly mudstone, siltstone, and sandstone in all five catchments, ranging from about 60% in Conwy and Clwyd, 73% in Tywi, and over 85% in Dyfi and Teifi. The catchments range in area covered from 1363 km^2 at the Tywi to less than half of that for the Conwy (564 km^2). The steepest catchment is the Dyfi, with an average slope of 14.2 degrees, being largely in the south of the Snowdonia region, while the Teifi in the south is the least steep catchment, with an average slope of 6.6 degrees.

4.3.2 Data

Hydrological and meteorological data for all five study catchments was obtained for the longest complete period possible for all datasets, that being the 34-year period from 1st October 1981 to 30th September 2015 (except flow data for the Dyfi, which was only available to 5th May 2014). Daily precipitation and air temperature data were obtained from the Centre for Ecology and Hydrology's (CEH) Climate, Hydrology and Ecology research Support System (CHESS) dataset. The mean daily value across all the 1 km grids contained within each catchment was calculated for both precipitation and temperature, giving a daily average value for each variable across each catchment. Daily streamflow data for the catchments was obtained from CEH's National River Flow Archive dataset; gauging station locations are shown in Figure 4.1.

Daily water abstraction volumes were obtained from DCWW, which is the main water supply company for this region. However, these data were only available for a 5-year period from 1st January 2012 to 30th September 2016. Therefore, comparison of water abstraction data with hydroclimatic data could only be completed for overlapping dates between the datasets, 1st January 2012 to 30th September 2015. The daily water abstraction data was provided for 22 abstraction locations within the five study catchments and has been used as a proxy for overall demand across the network for all consumers, as well as leakage.

4.3.3 Trend analysis

We selected the nonparametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) to detect any consistent trends in the hydroclimatic data over time. The decision to use a nonparametric test was taken due to the nature of both climate and hydrology data generally being non-normally distributed and displaying seasonality, which goes against the assumption of constant distribution (Kundzewics & Robson, 2004). Moreover, hydrology data often displays auto-correlation, making it unsuitable for parametric testing (Hamed & Rao, 1998). The MK test maintains the sequential order of the data and calculates Kendall's tau (a measure of association between two samples) between each value and all values proceeding it, to test for a monotonic increase or decrease relationship in the data over time (Helsel & Hirsch, 2002). MK has also been successfully applied to similar hydroclimatic data in various locations globally (Murphy *et al.*, 2013; Basarin *et al.*, 2016; Mwangi *et al.*, 2016; Hajani *et al.*, 2017) so was deemed suitable for use in this study. Details on the specific equations relating to the MK test can be found in Jaiswal *et al*. (2015).

Long-term average trends in the datasets were examined by analysing seasonal and annual averages for each catchment; where winter is December to February; spring is March to May; summer is June to August; autumn is September to November; and where, for example, the 1982 hydrological year runs from 1st October 1981 to 30th September 1982. For the abstraction data, we have taken the sum of abstractions in each catchment, with trend analysis being performed on this value, in order that the results are comparable to the hydroclimatic factors analysed. We also examined trends in the frequency and magnitude of extreme events relating to hydroclimatic factors. This was achieved firstly by analysis of trends in maximum and minimum temperatures; maximum 1-day precipitation total and cumulative rainfall totals; and maximum and minimum average 1-day streamflow volumes. Second, we undertook an analysis of "events over threshold", in order to establish whether there are generally more or less extreme weather events per year/season over the study period. This was completed by taking the 5th and 95th percentile values of a whole dataset (seasonally and annually) and analysing the number of times in each year and season that that value is surpassed (95th percentile) or not reached (5th percentile) for temperature and streamflow, and surpassing the 95th percentile only for precipitation. The MK test was applied with Sen's slope estimator (Sen, 1968) in order to estimate the size and direction of trends; Hamed and Rao's method of auto-correlation correction was also applied in order to remove any apparent trend which the data exhibits with itself over time (Hamed & Rao, 1998).

In order to detect any sudden changes in the hydroclimatic data, we undertook a breakpoint analysis on the seasonal/annual average and extreme event data. This analysis was completed using two well-established methods, the Standard Normal Homogeneity Test (SNHT) method (Alexandersson, 1986; Alexandersson & Moberg, 1997) and the Pettitt method (Pettitt, 1979). These two methods were used to ensure the widest possible detection of breaks in the data; with the SNHT being more accurate at detecting breaks at the start and end of time series, and the Pettitt method being more reliable in the middle (Hawkins, 1977; Hänsel *et al.*, 2016). If annual values of the variable being tested are identically distributed and independent, both methods accept the null hypothesis. The alternative hypothesis (that there is a change point in the series) will be accepted however, if a shift in the value of the mean has occurred (Hänsel *et al.*, 2016). Both methods are also location specific, so will identify the year at which the mean changed within the time series. For further information on the equations that drive the two methods, we suggest Hänsel *et al*. (2016) and Jaiswal *et al*. (2015).

4.3.4 Correlation analysis of hydroclimatic and abstraction data

In order to investigate the relationship between the three hydroclimatic factors and water abstraction we calculated both Pearson's & Spearman's rank correlation coefficients. The analysis was performed for each catchment with daily and monthly average temperature, precipitation and streamflow all being compared separately to daily and monthly total abstraction volume. We calculated Pearson's coefficient values (*r*) using Equation 4.1:

$$r = \frac{\sum_{i=1}^{n}\left(hc_i - \overline{hc}\right)\left(abs_i - \overline{abs}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(hc_i - \overline{hc}\right)^2\right)\left(\sum_{i=1}^{n}\left(abs_i - \overline{abs}\right)^2\right)}} \qquad \textbf{(Eq. 4.1)}$$

where hc_i refers to the daily average hydroclimatic variables studied, abs_i refers to daily total abstraction volume, and $\overline{hc}$ & $\overline{abs}$ represent the mean of the entire respective datasets. The nonparametric Spearman's correlation coefficient (*ρ*) was calculated using Equation 4.2, a modified version of Pearson's correlation coefficient which calculates correlation between ranks, as opposed to raw data:

$$\rho = \frac{\sum_{i=1}^{n}\left(R(hc_i) - \overline{R(hc)}\right)\left(R(abs_i) - \overline{R(abs)}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(R(hc_i) - \overline{R(hc)}\right)^2\right)\left(\sum_{i=1}^{n}\left(R(abs_i) - \overline{R(abs)}\right)^2\right)}} \qquad \textbf{(Eq. 4.2)}$$

where $R(hc_i)$ refers to the rank of the daily average hydroclimatic variables studied, $R(abs_i)$ refers to the rank of the daily total abstraction volume, and $\overline{R(hc)}$ & $\overline{R(abs)}$ represent the mean rank of the entire respective datasets.

4.4 Results

Our results indicate a north-south divide when looking at extreme temperature and streamflow changes. Additionally, a strong warming trend in average autumn temperatures across Wales is observed, however little change in precipitation is seen. Abstraction, as a proxy for overall water demand, is strongly positively correlated to temperature in all catchments and negatively with streamflow and precipitation in all catchments except the Dyfi. Below we provide a detailed breakdown and explanation of these results.

4.4.1 Trend and breakpoint analysis

4.4.1.1 Precipitation

We found no significant trends during MK analysis or breakpoint analysis of annual and seasonal precipitation averages in any of the five catchments for the study period; but Sen's slope indicator values do suggest a slight decrease in average spring precipitation across all catchments. In addition, only two significant trends were present in terms of extreme precipitation events; the first is a decrease in total cumulative spring precipitation in the Clwyd catchment throughout the period (Tau = −0.184, p = 0.040; Sen's Slope = −1.196). The second is a decrease in the number of extreme wet autumn days in the Teifi catchment (Tau = −0.593, p = 0.003; Sen's Slope = −0.138). Although both of these trends are mirrored in the other catchments, those trends are not statistically significant, highlighting the need to study individual catchments to account for varying characteristics. Additionally, the Pettitt breakpoint analysis showed a marked increase in winter cumulative precipitation in the Conwy after 1989 (p = 0.040), the mean for the post 1989 period increasing by 13.4% compared to the pre-1989 period.

4.4.1.2 Temperature

Unlike precipitation, air temperature data does display significant trends in Wales over the course of the study period. In all catchments, we observe a warming trend in average autumn temperature (Figure 4.2); the rate of increase is marginally higher in the two north Wales catchments compared to the two in the south of the country (Table 4.2).

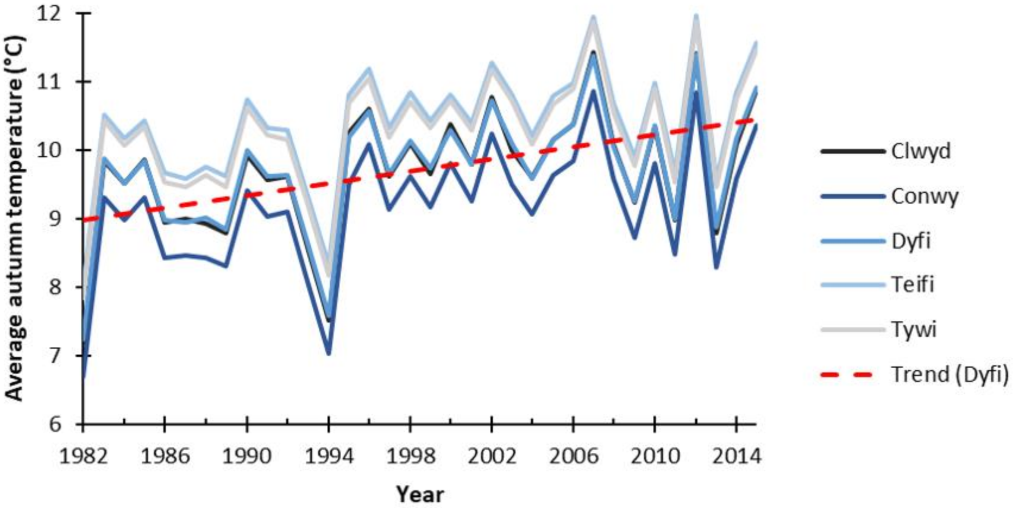

Figure 4.2. Warming trend in average autumn temperatures displayed in all catchments. Linear trend for the Dyfi catchment shown with red dashed line to exemplify the linear trend in all catchments.

Table 4.2. Mann-Kendall trend analysis and Sen's slope indicator results for average autumn air temperatures trends (1981-2015) in each of the five study catchments. Values for Kendall's Tau underlined are significant at p <0.05, and those in bold are significant at p <0.01.

River	Kendall's tau	Sen's slope
Clwyd	**0.337**	0.041
Conwy	0.348	0.040
Dyfi	**0.344**	0.038
Teifi	**0.337**	0.038
Tywi	**0.344**	0.038

These findings correlate with both the Pettitt and SNHT breakpoint analysis in all catchments, which shows a step increase in autumn temperatures in 1994, with the percentage change in pre- and post-1994 mean temperatures being larger in the north (Table 4.3). We found no significant trends in the MK analysis of annual, winter, spring, or summer datasets, however when looking at the breakpoint analysis, further changes are seen. In the two most northerly catchments, winter temperatures show a break and increase under SNHT analysis in 1987 (p = 0.042 & 0.048 for the Clwyd and Conwy respectively). All catchments also show a breakpoint increase in average spring temperatures in 1987 and annual average temperatures in 1988, both under SNHT analysis.

Table 4.3. Pettitt and Standard Normal Homogeneity Test (SNHT) method breakpoint analysis statistics for shown stepped increase in annual average autumn temperatures since 1994 in all study catchments.

River	Pettitt *p* value	SNHT *p* value	% change in 1994-2015 mean from 1982-1993 mean
Clwyd	0.001	0.009	+12.2%
Conwy	0.002	0.008	+12.7%
Dyfi	0.003	0.011	+11.8%
Teifi	0.002	0.010	+10.3%
Tywi	0.003	0.010	+10.6%

When looking at extreme temperature events, the three most southerly catchments, Dyfi, Teifi and Tywi, display both a decrease in the number of hottest days annually (days above the whole dataset 95th percentile; Figure 4.3), as well as a decrease in the number of coldest summer days (days below the summer dataset 5th percentile; Figure 4.4); suggesting a narrowing of temperature ranges, especially in summer. The Conwy catchment in the north also displays the latter trend of fewer of the coldest summer days (Table 4.4). This narrowing of temperature ranges has however, not been abrupt enough to cause a breakpoint in the data, with no significant changes seen.

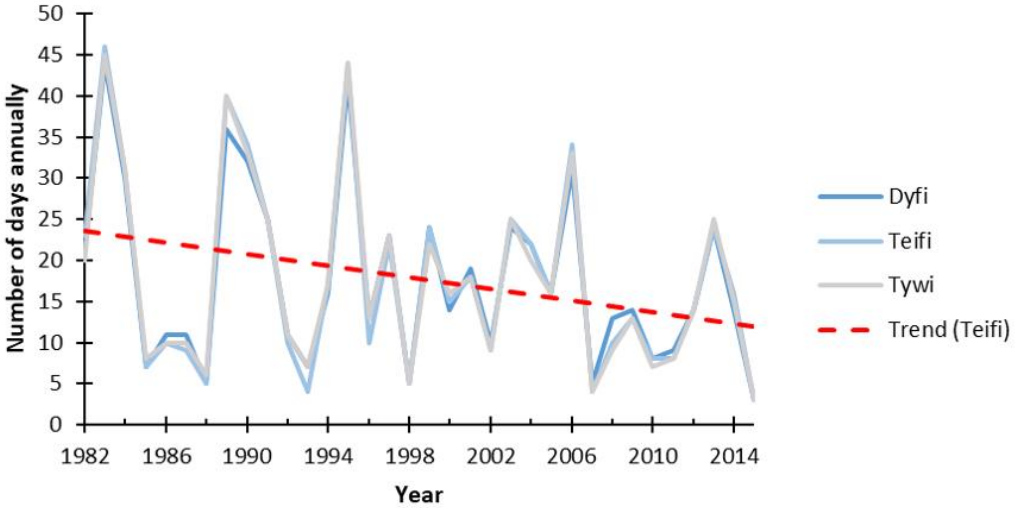

Figure 4.3. Number of occurrences annually where daily average temperature is greater than the 95th percentile temperature value for the full 34-year dataset. Linear trend for the Teifi catchment shown with red dashed line to exemplify the linear trend in all three catchments.

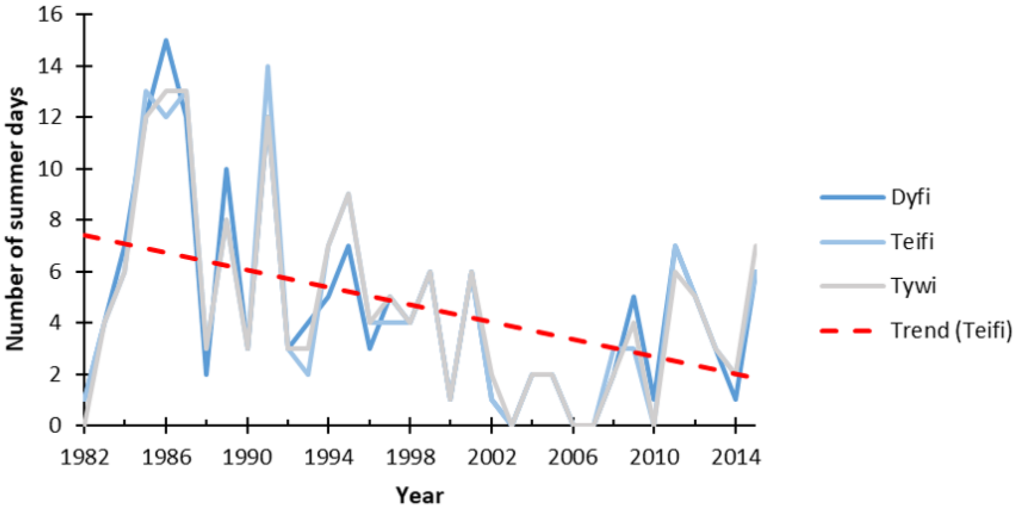

Figure 4.4. Number of occurrences during summer where daily average temperature is less than the 5th percentile temperature value for the full 34-year summer dataset. Linear trend for the Teifi catchment shown with red dashed line to exemplify the linear trend in all three catchments.

Table 4.4. Statistically significant Mann-Kendall trend analysis and Sen's slope indicator results for extreme temperature events (1982-2015) for all catchments. No significant trends were found in the Clwyd catchment. Values for Kendall's Tau underlined are significant at *p* <0.05.

River	Factor	Kendall's tau	Sen's slope
Conwy	Number of summer days below temperature dataset 5th percentile	−0.271	−0.125
Dyfi	Number of days annually above temperature dataset 95th percentile	−0.165	−0.250
	Number of summer days below temperature dataset 5th percentile	−0.260	−0.133
Teifi	Number of days annually above temperature dataset 95th percentile	−0.173	−0.250
	Number of summer days below temperature dataset 5th percentile	−0.269	−0.143
Tywi	Number of days annually above temperature dataset 95th percentile	−0.191	−0.286
	Number of summer days below temperature dataset 5th percentile	−0.266	−0.136

4.4.1.3 Streamflow

We observe only one statistically significant trend in seasonal and annual average streamflow data, this being in annual flows in the Teifi; here a significant increase in average annual flow (Figure 4.5) is detected over the study period (Tau = 0.240; Sen's slope = 0.204; p = 0.044). The Teifi also shows the only observed breakpoint in the average flow data, that being a step increase in winter flow in 2013 (p = 0.019) the mean for the post 2013 period increasing by 63.0% compared to the pre-2013 period.

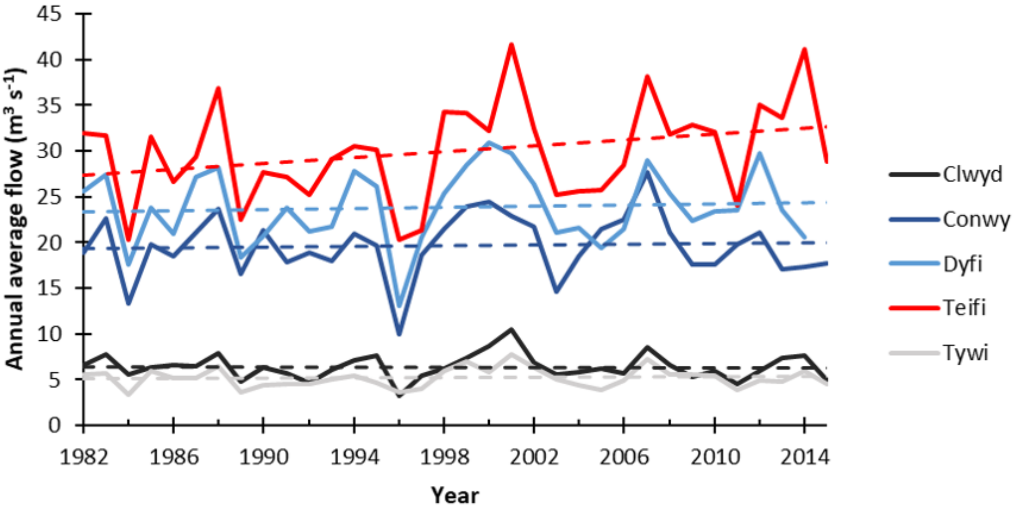

Figure 4.5. Annual average streamflows for study catchments, with linear trend lines also shown (dashed lines). The only statistically significant trend, an increase in streamflow in the Teifi catchment, is highlighted in red.

We found various trends in terms of extreme events in streamflow in Wales (Table 4.5); once again the three most southerly catchments show similar trends, in this instance, an increase in volume of the annual and summer 1-day minimum flow volume. The Conwy shows an increase in winter minimum flow volume, along with an increase in the maximum summer flow, while the Clwyd displays an increase in annual maximum flow volume.

Table 4.5. Mann-Kendall trend analysis and Sen’s slope indicator results for statistically significant trends in extreme streamflow events (1982-2015). Values for Kendall’s Tau underlined are significant at $p < 0.05$, and those in bold are significant at $p < 0.01$.

River	Factor	Kendall’s tau	Sen’s slope
Clwyd	Annual 1-day maximum	0.239	0.406
Conwy	Summer 1-day maximum	0.252	1.882
	Winter 1-day minimum	0.193	0.030
Dyfi	Summer 1-day maximum	0.222	1.341
	Annual 1-day maximum	**0.184**	1.238
	Spring 1-day minimum	**0.339**	0.065
	Summer 1-day minimum	0.317	0.048
	Annual 1-day minimum	**0.355**	0.045
Teifi	Winter 1-day maximum	0.269	2.037
	Spring 1-day minimum	0.237	0.071
	Summer 1-day minimum	0.237	0.059
	Annual 1-day minimum	0.254	0.056
Tywi	Autumn 1-day minimum	0.239	0.019
	Summer 1-day minimum	**0.348**	0.012
	Annual 1-day minimum	**0.320**	0.011

4.4.2 Correlation analysis of hydroclimatic and abstraction data

When looking at the daily actual abstraction data (1st January 2012 to 30th September 2015) under both correlation coefficient tests, all catchments display a positive relationship between air temperature and volume of water abstracted (Table 4.6), except for the Dyfi, which shows the reverse trend. All catchments, except the Dyfi, also show a statistically significant negative correlation between precipitation and volume of water abstracted, and consequently a negative relationship between streamflow and abstraction volume (Table 4.6). In order to investigate the situation for Wales as a whole, we have also included in Table 4.6 the correlation results for total daily and monthly abstraction volume in all five catchments with average daily/monthly temperature, total daily/monthly rainfall volume, and total daily/monthly streamflow volume, for all five catchments combined. The correlations seen in this dataset are consistent with those seen in most individual catchments. In addition, all catchments also display a positive relationship between streamflow and precipitation, and a negative one between streamflow and air temperature.

Table 4.6. Pearson's and Spearman's rank correlation coefficient results for daily and monthly abstraction data with hydroclimatic factors (2012-2015). Statistics relating to a combined analysis of total daily/monthly abstraction in all catchments with average daily/monthly temperature, total streamflow volume and total precipitation volume across all catchments are also provided. Values for *r* and *ρ* underlined are significant at *p* <0.05, and those in bold are significant at *p* <0.01.

River	Hydroclimatic variable	Daily		Monthly	
		Pearson's *r*	Spearman's *ρ*	Pearson's *r*	Spearman's *ρ*
Clwyd	Temperature	**+0.369**	**+0.403**	**+0.619**	**+0.665**
	Precipitation	**−0.181**	**−0.225**	**−0.509**	**−0.485**
	Streamflow	**−0.615**	**−0.553**	**−0.868**	**−0.808**
Conwy	Temperature	**+0.197**	**+0.197**	+0.279	+0.248
	Precipitation	**−0.111**	**−0.182**	**−0.415**	−0.381
	Streamflow	**−0.169**	**−0.298**	**−0.389**	**−0.429**
Dyfi	Temperature	**−0.398**	**−0.404**	−0.372	−0.250
	Precipitation	−0.054	**−0.140**	-0.171	−0.250
	Streamflow	+0.012	+0.018	+0.055	−0.014
Teifi	Temperature	**+0.073**	**+0.094**	0.094	+0.125
	Precipitation	**−0.073**	**−0.082**	−0.147	−0.256
	Streamflow	**−0.117**	**−0.235**	−0.148	−0.374
Tywi	Temperature	**+0.177**	**+0.218**	**+0.485**	**+0.482**
	Precipitation	**−0.165**	**−0.202**	**−0.768**	**−0.724**
	Streamflow	**−0.509**	**−0.559**	**−0.942**	**−0.961**
Combined	Temperature	**+0.207**	**+0.252**	**+0.504**	**+0.489**
	Precipitation	**−0.190**	**−0.223**	**−0.755**	**−0.729**
	Streamflow	**−0.547**	**−0.581**	**−0.925**	**−0.943**

Figure 4.6 shows the aforementioned combined data at a daily time-step from all catchments which has been normalised to each factor's maximum and minimum dataset value. Clear relationships between the hydroclimatic factors and actual abstraction data are observed. When looking at temperature, a positive correlation can be seen in the scatter plot, while the time series plot clearly also shows a large amount of consistency between the average temperature and total water abstraction volume. Arguably the clearest trend seen in the scatter plots is total streamflow volume and total actual abstraction volume, showing a negative correlation. This can also be seen in the time series plot that clearly shows drops in abstraction volume at times of largest flow volumes. Generally, the weakest correlations shown in Table 4.6 relate to precipitation and actual abstraction, the same is true for the graphs presented in Figure 4.6. Although peaks in precipitation do tend to coincide with a drop in abstraction, there is much more noise in the precipitation dataset, which makes these relationships more difficult to pinpoint.

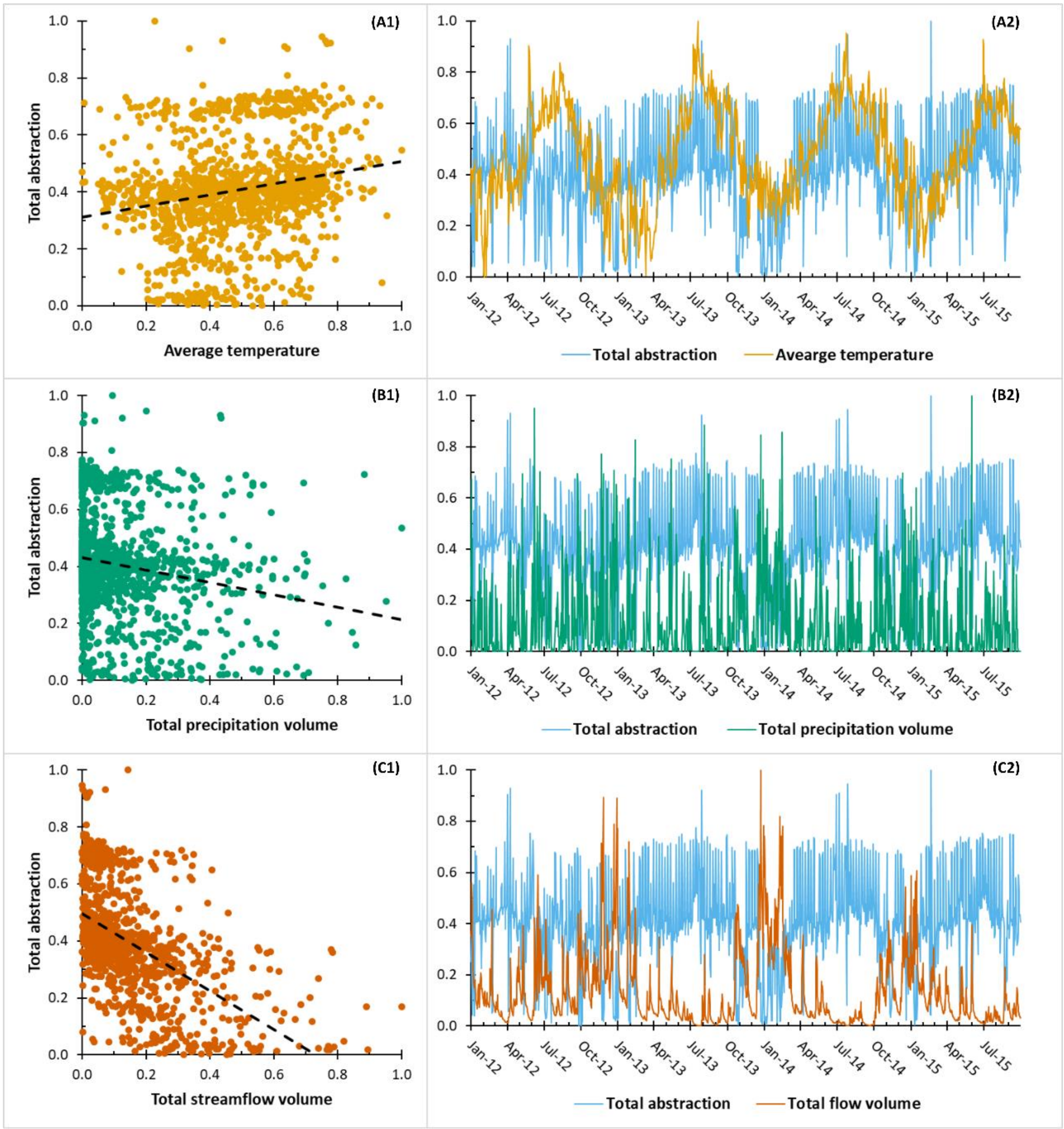

Figure 4.6. Normalised daily hydroclimatic data compared with normalised daily abstraction data for the period 1st January 2012 to 30th September 2015, for all study catchments combined. (**A1**, **B1**, **C1**) Paired comparison, with black dashed lines representing trend direction; (**A2**, **B2**, **C2**) time series comparison. Combined data is based on an average across all catchments for temperature, while precipitation, streamflow and abstraction volumes are all total volumes summed from all catchments.

The correlations and relationships seen in the daily data are made more evident when looking at the combined normalised monthly data, as shown in Figure 4.7. Clear negative trends can be seen between total abstraction volume with both total precipitation and total streamflow volume, when looking at scatter and time series line graphs. Clear peaks in abstraction can be seen at times of lowest streamflow and precipitation levels, and vice versa. Temperature and total abstraction are shown to also be broadly in-line when looking at the time series plot, with a clear positive trend shown when looking at the scatter data.

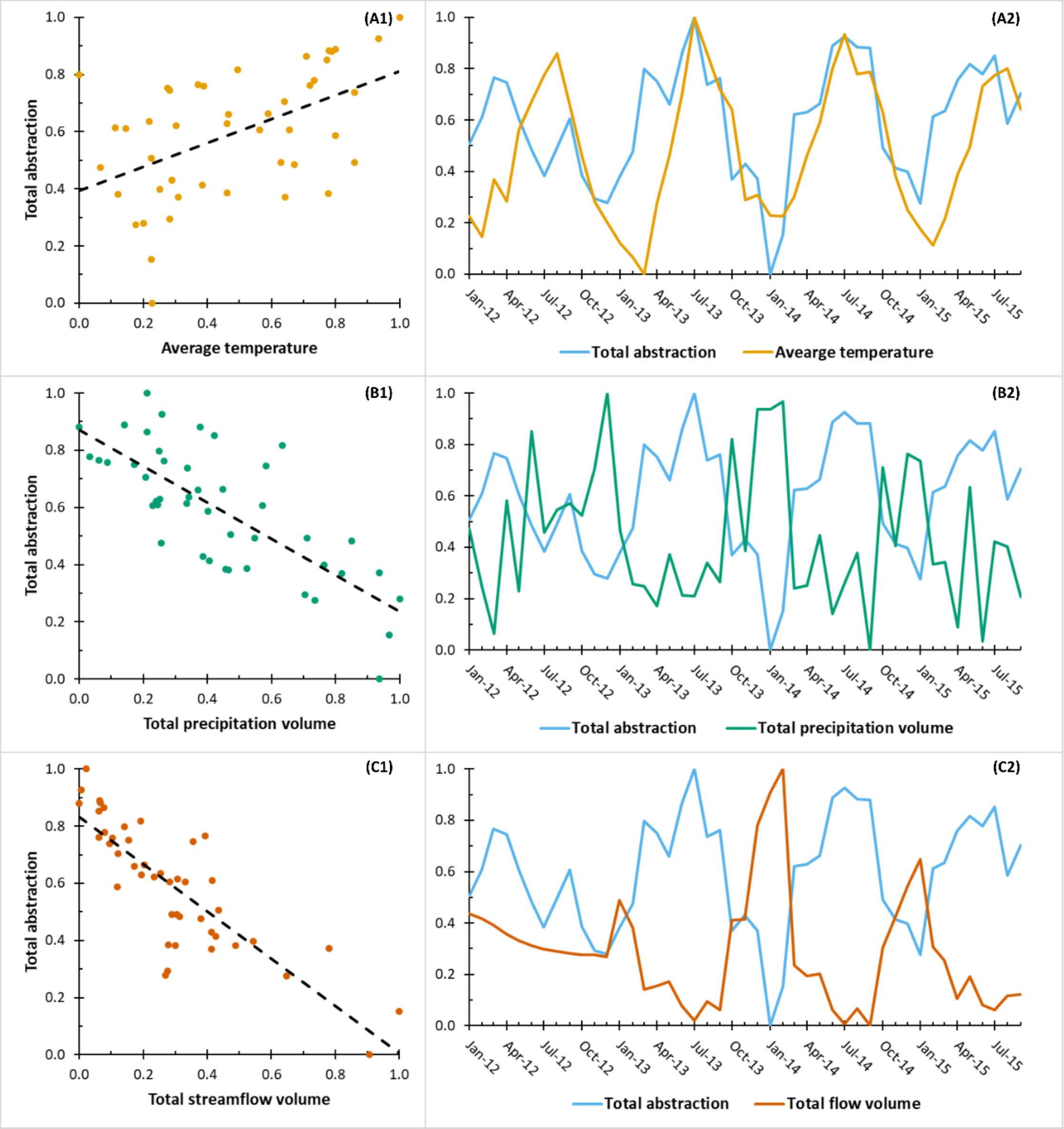

Figure 4.7. Normalised monthly hydroclimatic data compared with normalised monthly abstraction data for the period 1st January 2012 to 30th September 2015, for all study catchments combined. (**A1**, **B1**, **C1**) Paired comparison, with black dashed lines representing trend direction; (**A2**, **B2**, **C2**) time series comparison. Combined data is based on an average across all catchments for temperature, while precipitation, streamflow and abstraction volumes are all total volumes summed from all catchments.

4.5 Discussion

4.5.1 Hydroclimatic trends

The results of the trend, breakpoint, and correlation analyses show a selection of spatially varying changes across the five catchments over the 34-year study period. Wales has a maritime climate which is strongly influenced by the North Atlantic Oscillation (NAO), a major cause of atmospheric circulation variability in the north Atlantic region (Dixon *et al.*, 2006;

Beranová & Huth, 2007). This is important to consider when analysing changes that have occurred across all catchments. NAO displays year-to-year and longer-term variability, therefore breakpoints in temperature, precipitation, and streamflow data that occur across all five catchments and likely to be rooted in changes in NAO. However, when explaining changes that affect a subset of the catchments, it is likely that catchment characteristics in terms of topography, LULC and surrounding landscapes have had an impact by interacting with these large-scale meteorological processes (West *et al.*, 2019). The breakpoint analysis is a prime example of this interplay, a combination of NAO, climate change and other non-climate/weather related changes at a catchment and at a national level are likely to have impacted on the climatology breaks shown. No single factor accounts for all of breaks shown across the catchments. While a change in NAO is likely to have been a key driver, other factors such as LULC change and climate variations may well have had an impact on spreading the breakpoints out over the range of approximately seven years shown (1987-1994).

When looking at both temperature and streamflows, a north-south divide in results can often be seen. Taking the extreme events results for streamflows as an example, it can be seen that in the two northerly catchments, the Clwyd and Conwy, the largest annual 1-day discharge events have become larger over the study period. Meanwhile the two most southerly catchments, the Teifi and Tywi, have seen the smallest 1-day flow values becoming larger, in particular when looking at annual and summer flows. These results are consistent with the findings of Dixon *et al*. (2006) who showed that in the period 1977-2001, summer minimum flow volume values had increased significantly in south Wales catchments, but not the north—mainly due to the more mountainous terrain of north Wales (Figure 4.1). Furthermore, increases in the lowest summer flow values were also seen in Osborn and Hulme (2002), and were linked to increased light summer rainfall over the period. The Dyfi catchment in mid-Wales shows a combination of these two patterns with maximum and minimum 1-day flows increasing in the summer and annually, showing a shift to generally wetter summers over the period, again corresponding to the reasoning and results put forward in Dixon *et al*. (2006) for mid-Wales. These results are also consistent with the mean catchment slope data shown earlier (Table 4.2) with the Dyfi and Conwy in particular being the steepest catchments, and arguably the flashiest, of the five studied. This factor may well contribute to the increase in summer maximum flows observed over the study period.

It is interesting to note that the aforementioned changes in streamflows occur despite a lack of corresponding statistically significant change in annual or seasonal average precipitation, an observation also made by Macdonald *et al*. (2010). This mismatch of significant trends between precipitation volumes and streamflows is surprising, as the two factors are correlated significantly in all catchments, suggesting that flows in the catchments are highly sensitive to small changes in precipitation. Similarly, the only statistically significant trend seen in extreme precipitation events, a decreasing trend in cumulative spring rainfall in the Clwyd, does not relate to a corresponding change in average or extreme spring streamflows during the study period. Although not analysed in this study, it is also possible that changing LULC during the study period could have had an effect on streamflows, independent of precipitation. Changes in agricultural land use in particular could have a large impact in the study catchments, affecting processes such as water infiltration and runoff (Wheater & Evans, 2009). Between the early 1980s and the late 2000s there was an increase in the amount of agricultural land classified as permanent grassland and rough grazing, despite overall agricultural land area remaining relatively stable (Welsh Government, 2019c). From the late 2000s to present, the total amount of agricultural land has grown to its highest level since World War II, with the vast majority of this being for grazing (Welsh Government, 2019c). Furthermore, forest cover has been continually increased throughout the study period, with greater planting taking place at the start of the study period and the rate steadily declining throughout (Welsh Government, 2015a). Forested land also impacts on the connectivity of river flows and precipitation, with processes such as evapotranspiration and interception storage diverting water from, or delaying water reaching, rivers (Wheater & Evans, 2009). This could once again explain some of the mismatch between significant precipitation and streamflow trends.

Changes in seasonal and annual averages, as well as extreme events are most observed in temperature, for the factors studied. Once again, a north-south divide can be seen in parts of these results, with the three southernmost catchments displaying a decrease in both the annual number of days that are hotter than the dataset 95th percentile, and the number of summer days that are colder than the dataset 5th percentile. These two changes suggest a narrowing of the temperature ranges in these catchments, with less extreme hot days annually and less extreme cold days in the summer. These findings are in line with wider UK research such as Dessai & Hulme (2008) who showed, via the Central England Temperature record, that annual average summer temperatures increased between 1960-2007 when compared to a 1961-1990 mean. Nesbitt *et al*. (2016) also presented a trend for summer days becoming warmer over the period 1954 to 2012 for south-east and south-central UK, as did Luterbacher *et al*. (2004) for the period 1977 to 2003. Annual NAO index has been largely negative on average throughout the study period, especially so in the latter two thirds (Figure 4.8). Negative NAO has been linked to colder maximum temperatures (Beranová & Huth, 2007), while climate change has been causing increasing summer temperatures on average. These two factors combined could be contributing to the narrowing temperature range observed, with NAO bringing down the maximum, and climate change bringing up the minimum. Furthermore, in all catchments, an increase in average autumn temperatures across the study period has been observed, with this being slightly more pronounced in the two north Wales catchments. All of the observed trends also fit with general UK observations of a greater degree of warming in the south of the country than the north, and the exacerbation of the temperature gradient between them. Furthermore, the north-south divide also fits when considering the surrounding geography of the catchments, the mountainous Snowdonia region lies just to the south of the two most northerly catchments, heavily influencing the climate here and causing local variation in the weather that is brought in from the Atlantic (Dixon *et al.*, 2006).

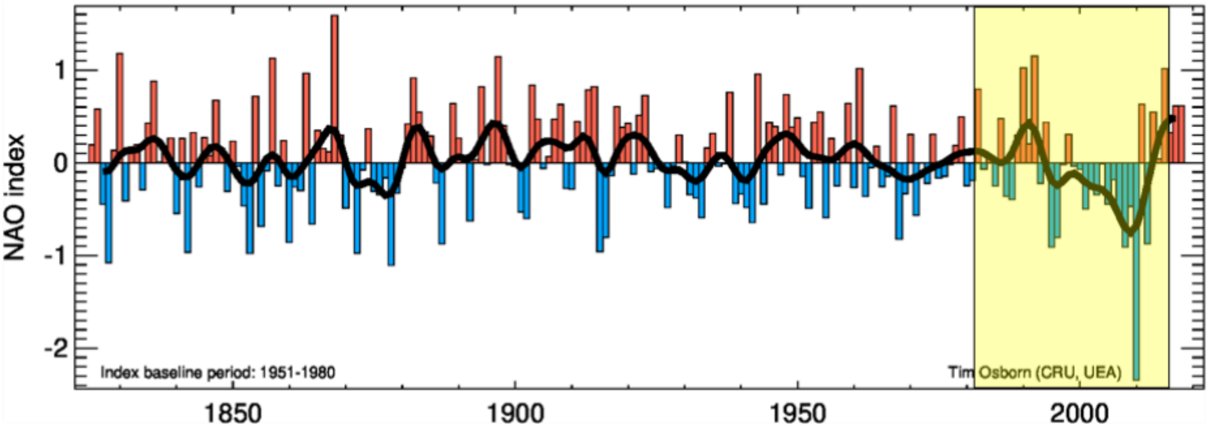

Figure 4.8. Annual North Atlantic Oscillation (NAO) index 1825-2019 relative to the 1951-1980 average index value (0 on this plot). Our study period has been highlighted in yellow; updated and adapted from Osborn (2011).

4.5.2 Weather and demand for water

When looking at the correlations between daily and monthly total abstraction data and hydroclimatic factors, it is clear that both average temperature and precipitation volume play a crucial role in influencing the total amount of water abstracted; volumes abstracted increasing in higher temperatures and decreasing on wetter days. Given that the data takes account for total abstraction volume, these relationships are not surprising, as it is likely that on hotter days there will be both more domestic demand (more showers, car washing, garden watering etc.), as well as higher demand from agriculture, in particular for water for livestock in the catchments studied. The opposite is true for wetter days, which reduce the agricultural demand from public water supplies and reduce domestic demand, especially for water use on external areas of a property. These overall relationships do fit with other work that has sought to quantify the relationship between climate variables and domestic demand, both in the UK and abroad. Slavíková *et al*. (2013) showed that in the Czech Republic, air temperature relative to the season average, accounted for most variability in residential water consumption. Similarly in the UK, Goodchild (2003) showed that domestic water demand in 41 houses in an Essex case study correlated with an R^2 value of 0.44 with days when maximum temperatures were over 25 °C. Additionally, total daily sunshine hours were shown to have a stronger correlation with demand, having an R^2 value of 0.53 (Goodchild, 2003). Work by Xenochristou *et al*. (2020) also found that sunshine hours and air temperature were the most influential weather variables on domestic demand, along with humidity.

However, using total abstraction volumes as a proxy for demand does present some challenges. For example, factors such as the usage of water internally, within drinking water treatment plants, as well as network water leakage, may mask or alter observed trends in the dataset. In addition, it is difficult to apportion the total abstraction volume to different user groups, such as domestic, industrial, and agricultural on a daily basis. Furthermore, different user groups may have different relationships with weather conditions, for example Massoud *et al*. (2018) showed for California's Central Valley, that while agricultural demand increased in drier years, precipitation volume had little impact on urban water demand. Additionally, we recognise that the comparison period between the hydroclimatic factors and abstraction data is relatively short in this study, at four years. This does not give the opportunity to investigate relationships such as the effect of prolonged drought on water use, or other longer-term patterns. Nevertheless, the overall abstraction data does give a baseline relationship to work with when considering the impact of future climate change on total water demand.

4.5.3 Study implications

Our study has shown that the climate of Wales has changed since the early 1980s, and that this will have contributed to both the supply and demand of water in the region. On the basis of the results found, it is clear that these changes have been more keenly felt in terms of average air temperatures than precipitation volumes; this applies to both annual and seasonal averages as well as extreme events. When looking at the impact that these climatic changes have had on streamflows it can be seen that seasonal and annual average flows have remained largely unchanged, instead it is extreme flow events that have been more greatly affected. These changes occur with a north-south divide, with the largest annual flow events getting larger in the north, and the south becoming less dry in the summer when looking at the lowest flows. These changes could have important impacts if they are continued into the future, with implications not only for water supply, but also in terms of water resource management, to prevent flooding and other related natural disasters. Furthermore, large industrial users as well as applications such as hydroelectric developments could be impacted by changes in river regime. In particular the viability of some small-scale hydroelectric installations could be called in to question in some areas due to changing streamflow characteristics and flow duration curves, further emphasising the importance of a solid understanding of the relationship between, and emerging trends in, hydroclimatic factors.

Climate change induced alterations in the future timing, quantity, and quality of water available for supply, as well as policy relating to adaptation and management methods to cope with these predicted changes, needs to be further researched for Wales. In particular, hydrological modelling studies comparing current baseline streamflow (such as that presented in this study) to future streamflow under various climate change scenarios, could prove to be particularly useful. This work is crucial to better inform future water supply-demand dynamic assessments, water resource management, and adaptation planning. This is especially true if projected increases in the reoccurrence, duration, and intensity of extreme events under future climate change, as suggested in other research (Slingo, 2014; King &

Karoly, 2017; Betts *et al.*, 2018; Met Office, 2019; Harkness *et al.*, 2020), are correct. This suggested research would also go some way to addressing some of the aforementioned priority research questions laid out in Brown *et al*. (2010); but must however also keep in mind the cost and practicality of adaptation measures, in order to ensure both a continued unbroken water supply service, and affordable water for all. More broadly, this research has shown the need to research and understand historical trends and future projections of hydroclimatic factors at local, catchment levels. This is clear when looking at the presented differences in observed trends seen over small spatial distances, due to changing land characteristics, and it is these nuances that are vital to incorporate into future planning for any industry that relies on surface water abstraction.

4.6 Conclusions

This research has highlighted the potential for water scarcity problems even in a relatively water-rich region such as Wales. For example, with observed trends such as warmer average autumn temperatures providing for potentially greater water use in the season, the pressures on summer water supply could in the future extend further into the autumn. Although potentially increased demand could be countered by a trend of the largest discharge events becoming larger in the north of Wales, and summers becoming less dry in the south of Wales, any increase in flow is of little use if the capacity to store this additional water is not sufficient to make use of it.

Finally, we suggest that further research should focus on how future climate change will affect the relationship between weather factors, streamflow, and water demand, both in Wales and globally. For example, research concerning trigger temperatures for significant increases in water use, or the effect of long-term higher than averages temperatures on water demand, would aid understanding of the finer detail of the dynamic between hydroclimatic factors and total water abstracted. We also hope that this study will set a frame onto which future climate change research focusing on surface waters, and the future provision of water services can be built; being one of the first steps in securing the long-term sustainability of water supply services in the region and further afield.

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CHAPTER 5: STUDY II

Modelling the impact of future climate change on streamflow and water quality in Wales, UK

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Author contributions

Richard Dallison: conceptualisation, methodology, software, validation, formal analysis, investigation, data curation, writing – original draft, writing – review & editing, visualisation

Prysor Williams: writing – review & editing, supervision

Ian Harris: resources, writing – review & editing

Sopan Patil: conceptualisation, software, writing – review & editing, supervision

5.1 Abstract

Climate change is likely to have a major impact on future hydrological regimes, impacting numerous sectors reliant on surface waters. We use the Soil and Water Assessment Tool (SWAT) to model future (2021-2080) streamflow and water quality variables (nitrogen, phosphorus, suspended sediment, and dissolved oxygen), in five catchments in Wales, under a worst-case scenario of future greenhouse gas concentrations (RCP8.5). Results show a decline in annual average flows (-4% to -13%) but larger changes seasonally (spring, up to 41% increase; autumn, up to 52% reduction). The magnitude and frequency of high flow events increases in spring (magnitude: Sen's slope range 0.165-0.589, p <0.01), with more low flows in autumn (Sen's slope range 0.064-0.090, p <0.01). Water quality declines, with higher nitrogen, phosphorus, and sediment concentrations and lower dissolved oxygen levels. The findings have economic and environmental implications for abstractors, as water resources will become more unreliable, seasonal, and polluted.

Keywords: Hydrological modelling; Particle swarm optimisation; Trend analysis; UKCP18; Water resource management; Water supply

5.2 Introduction

Globally, river catchments are likely to face significant changes due to a variety of factors, including climate change, land use/land cover change, increasing urbanisation, increased population, and greater demand for water (Rockström *et al.*, 2009; Gleick & Palaniappan, 2010; Heathwaite, 2010; Cosgrove & Loucks, 2015; Bijl *et al.*, 2016). The Intergovernmental Panel on Climate Change (IPCC), in their fifth assessment report (AR5), project a rise in both surface temperatures and the number and intensity of extreme precipitation events under all future greenhouse gas emissions scenarios throughout the 21st century (IPCC, 2014b). For the UK, a small increase is projected in average precipitation by 2100, compared to the 1986-2005 baseline; average temperatures are also expected to increase (IPCC, 2014b). Furthermore, the UK Climate Projections 2018 (UKCP18) Science Overview Report suggests a move towards warmer, wetter winters, and hotter, drier summers, as well as an increase in extreme weather events (Lowe *et al.*, 2018). These changes will have implications for catchments in terms of annual and seasonal average flows, high and low flows, and water quality.

When studying past trends, various studies have shown that alterations in streamflow patterns have already occurred due to climate change, as well as other factors. Hannaford (2015), conducted a review of climate-induced changes specifically on UK streamflows, using the 130 benchmark network gauging stations with near-natural flow regimes. The results show an increase in annual outflows, albeit only statistically significantly in Scotland, with greater seasonal variability. Winter and autumn average flows are shown to have increased between 1961-2010 across the UK, with spring and summer flows increasing in Scotland and Wales, and decreasing in England (Hannaford, 2015). High flows are also shown to have increased in Scotland and Wales significantly (p <0.05), rising 22.4% and 26.5% respectively over the 50-year period. These results are consistent with studies such as Harrigan *et al*. (2018), which shows similar trends in UK catchments over the period 1965-2014; for example a UK-wide increase in annual and winter mean flows. In contrast to Hannaford (2015) however, large decreases in spring flow were seen across Britain (Harrigan *et al.*, 2018). Additionally, Dixon *et al*. (2006) found for catchments in western Britain, that there was an increase in annual, autumn and winter maximum flows; but little change in annual average flows. Furthermore, Dallison *et al*. (2020)[2] analysed 34 years of historical streamflow and climate data for five catchments in Wales and also found little change in annual average flows. However, low flow volumes were shown to have increased in the summer in the three most southerly catchments, while annual maximum flow increased in the northerly catchments.

Several studies have analysed future seasonal and annual average streamflows for the UK, mostly using UK Climate Projections data (UKCIP02, UKCP09 & UKCP18). While little work has been published using the new UKCP18 data, Kay *et al*. (2020) compared it with the UKCP09 projections across ten catchments in the UK and found the estimates of change under both models were similar, although uncertainty was higher in the most recent version. A study using UKCP09 data by Watts *et al*. (2015a) suggests that although little change is seen in annual average rainfall, seasonal changes are more pronounced. Precipitation increases in winter are likely to be greatest along the western coast of the UK, while the largest summer decreases in precipitation are expected in southern England (Watts *et al.*, 2015a). Investigating the impact of these changes on river flows in the short and long-term respectively, Christiersen *et al*. (2012) and Prudhomme *et al*. (2012) both projected annual averages flows to remain relatively stable. Both studies also project a reduction in spring flows, with small increase in the winter. However, the most consistent trend seen is a decrease in summer flows across the UK, especially in the north and west (Christierson *et al.*, 2012; Prudhomme *et al.*, 2012). These results are consistent with the findings of Chun *et al*. (2009) and Charlton & Arnell (2014) which both state that, despite variations due to different catchment characteristics, UK annual average streamflows will decline, with the magnitude of change less than that seen seasonally.

For extreme events in the UK, such as large discharge events/flooding and long-term drought, it is likely that climate change with alter their frequency, duration, and severity (IPCC, 2014b; Watts *et al.*, 2015a; Sayers *et al.*, 2016; Miller & Hutchins, 2017). Extreme streamflow changes are mainly driven by changes in precipitation regime. Fowler & Ekström (2009), when examining extreme rainfall for example, forecast increases in winter, spring and autumn to the 2080s, with this being especially pronounced in the west and Wales. Furthermore, Rau *et al*. (2020) found that extreme hourly precipitation is set to increase under a high future

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[2] As presented in Chapter 4.

emission scenario, especially in the long-term (2070-2100), up to 112% in some areas. Collet *et al*. (2018) demonstrated using the future flows hydrology database (Prudhomme *et al.*, 2013b), that for western areas of Britain especially, an increase in the frequency, duration and magnitude of future flood events is likely when comparing the period 1961-1990 to 2069-2098. A large, but less likely increase in the duration and magnitude of droughts is also shown (Collet *et al.*, 2018). Similarly, Charlton & Arnell (2014) showed an increase in high flows and decrease in low flows in six study catchments using the UKCP09 data. These changes were particularly linked to changes in winter precipitation for high flows, and summer temperature and precipitation for low flows (Charlton & Arnell, 2014).

In terms of changes to water quality, it is likely that the aforementioned projected alterations in average and extreme streamflows will have a deleterious impact in many instances. However, individual catchment characteristics will have a large impact on the magnitude of these changes. Whitehead *et al*. (2009a), for example, showed across six UK catchments that patterns in future water quality varied greatly based on the geology, topography, urbanisation, agricultural land use and point source inputs of each catchment. Furthermore, their research also showed that variation is also possible within catchments. For example, the River Tweed showed a trend of decreasing nitrate levels in the upland headwaters in summer, but increasing levels in the lower reaches (Whitehead *et al.*, 2009a). A further study by Whitehead *et al*. (2009b) discussed the varied future drivers of water quality changes. These drivers include variations in flow influencing stream power and therefore the erosion and transport of sediment. Streamflow regime variations also impact the dilution and movement of pollutants; in addition, changing water temperature can alter in-stream chemical process. Delpla *et al*. (2009) also reviewed the impact of both flood and low flow events on water quality, finding that increases in the magnitude of rain events, as well as changing drought-rewetting cycles, are likely to increase the amount of organic matter reaching streams. These findings correspond with those shown by Ockenden *et al*. (2017), who showed a clear positive trend between total phosphorous load and annual rainfall, and therefore streamflow. Furthermore, Mortazavi-Naeini *et al*. (2019) demonstrated a positive relationship between suspended sediment concentrations and extreme winter floods, as well as an increase in total phosphorus levels during low flow events. Finally, Watts & Anderson (2016) suggest that generally lower summer flow will increase the likelihood of algal blooms and lower dissolved oxygen levels, while subsequent summer flood events will increase wash of pollutants such as nutrients into river systems.

This work aims, via hydrological modelling, to investigate alterations to streamflow and water quality brought about by climate change in five catchments in Wales, UK. This is arguably an under-studied region of the UK in this context, especially when compared to drier regions, such as southeast England. It is a key area to study however, due to the importance of the river networks to the region. An obvious example of this is public water supply, 95% of which is taken from surface water sources (DCWW, 2019b). With some water supply zones already being in deficit in the region (DCWW, 2019b), future water supply sustainability is crucial to understand. Furthermore, Wales exports large quantities of water to metropolitan areas in central and northern England (Warren & Holman, 2012; DCWW, 2016a), meaning that alterations in future flow regime could have impacts beyond the country's borders. In addition, understanding future flow characteristics is important to sectors such as hydroelectricity generation, which is abundant, and growing, in Wales. Over 360 hydroelectric projects operate on rivers in Wales, ranging from small (<1 MW) to large (>70 MW) with a total estimated generation off 389 GWh, accounting for approximately 1.3% of total electricity generation in Wales in 2018 (Welsh Government, 2019b). Surface waters are also an important part of the tourism economy, with 96 million day visits to Wales in 2018 (Welsh Government, 2020), many attracted to the region for its natural beauty, and often visiting rivers, lakes and coast. The industry contributed £3,064 million to the Welsh economy in terms of gross value added in 2016 (Welsh Government, 2020), therefore understanding changes that may affect the natural landscape and resources of the region, and its continued appeal to tourists, is crucial. Finally, any changes in flow characteristics or water quality in particular, could have important implications for river ecology and aquatic life in both rivers and coastal waters. To ensure sufficient protection, it is important to understand potential future changes and challenges now, and to plan mitigation measures.

5.3 Data and methods

5.3.1 Study catchments

Our study focusses on five catchments in Wales: the Clwyd, Conwy, Dyfi, Teifi, and Tywi (Figure 5.1). These catchments have been selected for study due to the variety of different characteristics displayed, in factors such as topography (Figure 5.1), land use/land cover (LULC), and soil types (Figure 5.2). These are also among the largest catchments contained, source to sink, entirely within Wales; key details relating to the characteristics of each catchment are provided in Table 5.1. In addition, the catchments are important economically, socially and environmentally, in line with the reasons for selecting Wales as a study region. Water from these catchments, for example, directly contributes to the supplies of over 975,000 people (derived from DCWW, 2019b), as well as over 70 hydroelectricity scheme abstractions (derived from NRW, 2019a). Furthermore, these catchments are also important environmentally, with various land protections and designations covering areas of the catchments, such as National Parks, Sites of Special Scientific Interest, National Nature Reserves, and Special Areas of Conservation. Finally, the catchments also flow into waters that are spawning and/or nursery grounds for a variety of fish species such as cod, sole, plaice, spotted ray and sandeel (Ellis *et al.*, 2012).

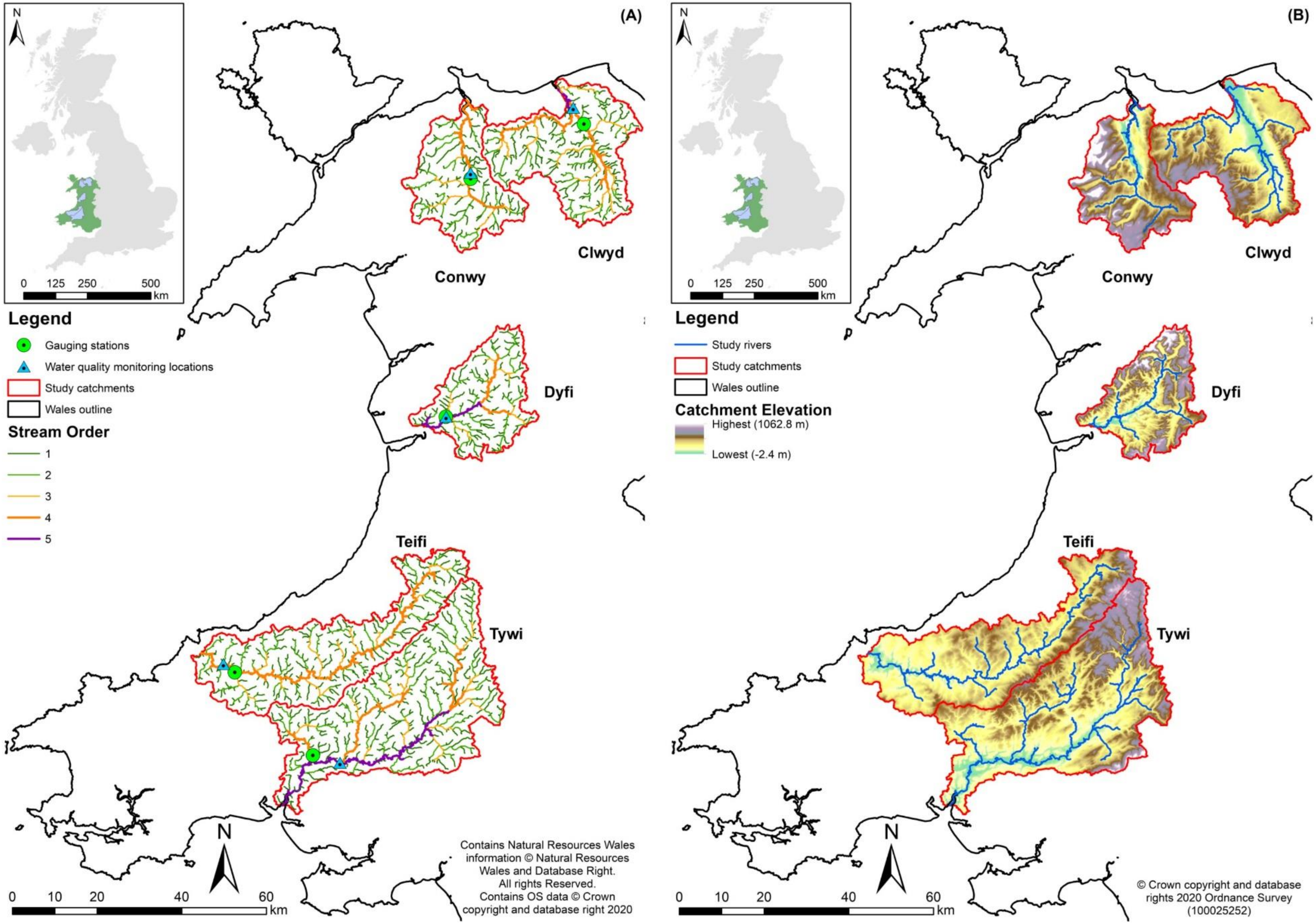

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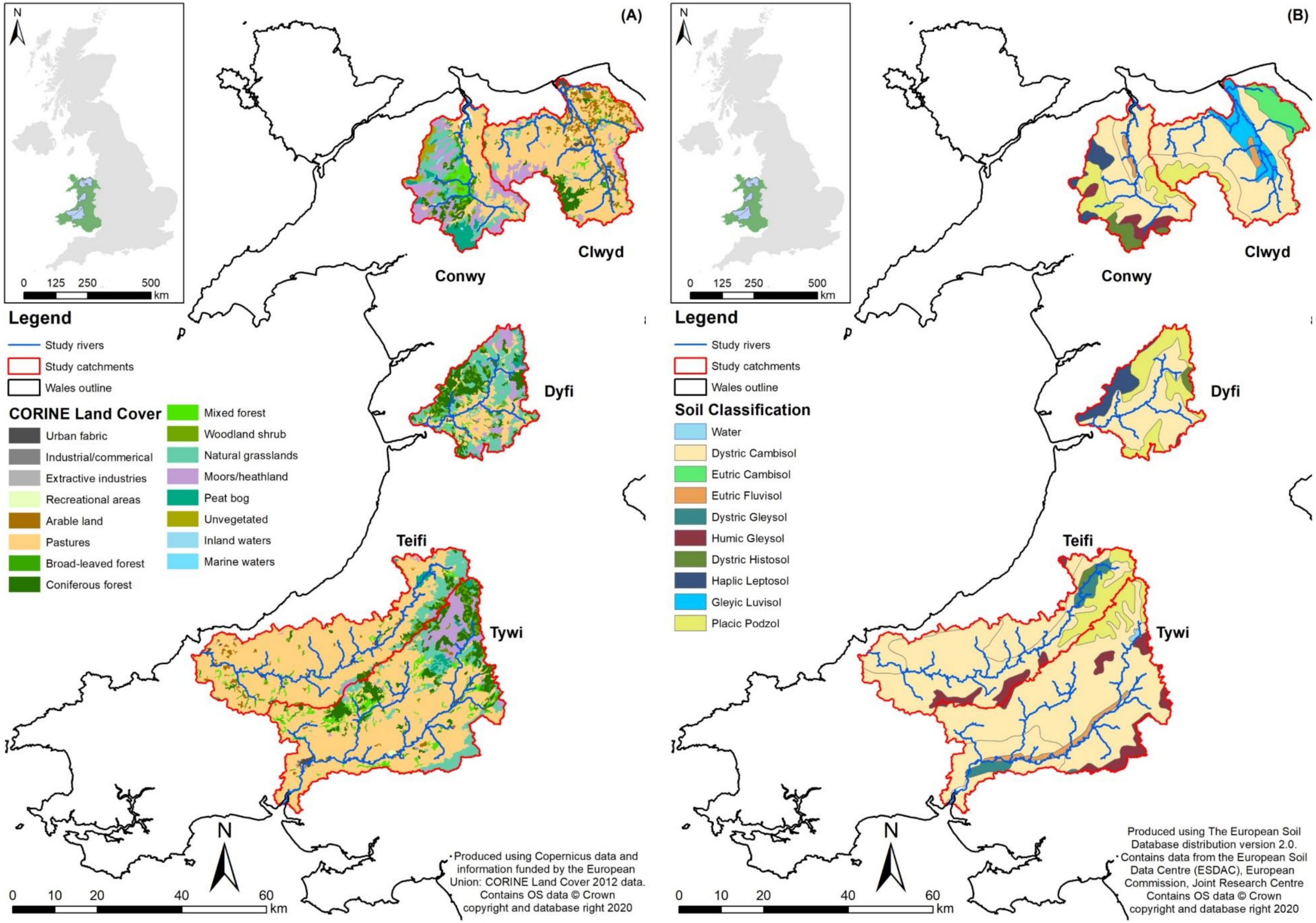
Figure 5.1. Study catchments as delineated in SWAT. (A) Streams and stream orders (derived by Strahler method), gauging stations and water quality monitoring locations. (**B**) Catchment elevation and streams (third order and larger).



Produced using Copernicus data and information funded by the European Union: CORINE Land Cover 2012 data. Contains OS data © Crown copyright and database right 2020

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Figure 5.2. (**A**) Catchment land use/land cover categorisation derived from CORINE Land Cover data (EEA, 2012). (**B**) Catchment soil classification derived from the EU Soil Database (European Commission, 2004).

Table 5.1. Key study catchments details. Catchment area refers to area modelled in SWAT. Elevation data derived from 5 m resolution OS Terrain 5 DEM from Ordnance Survey; land use/land cover data derived from 2012 CORINE Land Cover data (EEA, 2012).

		Clwyd	Conwy	Dyfi	Teifi	Tywi
Catchment area (km^2)		750.1	541.8	507.2	995.3	1364.6
Maximum catchment elevation (m)		557	1062	903	591	801
Mean catchment elevation (m)		210.4	309.8	271.4	198.1	212.5
Catchment land use/land cover (%)	**Urban**	**2.4**	**0.7**	**0.3**	**0.8**	**0.7**
	Agriculture	**80.9**	**30.6**	**30.0**	**83.0**	**64.6**
	Arable	9.3	0.1	0.4	1.8	0.7
	Pasture	71.6	30.5	29.6	81.2	63.9
	Forest	**7.3**	**13.7**	**21.5**	**5.5**	**16.0**
	Broadleaf	1.6	2.7	1.8	1.2	1.0
	Coniferous	4.5	5.5	18.9	3.2	10.1
	Mixed	1.2	5.5	0.8	1.1	4.9
	Scrub	**9.4**	**42.1**	**45.3**	**9.7**	**17.1**
	Natural grassland	2.3	16.6	30.4	7.2	8.4
	Moors and heathland	6.6	23.6	11.3	1.2	6.5
	Transitional woodland scrub	0.5	1.9	3.6	1.3	2.2
	Peat bog	**0.0**	**8.4**	**2.6**	**0.9**	**1.3**
	Sparsely vegetated areas	**0.0**	**4.1**	**0.2**	**0.0**	**0.0**

The catchments range in size from Dyfi at 507 km^2 to Tywi at over two and half times the size (1365 km^2). In terms of LULC, agriculture and scrubland are the two main land cover types across the five catchments, with Clwyd, Teifi, and Tywi being heavily agriculture based (83% to 65%), and Conwy and Dyfi having higher propositions of scrubland (42% and 45%, respectively) such as natural grasslands, moors and heathlands. Most of the agricultural land in all catchments is pasture used for grazing sheep and cattle, with Clwyd having the highest proportion used for growing crops. Urban areas account for little land area in all our study catchments. Where urban areas are present, they tend to be located in the coastal regions. Forested land is the third largest land cover in all catchments, with this mostly being coniferous and often located in mid to high elevations. In terms of underlying soil classification, the vast majority in all catchments is young Cambisol (brown soil), while Podzols are most commonly found in higher altitude areas.

5.3.2 Future climate change data

UKCP18 data were used as future weather input for hydrological modelling, specifically the 'Regional Projections on a 12 km grid over the UK for 1980-2080' dataset (MOHC, 2018b). This provided an ensemble of twelve regional climate model (RCM) projections derived and, dynamically downscaled, from the 60 km HadGEM3-GC3.05 global coupled model (GCM) perturbed parameter ensemble (Murphy *et al.*, 2018). The 12 RCM ensemble members are modelled on the basis of no downturn in greenhouse gas emissions, using the Representative Concentration Pathway 8.5 (RCP8.5), therefore taking a worst-case scenario approach in a similar vein to studies such as Ficklin & Barnhart (2014) and Lee *et al*. (2018). Uncertainty in the GCM, as well as the natural climate variability cause the 12 ensemble members to differ (Kendon *et al.*, 2019). The 12 km gridded UKCP18 data were extracted to a single point at the centre of each grid square, and these points were treated as pseudo-meteorological stations. Out of the total 28 grid squares that have the centre point lying within one of the five catchments, 13 were selected as pseudo-meteorological stations (Figure 5.3).

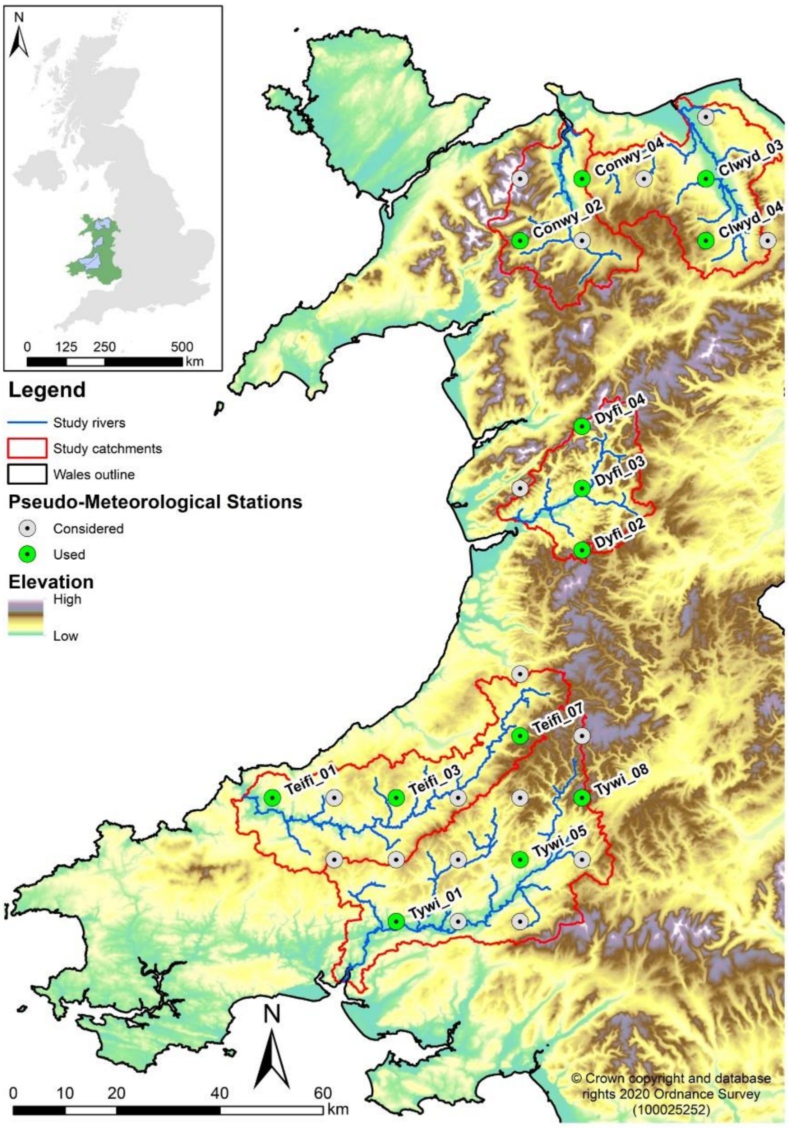

Figure 5.3. Pseudo-meteorological stations used in SWAT future weather input, those selected for use in the study are highlighted in green and labelled.

These selections were made to ensure good coverage across all catchments, considering the potential changes in precipitation and temperature based on elevation, and to manage the computational resource limitations in the process of extracting grid values to the point locations. Where catchments share a boundary (Clwyd and Conwy; Teifi and Tywi), all pseudo-meteorological stations in both catchments were made available as inputs to each individual catchment model to provide additional weather data coverage.

5.3.3 Hydrological modelling

In this study, we have used the Soil and Water Assessment Tool (SWAT), a physically based, semi-distributed hydrological model developed by the US Department of Agriculture's Agricultural Research Service (Arnold *et al.*, 1998). SWAT has been used internationally and for a variety of purposes due to the wide range of catchment processes that the model considers (Gassman *et al.*, 2014). In recent years, SWAT has been used for purposes such as ecological impact assessments (Chambers *et al.*, 2017; Kakouei *et al.*, 2018), crop/agricultural planning studies (Fereidoon & Koch, 2018; Yang *et al.*, 2018), hydropower assessment (Park & Kim, 2014; Haguma *et al.*, 2017; Abera *et al.*, 2018), and future flood flow characterisation (Singh & Goyal, 2017; Xu *et al.*, 2019). The model has also been widely used for investigating changes in the quantity and timing of streamflows under climate change in a variety of catchment types; for example, Coffey *et al*. (2016) for two catchments in Ireland, Perra *et al*. (2018) for a Mediterranean catchment, Sultana & Choi (2018) for a snow-dominated catchment in northern California, and Yuan *et al*. (2019) for the Yangtze River in China. Water quality impacts under future climate change have also been studied using SWAT, with papers such as Nerantzaki *et al*. (2016) and Jilo *et al*. (2019) studying the sediment yield in catchments in Greece and Ethiopia, respectively; Pesce *et al*. (2018) inspecting nitrogen, phosphorous and dissolved oxygen in a catchment in Italy, and Yang *et al*. (2017) investigating total nitrogen changes in a river in northeast China.

SWAT operates at a daily time-step and is designed for river basin-scale use. Being semi-distributed, SWAT makes use of sub-basins, which are further divided into Hydrological Response Units (HRUs) of areas with similar soil type, LULC and topography. The model is computationally efficient due to calculations being performed for each HRU and later summed together at sub-basin outlets (Bailey *et al.*, 2016). Full and detailed information on the equations, inputs and processes that govern the behaviour of the model, as well as the outputs, are provided in the SWAT theoretical documentation (Neitsch *et al.*, 2011) and the input/output documentation (Arnold *et al.*, 2012).

Here, SWAT has been used to simulate daily streamflow and four water quality parameters, total nitrogen (TN), total phosphorus (TP), suspended sediment (SS), and dissolved oxygen (DO). Each study catchment was set-up, calibrated, and validated separately. The key inputs to the SWAT model are elevation, LULC, soil characteristics, and weather data. The 5 m resolution OS Terrain 5 DEM from Ordnance Survey was used alongside soil data from the EU soil database (European Commission, 2004) and land cover data from the CORINE Land Cover dataset (Copernicus Land Monitoring Data; EEA, 2012). Historical daily observed air temperature and precipitation data were obtained from the Centre for Ecology and Hydrology's (CEH) Climate, Hydrology and Ecology research Support System (CHESS) dataset (Robinson *et al.*, 2017). Historical streamflow data was obtained from CEH's National River Flow Archive dataset (NRFA, 2020).

Calibration and validation was completed with the SWAT Calibration and Uncertainty Programme 2012 (SWAT-CUP), specifically using the Particle Swarm Optimisation (PSO) method (Kennedy & Eberhart, 1995). The PSO method iteratively improves the model simulation proficiency, taking into consideration the previous best-known calibration point, and allows for a quicker and more efficient calibration process (Clerc & Kennedy, 2002; Coello *et al.*, 2004). SWAT was calibrated at each study catchment against observed daily average streamflow only. Calibration was undertaken for the period 1985 to 1998, with a 3-year model warm-up period occurring beforehand and ten simulations with ten iterations per simulation were completed for each catchment calibration. Kling-Gupta efficiency (KGE; Equation 5.1) was used as the goodness-of-fit metric for model calibration (Gupta *et al.*, 2009):

$$KGE = 1 - \sqrt{(r-1)^2 + (a-1)^2 + (\beta-1)^2} \qquad \textbf{(Eq. 5.1)}$$

where r is the linear correlation between observations and simulations; α refers to the ratio between the standard deviation in the simulated flow and the standard deviation in the observed flow; and β is the ratio between the mean simulated and mean observed flow.

The calibrated SWAT model was then used for a validation run for the period 1999 to 2014, once again with a 3-year warm-up period beforehand. Calibration and validation KGE values for each catchment are shown in Table 5.2[3]. A total of 17 parameters were used in the calibration, the names and details of these are provided in Table 5.3. These parameters were selected based on a literature review of similar catchments, and after consultation with experienced SWAT modellers.

Table 5.2. Number of hydrological response units (HRUs) and sub-basins per catchment model. Number of sub-basin containing gauging station also show, along with Kling-Gupta efficiency (KGE) values for the calibration and validation periods.

Catchment	Total HRUs	Total sub-basins	Gauge sub-basin (outfall)	Calibration KGE	Validation KGE
Clwyd	697	302	297	0.810	0.788
Conwy	770	202	194	0.770	0.718
Dyfi	662	227	223	0.788	0.728
Teifi	1333	425	420	0.851	0.723
Tywi	1697	496	459	0.841	0.717

Table 5.3. SWAT parameters calibrated through SWAT-CUP programme using particle swarm optimisation method.

Parameter	Description	Input file location
ESCO	Soil evaporation compensation factor	.bsn
EPCO	Plant uptake compensation factor	.bsn
SURLAG	Surface runoff lag time	.bsn
GW_Delay	Groundwater delay	.gw
Alpha_BF	Baseflow alpha factor	.gw
GWQMIN	Threshold depth of water in shallow aquifer for return flow to occur	.gw
RCHRG_DP	Deep aquifer percolation fraction	.gw
REVAPMN	Threshold depth of water in shallow aquifer for "revap" to occur	.gw
GW_REVAP	Groundwater "revap" coefficient	.gw
ALPHA_BF_D	Baseflow alpha factor for deep aquifer	.gw
CANMX	Maximum canopy storage	.hru
CN2	SCS runoff curve number for moisture condition 2	.mgt
CH_N2	Manning's "n" value for the main channel	.rte
CH_K2	Effective hydraulic conductivity in main channel alluvium	.rte
SOL_AWC	Available water capacity of the soil layer	.sol
SOL_K	Saturated hydraulic conductivity	.sol
SOL_Z	Depth from soil surface to bottom of layer	.sol

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[3] Charts comparing observed and simulated streamflow for each catchment during the calibration period can be found in Appendix 1, Figures A1.1 to A1.5.

Due to the lack of sufficient historical sampling data, water quality parameters were not calibrated. However, a validation of the water quality output was attempted, by comparing model output to the limited measured water quality data available from the Natural Resources Wales (NRW) water quality data archive (NRW, 2019b). While the water quality validation showed a good degree of correlation for DO in most catchments, the correlations for the other factors were less agreeable (Table 5.4). The modelled TP, TN and SS output do all correlate well with modelled streamflow however (Table 5.5), suggesting that this is the key driver of change in the uncalibrated model.

Table 5.4. Pearson's correlation values between observed (where available) and modelled water quality concentrations. Underlined values indicate a correlation significant at *p* <0.05, those shown in bold are significant at *p* <0.01.

Catchment	Suspended sediment	Total phosphorous	Total nitrogen	Dissolved oxygen
Clwyd	-0.033	0.174	0.109	**0.646**
Conwy	0.200	-0.026		0.022
Dyfi	-0.139	-0.090		0.060
Teifi	0.099	0.024	0.075	**0.806**
Tywi	**0.788**	-0.172	0.116	**0.788**

Table 5.5. Pearson's correlation values between modelled water quality concentrations and streamflow. Underlined values indicate a correlation significant at *p* <0.05, those shown in bold are significant at *p* <0.01.

Catchment	Suspended sediment	Total phosphorous	Total nitrogen	Dissolved oxygen
Clwyd	0.033	0.035	**0.063**	**0.185**
Conwy	**0.654**	**0.626**	**0.707**	**-0.539**
Dyfi	**0.923**	**0.602**	**0.595**	**-0.588**
Teifi	-0.022	-0.024	**0.361**	**0.204**
Tywi	**0.091**	**-0.093**	**0.442**	**0.226**

Future runs of the calibrated and validated SWAT model were completed for the hydrological years 2021 to 2080, where a hydrological year runs from 1st October to the following year's 30th September and is named after the later year. Some discontinuity in the model output is caused by the need to run the models in sections due to database size restrictions on the output files. This was mitigated as far as possible by including a 7-year warm-up period at the start of all model run sections. Model run sections were as follows, Conwy and Dyfi: 2020-2050, 2051-2080; Clwyd: 2020-2040, 2041-2060, 2061-2080; Teifi and Tywi: 2020-2035, 2036-2050, 2051-2065, 2066-2080.

5.3.4 Trend analysis

To assess any trends displayed in the future climatic, streamflow, and water quality data, the Mann-Kendall (MK) test was performed (Mann, 1945; Kendall, 1975). MK tests for a monotonic positive or negative change in a time series by calculating Kendall's tau (association test) between each value and all of the proceeding values (Helsel & Hirsch, 2002). The nature of hydrological data lends itself to this nonparametric method as it is generally non-normally distributed and displays seasonality, going against a constant distribution assumption (Kundzewics & Robson, 2004). Additionally, auto-correlation is often also displayed in the data, making a parametric test further unsuitable; it is for this reason, that during the MK test the Hamed & Rao method of auto-correlation correction was also applied (Hamed & Rao, 1998). Sen's slope estimator (Sen, 1968) was also used in order to better estimate the size and direction of any detected trends.

Trend analysis for both streamflow volumes and water quality factors were conducted for annual (hydrological years) and seasonal (winter, December to February; spring, March to May; summer, June to August; autumn, September to November) averages. Streamflow extremes were also considered, testing seasonally and annually for trends in 1-day maximum flow, 1-day minimum flow, and number of low flow days (defined as days were streamflow is less than the 5th percentile value for the full 60-year dataset). High flow events have also been analysed, with the number of independent events per year with at least one streamflow peak above the 60-year 95th percentile value being calculated. Change in event length was also analysed, being defined as the period either side of any peak flow where streamflow was greater than baseflow; at the start and end of each event streamflow is therefore equal to baseflow. The digital filter method defined by Sawicz *et al*. (2011) has been used to calculate direct runoff, as per Equation 5.2, to subsequently enable the calculation of baseflow:

$$Q_{Dt} = cQ_{Dt-1} + \frac{1+c}{2}(Q_t - Q_{t-1}) \qquad \textbf{(Eq. 5.2)}$$

where Q_{Dt} is direct runoff at a given time-step, c is a constant with value 0.925, Q_{Dt-1} is direct runoff at the previous time-step (at time-step t = 0, Q_D is assumed to be 0) and Q is total streamflow. Baseflow (Q_{Bt}) for the same time-step was then calculated using Equation 5.3:

$$Q_{Bt} = Q_t - Q_{Dt} \qquad \textbf{(Eq. 5.3)}$$

An event containing multiple peaks above the dataset 95th percentile is classified as a single event. In addition, a trend analysis was also performed on the input future temperature and precipitation data to identify any annual or seasonal changes occurring.

5.4 Results

Our results show a large decrease in summer and autumn average streamflows, with a corresponding increase in spring and winter flows. Overall, these seasonal changes result in a small decrease in annual average flows. Trends in extreme streamflows show much greater variability between catchments and seasons. However, all catchments display a trend for an increasing number of extreme low flow days, as well as lower 1-day minimum flow volumes. Water quality appears to be highly linked to streamflow, especially changes in extreme high and low flows. Summer, in particular, shows lower water quality standards across all catchments and variables. To provide further context to the streamflow and water quality results, we first include a brief trend analysis of seasonal and annual average mean temperatures and precipitation. As with all of the trend analysis subsequently presented, this has been completed using the MK trend test. Due to the lack of calibration of water quality parameters, only long-term seasonal and annual average trends have been presented in this study, unlike streamflows, where extreme flows have also been analysed.

5.4.1 Climate projections

Future air temperature shows a significant ($p < 0.01$) increase for all stations in all seasons, as well as annually, as can be seen in the statistics reported in Figure 5.4 relating to the mean temperature of all stations. For precipitation trends, winter volumes increase across the board ($p < 0.01$), while summer volumes decrease ($p < 0.01$). Although autumn precipitation volumes all decrease across the future study period, at only six of the thirteen stations is this highly significant ($p < 0.01$), a further two are significant at $p < 0.05$, and the remaining five are not significant; the average across all is significant at $p < 0.05$. For spring, there is combination between upward and downward trends, but none are significant.

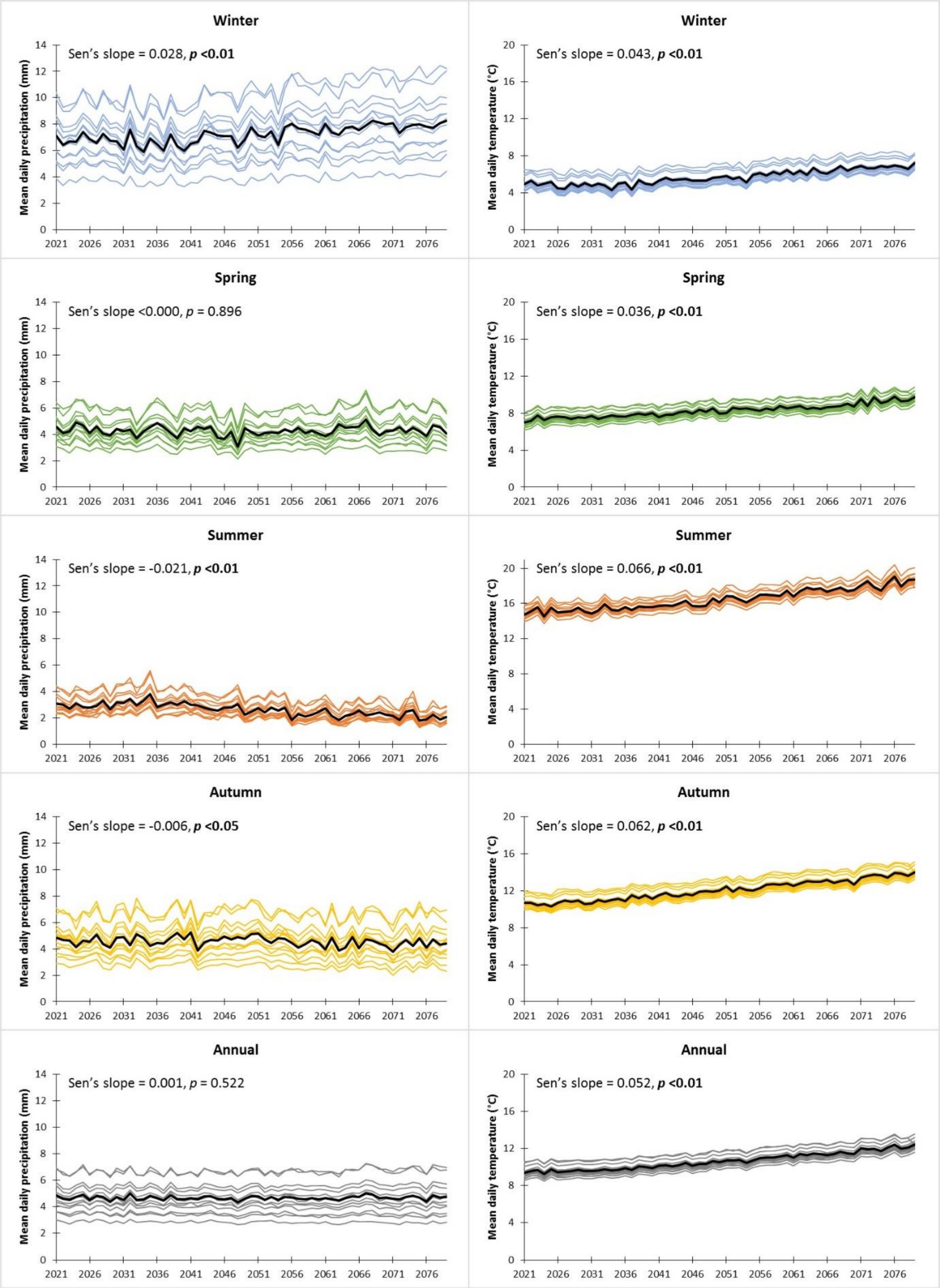

Figure 5.4. Future projections (2021-2080) for seasonal and annual daily mean precipitation (left) and temperature (right). Thin coloured lines represent the 13 pseudo-meteorological stations in the catchments; thick black line denotes the average across all stations. Sen's slope statistics for the thirteen station mean also show, bold *p* values are significant at <0.05.

5.4.2 Streamflow

5.4.2.1 Long-term averages

Data relating to the average of all twelve model outputs[4] for future streamflows display long-term trends both annually and seasonally, however, the direction and statistical significance of these varies between catchments. Using the 1990-2010 period average as a baseline, it can be seen that in most cases there is consistency between catchments (Figure 5.5). Where there are exceptions to this, these mainly relate to the Dyfi catchment, which generally displays a smaller magnitude of change, especially in the spring, autumn, and annual average. Another notable outlier is the Clwyd catchment in winter, which shows a clear decrease in the latter half of the study period, which is not observed in the other catchments. These relationships are further highlighted in the MK trend analysis results, which are summarised in Figure 5.6. A statistically significant increase in spring flows is observed in all catchments (Clwyd & Dyfi p <0.05; Conwy, Teifi & Tywi p <0.01), while a corresponding highly significant (p <0.01) decrease in autumn flows is identified in all catchments except the Dyfi (p = 0.530). Summer streamflows also decrease in all catchments, but only statistically significantly in the Conwy (p <0.05) and Dyfi (p <0.01). Winter streamflows are the most varied, with the Clwyd and Teifi decreasing, and the Conwy, Dyfi and Tywi increasing; these trends are only significant for the three most northerly catchments (p <0.01). Finally, when looking at annual average streamflows, all catchments except the Dyfi display declining trends, albeit only significantly in the Clwyd (p <0.01); the Dyfi increases significantly (p <0.01).

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[4] Projected seasonal and annual average streamflow for each individual ensemble member and catchment can be found in Appendix 2, Figures A2.1 to A2.5.

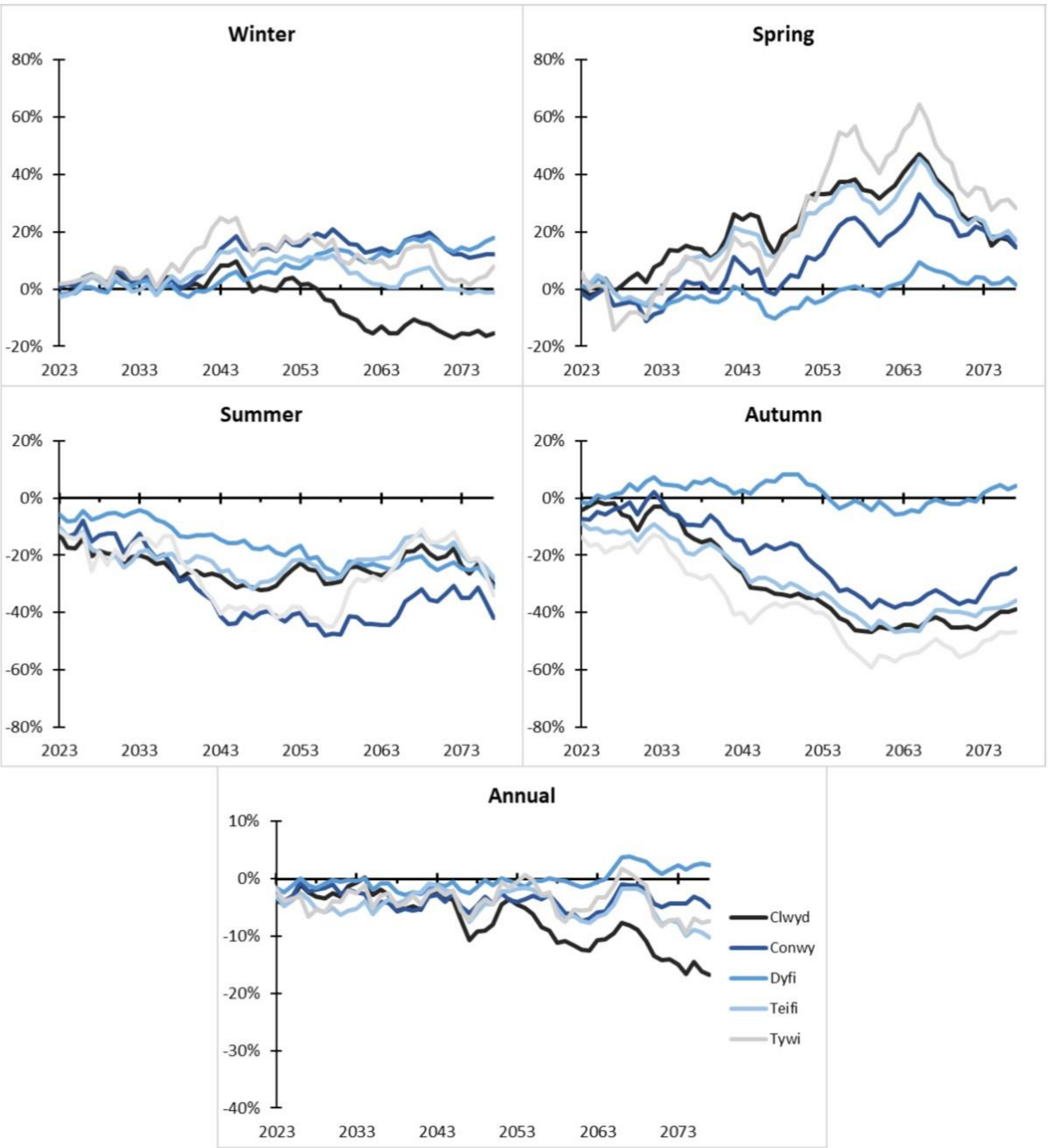
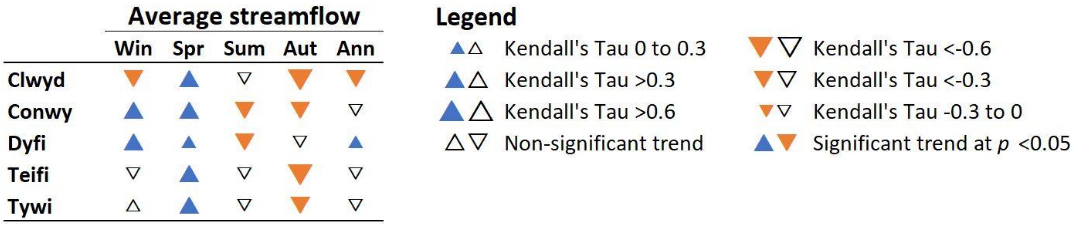


Figure 5.5. Percentage change from the 1990-2010 baseline average (y-axis) for a 5-year moving average of 2021-2080 future streamflow data (x-axis). Seasonal and annual averages shown for each catchment. Please note that the y-axis scale on the annual average graph (bottom) is a factor of two smaller than the seasonal average graphs.



Average streamflow

	Win	Spr	Sum	Aut	Ann
Clwyd	▼	▲	▽	▼	▼
Conwy	▲	▲	▼	▼	▽
Dyfi	▲	▲	▼	▽	▲
Teifi	▽	▲	▽	▼	▽
Tywi	△	▲	▽	▼	▽

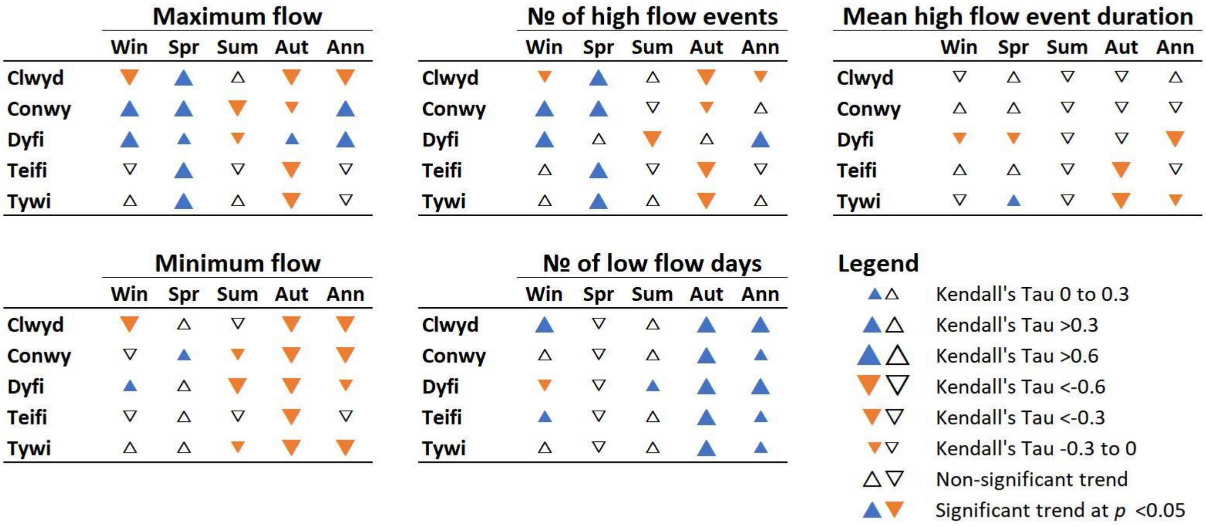
Legend

▲△ Kendall's Tau 0 to 0.3
▲△ Kendall's Tau >0.3
▲△ Kendall's Tau >0.6
△▽ Non-significant trend
▼▽ Kendall's Tau <-0.6
▼▽ Kendall's Tau <-0.3
▼▽ Kendall's Tau -0.3 to 0
▲▼ Significant trend at *p* <0.05

Figure 5.6. Overview of the direction, magnitude and significance of annual and seasonal average trends in projected future (2021-2080) average streamflow, as detected by Mann-Kendall trend analysis, based on the average of all 12 RCM model outputs.

5.4.2.2 Extreme streamflows

Firstly, we can see that across all catchments, maximum 1-day flows are increasing significantly (*p* <0.01) in spring, while a decrease is shown in autumn in all catchments except the Dyfi (Figure 5.7). Furthermore, the Conwy and Dyfi display a significant change (*p* <0.01) in maximum 1-day flow volume in winter and summer, an increase and decrease respectively. Minimum 1-day flows decrease in summer, autumn and annually in all catchments, with this trend being statistically significant in autumn in all catchments (Figure 5.7).



Maximum flow

	Win	Spr	Sum	Aut	Ann
Clwyd	▼	▲	△	▼	▼
Conwy	▲	▲	▼	▼	▲
Dyfi	▲	▲	▼	▲	▲
Teifi	▽	▲	▽	▼	▽
Tywi	△	▲	△	▼	▽

№ of high flow events

	Win	Spr	Sum	Aut	Ann
Clwyd	▼	▲	△	▼	▼
Conwy	▲	▲	▽	▼	△
Dyfi	▲	△	▼	△	▲
Teifi	△	▲	▽	▼	▽
Tywi	△	▲	△	▼	△

Mean high flow event duration

	Win	Spr	Sum	Aut	Ann
Clwyd	▽	△	▽	▽	△
Conwy	△	△	▽	▽	▽
Dyfi	▼	▼	▽	▽	▼
Teifi	△	△	▽	▼	▽
Tywi	▽	▲	▽	▼	▼

Minimum flow

	Win	Spr	Sum	Aut	Ann
Clwyd	▼	△	▽	▼	▼
Conwy	▽	▲	▼	▼	▼
Dyfi	▲	△	▼	▼	▼
Teifi	▽	△	▽	▼	▽
Tywi	△	△	▼	▼	▼

№ of low flow days

	Win	Spr	Sum	Aut	Ann
Clwyd	▲	▽	△	▲	▲
Conwy	△	▽	△	▲	▲
Dyfi	▼	▽	▲	▲	▲
Teifi	▲	▽	△	▲	▲
Tywi	△	▽	△	▲	▲

Legend

▲△ Kendall's Tau 0 to 0.3
▲△ Kendall's Tau >0.3
▲△ Kendall's Tau >0.6
▼▽ Kendall's Tau <-0.6
▼▽ Kendall's Tau <-0.3
▼▽ Kendall's Tau -0.3 to 0
△▽ Non-significant trend
▲▼ Significant trend at *p* <0.05

Figure 5.7. Overview of the direction, magnitude and significance of annual and seasonal trends in projected future (2021-2080) extreme streamflows, as detected by Mann-Kendall trend analysis, based on the average of all 12 RCM model outputs.

In terms of number of extreme low flow days and high flow events, a decrease in autumn is seen for high flows, alongside an increase in the number of low flow days (Figure 5.7), suggesting a general reduction in streamflows in autumn corresponding with the average autumn flow data. Similarly, for spring in all catchments except the Dyfi, there is a statistically significant (*p* <0.01) increase in the number of extreme high flow events, once again corresponding to an increase in average spring flows too. Annually, a statistically significant (*p* <0.01) increase in the number of extreme low flow days is observed in all catchments (Figure 5.7), suggesting generally drier conditions in the catchments on average.

When 1-day maximum flow volume and number of extreme high flow events are compared, the trends observed are almost identical in all catchments and seasons (Figure 5.7). In some cases, winter and spring in particular, this combination suggests an increase in both the magnitude and frequency of the largest flows. When looking at the mean high flow event duration, it can be seen that change is projected to be smaller, with a general trend towards shorter events in summer and autumn and longer events in the spring. This leads to a picture of fewer, shorter flooding events in summer and autumn across the country, with spring high flow events becoming more frequent and generally longer. Similarities can also be seen in the 1-day minimum flow volume and number of extreme low flow days; the vast majority of significant increases or decreases in minimum flows are mirrored by a decrease or increase respectively in the number of extreme low flow days. This suggests that in summer and autumn, as well as annually on average, catchments will see a greater number of low flow days, which are also more severe.

5.4.2.3 Annual flow exceedance characteristics

It is clear that significant alterations are projected to take place in future streamflow in terms of both seasonal/annual averages, and extreme flows. These changes in flow regimes of the catchments are also clear when comparing the flow duration curves (FDC) of streamflow for the baseline period (1990-2010) with late-future period streamflow (2060-2080; Figure 5.8). As can be seen, in all catchments, the water volumes that are most regularly exceeded (>75% of the time) are projected to become lower. This decrease is particularly prominent in the lowest flow volumes, those exceeded more than 95% of the time; in keeping with the extreme flows MK trend analysis which also shows minimum flow levels decreasing and more extreme low flow days. High flows vary between catchments, once again in line with the extreme flows trend analysis. The Conwy and Dyfi, for example, both display an increase in discharge volumes exceeded 0 to 25% of the time in the 2060-2080 period compared to the 1990-2010 period. This once again corresponds with the observed trends of larger maximum flows, and a greater number of large flow events per year, both seen in the MK trend analysis. The Teifi & Tywi display little change in high flows between the two periods in the FDCs, which reflects the lack of statistically significant trends seen in annual maximum flow volume and number of extreme high flow events seen in the MK trend analysis. The Clwyd displays the only statistically significant negative trend, in the MK analysis of annual maximum flow and number of extreme high flow events; this is also evident in the FDC, which shows future flow volumes being consistently lower than the 1990-2010 baseline.

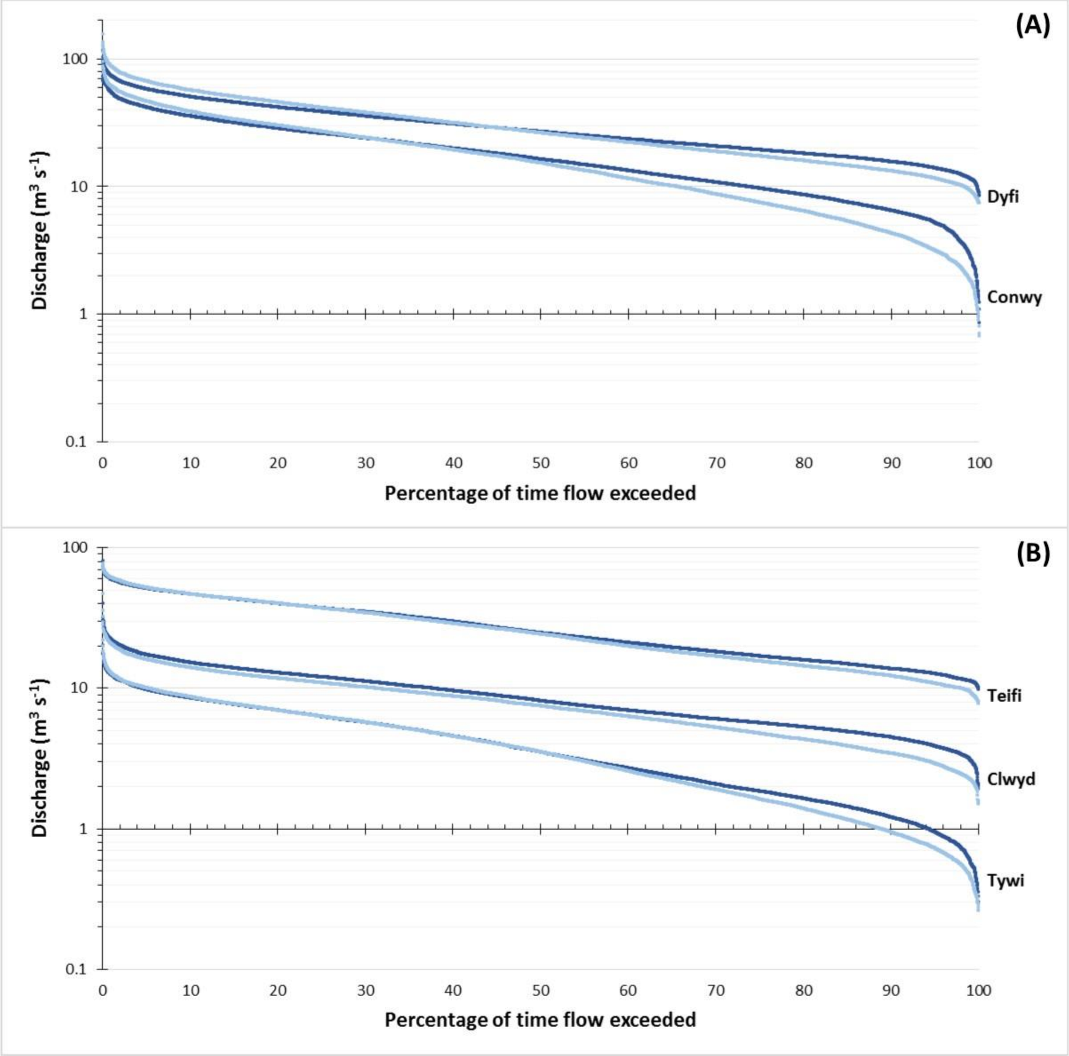


Figure 5.8. Flow duration curves for each catchment; darker of each colour pair represents daily 1990-2010 data; lighter colour represents daily 2060-2080 data. (**A**) Conwy and Dyfi catchments, showing accentuation of both high and low flows. (**B**) Clwyd, Teifi and Tywi catchments, showing accentuation of lower flows.

5.4.3 Water quality

As can be seen in Figure 5.9, in the majority of cases trends seen in each water quality factor are consistent across all catchments and seasons. In terms of SS and TP concentrations specifically, 88% of all of the trends are increasing, with the Dyfi being the only catchment showing negative trends in long-term TP concentrations, in winter, spring and annually.

Summer, in terms of SS concentrations, is the most spatially variable, with the Conwy and Dyfi both displaying a statistically significant decrease (p <0.01). The Tywi is also set slightly apart from the other catchments in terms of SS, in that it has the fewest significant trends, and also shows a significant decrease in autumn SS concentrations (p <0.01), the only catchment to do so. TN concentrations are also mostly consistent spatially, with the Dyfi once again being the main exception, with a decline in concentrations in line with those displayed for the catchment in TP. Additionally, TN levels are shown to be decreasing in winter in the Teifi also, albeit not statistically significantly. All catchments present a statistically significant (p <0.01) increase in summer TN concentrations, while the Conwy displays the same in all seasons and annually. DO levels are generally decreasing over the study period with autumn and annual trends in particular seeing a statistically significant (p <0.01) decrease in all catchment except the Teifi. In winter too, DO is decreasing in all catchment except the Teifi, while in spring the Clwyd, Conwy and Teifi all display an increasing trend. An increasing trend is also observed in the Dyfi for DO in summer, the opposite of that seen in the Clwyd, Teifi and Tywi.

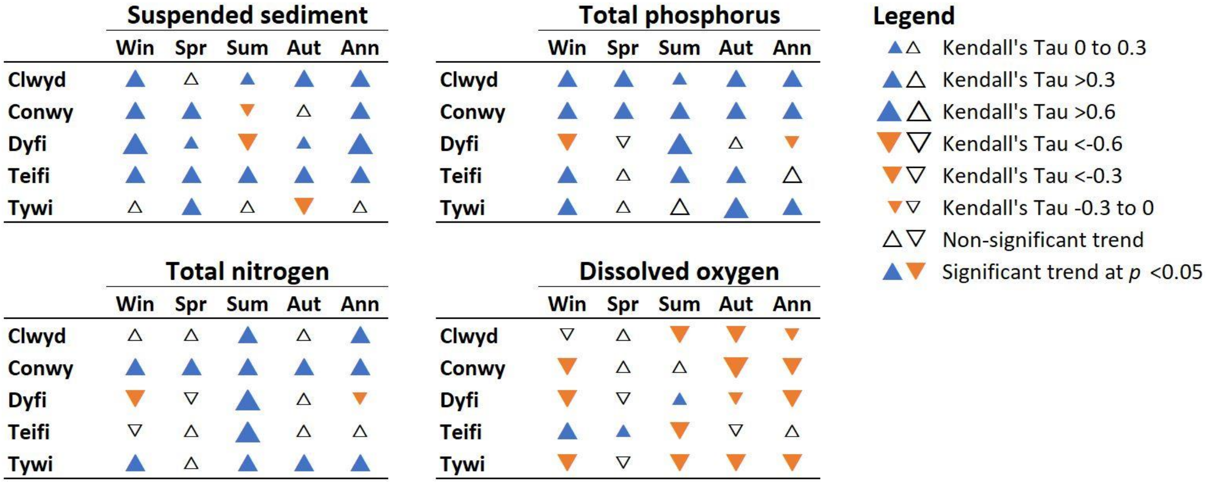


Figure 5.9. Overview of the direction, magnitude and significance of annual and seasonal average trends in projected future (2021-2080) water quality concentrations, as detected by Mann-Kendall trend analysis, based on the average of all 12 RCM model outputs.

5.5 Discussion

5.5.1 Streamflow trends

The results of the MK trend analysis show a selection of spatially varying changes across the five catchments, however, when studying summer and autumn average flows, there is a common pattern in all catchments of a general decrease. For the summer season, this trend is only statistically significant in the Conwy and Dyfi, and in autumn, it is significant in all catchments except the Dyfi. The projected general decline in summer and autumn streamflow is also observed in other research studying mean flows, such as UK CEH (2012) and Fowler & Kilsby (2007). The only trend seen at a statistically significant level in all study catchments, an increase in spring average streamflow, is also observed in these pieces of research. Annual average flows only change significantly in the Clwyd (decrease) and Dyfi (increase), with all other catchments displaying a non-significant decline. These findings are consistent with those of Kay *et al*. (2020), who showed a decreasing trend in mean annual streamflow for four catchments in the west of England and east Wales, as we observed in all catchments except the Dyfi. The same can be said for projections made by the UK Centre for Ecology and Hydrology (CEH), who also show a small decline in mean annual streamflow for Wales up to the 2050s (UK CEH, 2012). This change is primarily driven in all catchments except the Dyfi, by declines in summer and autumn average flow being greater in magnitude than increases in winter and spring.

Arguably, in terms of the magnitude of large streamflows, the Conwy and the Dyfi catchments once again show more similarity with each other, while the Clwyd, Teifi and Tywi are all more closely connected. This can be seen for the annual data, when looking at Figure 5.8 in particular, with the Conwy and Dyfi displaying an accentuation of both the highest and lowest flows, with greater accentuation in low flows than high. The remaining three catchments only show an accentuation of low flows, this being particularly prominent in the Clwyd and Tywi. The Dyfi and Conwy are the most mountainous, steeply sloping, and smallest in area of the catchments, which makes them highly responsive to precipitation, and flashy. It is these specific catchment characteristics that partly foster the observed statistically significant trends of increasing winter and annual maximum streamflow, as well as number of high flow events. Such physical catchment characteristics are known to cause high responsiveness, with studies such as Dunne (1978), Weiler & McDonnell (2006) and Hornberger *et al*. (2014) linking smaller catchment area and greater steepness to a quicker catchment response and larger streamflow events. These responses are further exacerbated by the soil characteristics of the catchments, with the Conwy and the Dyfi in particular being dominated in their upper reaches by peaty and gleysol soils, with the majority of this also lacking underlying groundwater or aquifer storage (Boorman *et al.*, 1995; European Commission, 2004). This once again causes greater overland and subsurface flow, rather than infiltration and storage, leading to a flashier catchment regime (Boorman *et al.*, 1995).

It is notable however, when comparing the Conwy and the Dyfi, that accentuation of future low flows is much greater for the Conwy than the Dyfi (Figure 5.8), with this likely due to the Dyfi displaying the opposite trend for winter minimum flow and number of low flow days, than the Conwy. In fact, the Dyfi is the only catchment to show a significant reduction in the number of low flow days in winter, as well as an increase in winter minimum flow volume. Such changes can be attributed to LULC characteristics, in this case the larger proportion of coniferous and mixed forestry present in the Dyfi. A study by Robinson *et al*. (2003) demonstrated that for western Europe, forest areas, in particularly those that are coniferous-dominated, help to maintain higher baseflow conditions. This relationship also aids in explaining the non-significant increase seen in the winter low flows for the Tywi, which has the second largest proportion by some margin of LULC designated as coniferous and mixed forestry. Furthermore, the statistically significant increase in annual average flows in the Dyfi is driven by increases seen in winter and spring streamflows, outweighing decreases in summer and autumn. This difference from the other catchments is also likely due to the large proportion of forested land in the Dyfi; Teutschbein *et al*. (2015), for example, showed that increased forest cover led to increased annual average flow in their study of sixteen small catchments in Sweden.

Annual low flows in all catchments show an accentuation of presently seen low flows, into the 2060-2080 period (Figure 5.8); this is likely due to the statistically significant declines seen in summer and autumn average flows into the future (Figure 5.6). These seasons traditionally have seen the lowest flows, so the fact that they are generally getting drier and warmer, would explain this decline in minimum flow volume. This trend observed in low flows across the catchments is in line with trends described in Kay *et al*. (2020), who showed for ten catchments in the UK, under RCP8.5 conditions, low flows are declining in volume. This is particularly seen in the more westerly of the catchments studied (Kay *et al.*, 2020), those closest to this study’s catchments.

Our results correspond with other research conducted recently in the UK in terms of seasonal changes in high and low flows, especially when considering the decrease in low summer and autumn flows, and the increase in high winter and spring flows. Visser-Quinn *et al*. (2019), for example, detailed an increase in the magnitude, duration and frequency of both high and low flow events for Wales in the far future (2090s) under RCP8.5. Our results also show an increase in the frequency and magnitude of such events, however, in terms of event duration we find the opposite trend, a decline in most seasons as well as annually. Our results also show an increasing number of extreme high winter flow events, and extreme low autumn flows specifically, also corresponding with the results of Collet *et al*. (2018). When studying the UK and Wales as part of wider studies, Marx *et al*. (2018) also showed a decline in mean annual low flows in Atlantic influenced western Europe, albeit the smallest change of all regions across Europe. Additionally, Thober *et al*. (2018) found an increase in high flows and flooding in the UK under future climate scenarios representing RCPs 2.6, 6.0 and 8.5.

5.5.2 Water quality trends

Unlike the streamflow trends discussed, the results of the MK trend analysis of water quality factors is much more homogenous across the study region. The exceptions to this are the Dyfi catchment in terms of TP and TN in particular, and the Teifi in terms of DO; these outliers can be explained by studying the catchment characteristics. The Dyfi catchment, for example, has the lowest proportion of land designated as agricultural of all of the catchments, and the largest proportion designated as both forest and scrub (Table 5.1). These characteristics give the Dyfi catchment a significantly different LULC make-up than the Clwyd, Teifi and Tywi in particular. Agricultural land is well documented to be one of the highest contributors to TP and TN levels in river systems (Edwards *et al.*, 2000; Burt *et al.*, 2011; Mockler *et al.*, 2017; Weigelhofer *et al.*, 2018). Burt *et al*. (2011) stated that on average in England and Wales, 60% of nitrogen in surface waters originates from agricultural land, but this can be as high as 90% in agriculturally-dominated catchments. Similarly, for phosphorus, the House of Commons Environmental Audit Committee (2018) reported that run-off from agricultural land was one of the main sources of TP in surface waters, especially at times of highest water levels, i.e. winter and spring in this study’s catchments. These relationships, and the significantly lower proportion of agricultural land in the Dyfi catchment, go some way to explain this marked departure from the trends seen in all other study catchments. This LULC with TP and TN relationship also explains the trends seen in all catchments except the Dyfi, for example increases in winter TP in the more agriculturally-dominated catchments. Furthermore, the increases seen in summer TP and TN in all catchments are also indicative of the dominance of in-stream processes on their generation during warmer conditions (Edwards *et al.*, 2000). Moreover, given the dependence of TP and TN concentrations on streamflow, as aforementioned and demonstrated in Table 5.5, it can also be observed that the declines in winter and spring TP and TN in the Dyfi relate to the unique streamflow trends observed in this catchment. Specifically, the Dyfi displays the only statistically significant increase in low volumes in winter, as explained previously. Additionally, decreases in TP and TN observed annually relate to the only statistically significant increase in annual average flows displayed in any of the five catchments. These correlations also help to explain the departure from the generally congruous trends in streamflow and water quality displayed between the Conwy and Dyfi, with the only major differences observed in their streamflow responses being in annual average and winter low flows.

The SS concentration results show a consistent rise across almost all catchments and seasons. The general uplift is likely due to a variety of reasons depending on the season. Certainly, in the spring and winter, increasing trends observed in the number and magnitude of high flow events is likely the cause, along with an increase generally in average flows. These larger flows not only increase debris washed into river systems by overland flow, but also increase bank and bed erosion, as well as bed transport (Zeiger & Hubbart, 2016; Janes *et al.*, 2017; Vercruysse & Grabowski, 2019), causing an increase in total SS concentrations. In summer and autumn, with temperatures increasing and precipitation decreasing, there is an increased likelihood of drought, as well as fewer rainy days. This means that when rain does arrive, there is much more dust and debris to be washed from the land surface into river systems, especially as dry land also has lower infiltration rates (Clark *et al.*, 2017; Pulley & Collins, 2019). Combined with the fact that lower streamflows have less dilution potential, this is the likely cause of the SS increases seen in these seasons (Whitehead *et al.*, 2009b). Negative trend shown in summer Conwy and Dyfi SS concentrations, are likely caused by statistically significant declines in maximum flow (both p <0.01) and average flow (Conwy p <0.05; Dyfi p <0.01) volumes during the season across the study period, not seen in the other catchments

The observed downward trends in DO seen for most seasons in the majority of catchments are likely linked to the rise in air temperatures seen in all seasons and annually (Figure 5.4). Raised air temperatures have been shown to correlate positively with average water temperatures, albeit this relationship can be masked or affected by factors such as discharge volume, upstream dams and point source inputs (Webb *et al.*, 2003; Caissie, 2006; Hannah & Garner, 2015; Beaufort *et al.*, 2020; Daniels & Danner, 2020). The known negative relationship between stream water temperature and DO concentration due to the decreased carrying capacity of warmer water (Ravansalar *et al.*, 2016; Chaturvedi & Misra, 2020), is therefore likely to be the cause of the declines seen in the study catchments. Furthermore, the broadly increasing concentrations of TP and TN shown in all catchments will likely also have an impact, causing an increase in aquatic plant growth during warmer temperatures, reducing oxygen levels in waters.

When studying water quality results as a collective, a clear decrease in water quality across all catchments and seasons can be observed. There is mostly agreement in terms of trend direction, in spring and autumn, however, in terms of statistically significant trends, more of these are present in summer, winter and annually. As previously mentioned, the key outlier is the Dyfi catchment, mainly due to its unique LULC characteristics compared to the other catchments, however, here too there are still significant water quality challenges, especially in the autumn.

5.5.3 Study implications

This research has been undertaken to provide a backdrop on which future planning, adaptation, and mitigation measures can be based for various industries. It is some of the first to make use of the new UKCP18 future climate projections and is certainly the first to investigate the impact of the projections for streamflow and water quality in Wales. It is hoped that by providing future projections of average and extreme high and low flows, as well as water quality changes, for a large area of Wales, that the results will be applicable to stakeholders in a variety of industries.

This study has shown how, under a worst-case scenario of future emissions, key river systems in Wales will be impacted by climate change in various ways in terms of both water quantity and quality. It is clear that the effects of climate change on streamflows will be most keenly felt seasonally, with annual average flows staying relatively stable in comparison. It is likely that seasonal streamflow patterns currently seen will be exacerbated in the future, with modelling results showing increases in winter and spring average flows and decline in summer and autumn flows. Trends in extreme events will also intensify, with large streamflow events (floods) generally increasing in magnitude and frequency in winter and spring, and low flows (droughts) increasing in frequency and magnitude in summer and autumn in particular. These streamflow trends could have important implications in terms of river ecology, flooding, droughts, and for a variety of stakeholders, not least of all water service providers (WSPs). Given that ~95% of water abstracted for public water supply in Wales is taken from surface sources (DCWW, 2019b), the trends seen could impact on the ability of WSPs to continue to meet demand, especially in summer months, during peak demand (Dallison *et al.*, 2020). Although annual average flows are relatively stable, if declining slightly in most catchments, it is the fact that there will be considerably less water in summer and autumn that could prove problematic from ecological and economic perspectives. Additionally, any increases in winter streamflow will do little to combat summer shortages if there is insufficient capacity to store it for use later in the year; this is particularly true for the Dyfi and Teifi, which are more reliant on river abstraction, compared to impoundment reservoirs used in the other catchments. Furthermore, the quality of incoming water could also cause problems at drinking water treatment plants, with SS, TP, and TN in particular potentially requiring plants to provide more treatment, negatively impacting on energy use, operation and maintenance costs, chemical use, and potentially plant capacity.

The changes seen in annual flow exceedance probabilities could have implications for all large water abstractors, with abstraction licences often stipulating conditions, for example minimum ‘compensation flow’ volumes. With lower flows expected to occur for a greater proportion of the time annually in the future, this could impact on the amount of water available for users such as industry, agriculture, and hydroelectric power generation. UK hydroelectric power generation schemes, both large and small, warrant the attention of future work in particular, due to the large potential impacts of changes in streamflow, and low flows especially. The timing, season length and total generation capacity of hydroelectric generation schemes could be impacted badly by changes in streamflow, potentially affecting the future electricity grid-mix in the UK.

Finally, the changes seen in water quality factors could have an array of impacts on the aquatic ecosystem supported by surface waters. Increases in TP and TN, for example could lead to increases in eutrophication in lakes and rivers. Additionally, the declining DO levels shown could seriously impact on fish species within catchments, with lower levels being well documented to decrease fish survival rates and badly impact spawning and development.

5.6 Conclusions

This research has presented the key changes in future seasonal and annual stream quantity and quality parameters in Wales. The results highlight the need for adaptation now, in order to prepare infrastructure and systems to combat changes, this is especially true for water supply, despite Wales being seen as a water rich region. Planning and mitigating now will help to ensure the continued supply and clean drinking water into the future, especially in the summer and autumn when lower flows and water quality will challenge WSPs.

Finally, we suggest a variety of areas for future research focus. Firstly, adaptation and mitigation measures required for all large abstractors impacted by future changes in river water quantity and quality need to be investigated, to ensure a robust defence against climate-induced changes. Relating to this, further hydrological modelling, using more optimistic projections for future emissions, such as RCPs 2.6, 4.5 and 6.0 would be useful, to enable a broader range of potential future impacts to be compiled, and more informed decisions to be made. This is particularly relevant to WSPs, to enable a continued high-quality future water supply, and to plan the future provision of drinking water treatment plants. Furthermore, investigation of the impact of streamflow changes on the total output generation potential of hydroelectric systems is needed at a national level, to enable robust planning across the country, to ensure stability in the national electricity grid. Lastly, research on climate change links to total water demand is also required, in order to ensure future water supply-demand budgets are achievable under future conditions, and to put in place management measures where necessary.

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CHAPTER 6: STUDY III

Impacts of climate change on future water availability for hydropower and public water supply in Wales, UK

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Author contributions

Richard Dallison: conceptualisation, methodology, software, formal analysis, investigation, data curation, writing – original draft, writing – review & editing, visualisation

Sopan Patil: conceptualisation, writing – review & editing, supervision

Prysor Williams: writing – review & editing, supervision

6.1 Abstract

Climate change is predicted to have a large impact on the hydrological regimes of Welsh rivers. However, its influence on the abstraction capability of key sectors, such as public water supply (PWS) and hydroelectric power (HEP), is not yet fully understood. We use the Soil and Water Assessment Tool (SWAT) to generate future (2021-2079) streamflows under a worst-case scenario of greenhouse gas emissions (Representative Concentration Pathway 8.5) at two catchments in Wales, the Conwy and Tywi. SWAT streamflow output is used to estimate total unmet demand for PWS and changes in generation characteristics for HEP. PWS unmet demand is assessed using the Water Evaluation And Planning (WEAP) system under increasing, static, and declining demand scenarios. Mann-Kendall analysis is performed to detect and characterise trends. Under all future demand scenarios, there is increased occurrence of insufficient streamflow to satisfy PWS demand. For HEP, a decrease in annual abstraction volume results in a loss of generation potential, despite an increasing number of days that maximum abstraction is reached. Changes in HEP generation and PWS availability are most pronounced in the medium-term (2021-2054), with rate of change slowing after 2060. We provide a novel perspective on future water resource availability in Wales, giving context to management planning to ensure future PWS sustainability and HEP generation efficiency.

Keywords: Hydroclimatic change; Hydroelectric power; Hydrological modelling; Trend analysis; Water resource management; Water supply-demand balance

6.2 Introduction

Climate change is a key driver of hydrological regime alteration globally, with prevailing weather conditions being inextricably linked with streamflow. Given the dependence of society on river systems for everyday life, it is of great importance to understand how climate change will impact water resource availability. In the UK, it is widely accepted that climate change will lead to hotter, drier summers and warmer, wetter winters, as well as an increase in the magnitude, frequency and duration of extreme weather events (ASC, 2016a; Lowe *et al.*, 2018). In terms of streamflow, an exacerbation of low and high flows is expected, as well as a reduction in average summer and autumn flows and an increase in winter and spring average flows; these opposing trends should leave annual averages relatively stable (Christierson *et al.*, 2012; Prudhomme *et al.*, 2012; Watts *et al.*, 2015a; Kay *et al.*, 2020). Climate change and streamflow responses in Wales specifically are projected to be in line with the trends suggested for the rest of the UK, with summer mean and maximum temperatures, as well as winter total and extreme precipitation volumes, predicted to increase (ASC, 2016b; Kay *et al.*, 2020). These changes have the potential to cause a large impact on major water consuming sectors such as agriculture, heavy industries, public water supply (PWS), and hydroelectric power (HEP) generation. The Adaptation Sub-Committee (ASC) of the Committee on Climate Change, for example, suggests that PWS and agricultural water demand for irrigation could be two of the most pressurised sectors in the UK under future climate and streamflow changes, with demand potentially outstripping available water resources (ASC, 2016a). Furthermore, Arnell & Delaney (2006) detailed how, even at that time of publication, PWS companies in England and Wales would need to adapt to ensure sufficient raw water resources due to changes to low flow regimes. In Wales, Carless & Whitehead (2013) demonstrate decreasing summer and autumn streamflows with corresponding increases in winter and spring. In the given context of a theoretical 99 kW micro-HEP installation, this causes an accentuation of seasonality in terms of energy generation, with extra supply in wetter seasons compensating for lower supply in drier seasons, leading to an annually stable situation (Carless & Whitehead, 2013). However, these changes are likely to be catchment-specific, depending on the individual catchment's topographic and land cover characteristics as well as the prevailing weather patterns.

In 2018, renewable energy in Wales accounted for 25% of the total electricity generated, with HEP making up 5.2% of this, and therefore 1.3% of overall Welsh electricity generation (Welsh Government, 2019b). A large increase in the number of small-scale HEP schemes has occurred in the last eight years due to financial incentives in the form of Feed-in-Tariffs (FiT; Welsh Government, 2019), and also given that most opportunities for large-scale schemes have been exhausted (Carless & Whitehead, 2013). However, due to the curtailment of the FiT scheme in 2019, the number of new developments has slowed, with further schemes only likely to be commissioned where conditions are optimal (Welsh Government, 2019b). These types of schemes, usually run-of-river in design, generally have little or no water impoundment, making them particularly vulnerable to changes in hydrological conditions. Run-of-river HEP schemes are usually designed and optimised on the basis of historical flow, with flow duration curves used to set abstraction conditions. While this method is a good starting point for designing the most efficient system to maximise power output, it neglects to account for future streamflows. Climate change has the potential to cause major alteration to the hydrological characteristics of river systems, modifying the timing and quantity of available water. High and low flows are particularly likely to be affected (Sayers *et al.*, 2015; Watts *et al.*, 2015a; ASC, 2016b; Kay *et al.*, 2020), and these extreme flows are often important in terms of HEP scheme design. In 2017, the Welsh Government set a target for 70% of electricity consumed in Wales to be generated by renewables by 2030 (Welsh Government, 2019b). HEP plays a small but important role in reaching this target, especially in the winter and spring seasons when electricity generation from other sources, such as solar PV, is lower. Therefore, understanding the nature of change in the abstractable flow for HEP schemes under future climate change is crucial. This will allow for more robust planning of the future energy mix in Wales as well as maximisation of resource use efficiency and electricity generation.

PWS also relies heavily on surface waters in Wales, such as rivers and lakes, with over 95% of the supplied water originating from these sources in the country (DCWW, 2019b). In Wales, PWS is largely under the authority of Dŵr Cymru Welsh Water (DCWW), who provide an average of 800 million litres of water per day to over three million people (DCWW, 2019a). While the majority of surface water used is from lakes and reservoirs, a substantial proportion is taken from lowland river abstractions, especially for rivers in south Wales, such as the Wye, Usk and Tywi, which are often supported by upstream reservoirs in times of low flow (DCWW, 2019a). While the water supply system in Wales is largely resilient to climate change, due to the amount of water stored, changes in climate still do have the ability to change the required water management and places greater pressure on the system (ASC, 2016b). The ASC report a 12% supply-demand surplus for PWS in Wales, however, this is set to decline under projected population growth and climate change, with three of DCWW's water resource zones expected to be in deficit by the 2080s (ASC, 2016b; DCWW, 2019b).

Projected increases in the occurrence of low flows will impact how often PWS and HEP operators are permitted to abstract water from rivers in the future, with stringent hands-off-flow (HoF) regulations applied to abstractions to ensure the protection of low flows downstream. In addition, a greater occurrence of large flow events will potentially be of little use to abstractors to compensate for less abstraction potential due to low flows, if system capabilities, such as turbine size for HEP, do not allow for it. It is therefore important to study these future changes now, to successfully plan for systems that are resilient to climate change and make the most of available future flows.

In this research, we study the impact of climate change on two catchments in Wales, UK, Conwy and Tywi, especially in terms of future water availability for small-scale HEP generation and PWS. This is a less-studied region of the UK in this regard, due to the perceived abundance of water resources in Wales. However, owing to both the reliance on surface waters for PWS and the large recent increase in small-scale HEP projects, this is an important area in which to understand future water resource changes.

6.3 Data and methods

6.3.1 Study catchments

Our two study catchments, Conwy and Tywi (Figure 6.1), were selected due to their contrasting physical characteristics, especially in terms of catchment land use/land cover (LULC), mean catchment slope, and catchment area (Table 6.1); all potentially giving rise to differences in hydrological regime. These catchments are also exploited for their water resources in the form of HEP and PWS, with Natural Resources Wales (NRW) providing licenses for sixteen HEP abstractions for non-impoundment run-of-river schemes in Conwy, and nine in Tywi (NRW, 2019). Both catchments are also used for PWS, however, only the Tywi catchment has an abstraction taken directly from the river, with PWS in Conwy sourced from reservoirs only (DCWW, 2019a). The downstream river-based abstraction in Tywi is supported in times of low flow by upstream releases from the Llyn Brianne reservoir (DCWW, 2019b). This abstraction supplies the largest drinking water treatment plant in DCWW's network, serving a population of ~400,000 in Swansea, Neath, Bridgend and the Vale of Glamorgan (DCWW, 2019a), making the abstraction an important location to study in terms of future water supply-demand balance.

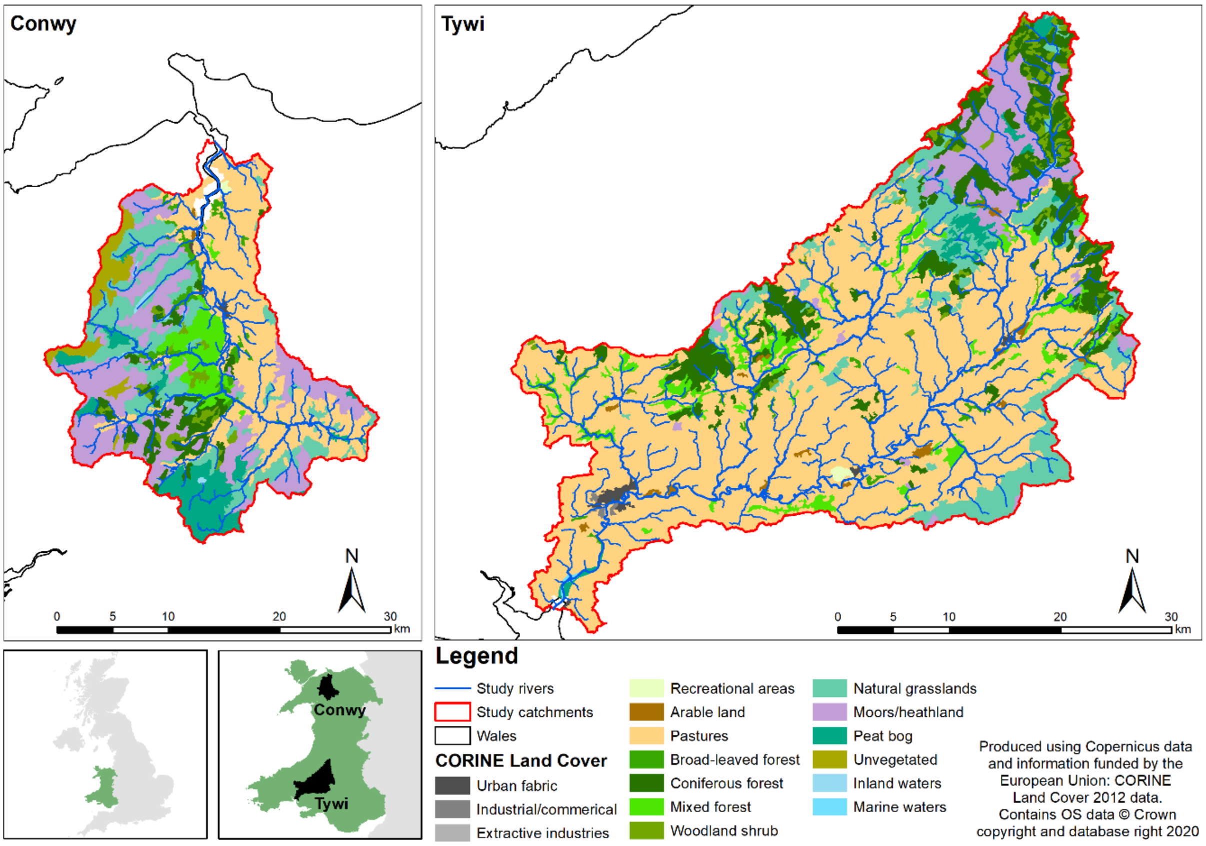

Figure 6.1. Study catchments, displaying CORINE Land Cover classification (EEA, 2012). Inset, location of catchments within Wales, and Wales within the UK.

The Conwy catchment is more mountainous in topography, with a steeper mean slope, and greater maximum elevation, peaking 261 m higher than the Tywi, at 1062 m, near the summit of Snowdon. The Tywi catchment, however, has more than double the drainage area of Conwy, at 1365 km^2 to Conwy's 541.8 km^2 (Table 6.1). The catchments are also contrasting in terms of LULC (Figure 6.1), with the Tywi being dominated by agriculture, pasture specifically (63.9%), which is well-distributed throughout all but the highest elevations in the catchment.

The Conwy catchment, on the other hand, has a larger proportion of scrubland (42.1%), in particular moors/heathland (23.6%) and natural grassland (16.6%), mostly to the west of the main channel, with the eastern side being more pasture-dominated (Figure 6.1). The Conwy also features a large peat bog in the south of the catchment, accounting for 8.4% of total catchment LULC; this is significantly more than is seen in the Tywi (Table 6.1). Forests cover a slightly larger area of the Tywi (16.0%) than the Conwy (13.7%), but the mix of forestry types is different, with notably more coniferous forest in the Tywi (10.1%), while the Conwy has equal proportions of coniferous and mixed forest (5.5%; Table 6.1).

Table 6.1. Key study catchments details. Catchment area, elevation, and slope data derived from 5 m resolution OS Terrain 5 DEM from Ordnance Survey; land use/land cover data derived from 2012 CORINE Land Cover data (EEA, 2012).

		Conwy	Tywi
Catchment area (km^2)		541.8	1364.6
Maximum catchment elevation (m)		1062	801
Mean catchment slope (%)		19.7	16.6
Catchment land use/land cover (%)	**Urban**	**0.7**	**0.7**
	Agriculture	**30.6**	**64.6**
	Arable	0.1	0.7
	Pasture	30.5	63.9
	Forest	**13.7**	**16.0**
	Broadleaf	2.7	1.0
	Coniferous	5.5	10.1
	Mixed	5.5	4.9
	Scrub	**42.1**	**17.1**
	Natural grassland	16.6	8.4
	Moors and heathland	23.6	6.5
	Transitional woodland scrub	1.9	2.2
	Peat bog	**8.4**	**1.3**
	Sparsely vegetated areas	**4.1**	**0.0**

6.3.2 Future streamflow and climate projections

Future streamflows for both catchments were modelled using the Soil and Water Assessment Tool (SWAT) at a daily time-step (Arnold *et al.*, 1998, 2012; Neitsch *et al.*, 2011) from 2021 to 2079. SWAT has been used extensively in the context of future hydrological regime change and water resources assessment globally (Coffey *et al.*, 2016; Perra *et al.*, 2018; Sultana & Choi, 2018; Yuan *et al.*, 2019; Khan *et al.*, 2020), with publications focussing on both HEP (Park & Kim, 2014; Shrestha *et al.*, 2016; Haguma *et al.*, 2017; Abera *et al.*, 2018) and water availability (Sharma *et al.*, 2016; Veettil & Mishra, 2016; Bessa Santos *et al.*, 2019; Rivas-Tabares *et al.*, 2019).

Input data for SWAT were obtained from Ordnance Survey (5 m resolution OS Terrain 5 DEM; Ordnance Survey, 2020), the EU soil database (European Commission, 2004) and the CORINE Land Cover dataset (Copernicus Land Monitoring Data; EEA, 2012). Additionally, historical daily weather data (air temperature and precipitation) and streamflow data, both used for model calibration and validation, was sourced from the Centre for Ecology and Hydrology's (CEH) Climate, Hydrology and Ecology research Support System (CHESS) dataset (Robinson *et al.*, 2017) and the National River Flow Archive dataset (NRFA, 2020), respectively. Streamflow data was taken from gauges with as close to natural flow as possible, station 66011 for Conwy, and 60006 for Tywi. The catchments were calibrated individually with the streamflow data, for a 14-year period of 1985-1998. We used the Particle Swarm Optimisation method (Kennedy & Eberhart, 1995) for model calibration, with the Kling-Gupta efficiency (KGE) as the goodness-of-fit metric (Gupta *et al.*, 2009). The calibration KGE values were 0.770 for Conwy and 0.841 for Tywi. Following the calibration of model parameters, we validated the model for the 1999-2014 period and obtained the KGE values of 0.718 for Conwy and 0.717 for Tywi.

Future streamflows were projected based on the weather input derived from the UK Climate Projections 2018 dataset, 'Regional Projections on a 12 km grid over the UK for 1980-2080' (MOHC, 2018b). A worst-case scenario approach was taken, using an ensemble of twelve regional climate models downscaled from the 60 km HadGEM3-GC3.05 global coupled model (Murphy *et al*., 2018), under Representative Concentration Pathway 8.5 (RCP8.5) conditions. RCP8.5 represents a scenario of high population growth, continued coal use, and no downturn in global greenhouse gas emissions. This approach allows planners the ability to take account of the most extreme adaptation/mitigation potentially need. A summary of future temperature, precipitation and streamflow is shown in Figure 6.2. Temperatures are projected to increase in all seasons, while precipitation and streamflow both increase in the winter and spring, but decrease in the summer and autumn, leading to a small overall annual reduction.

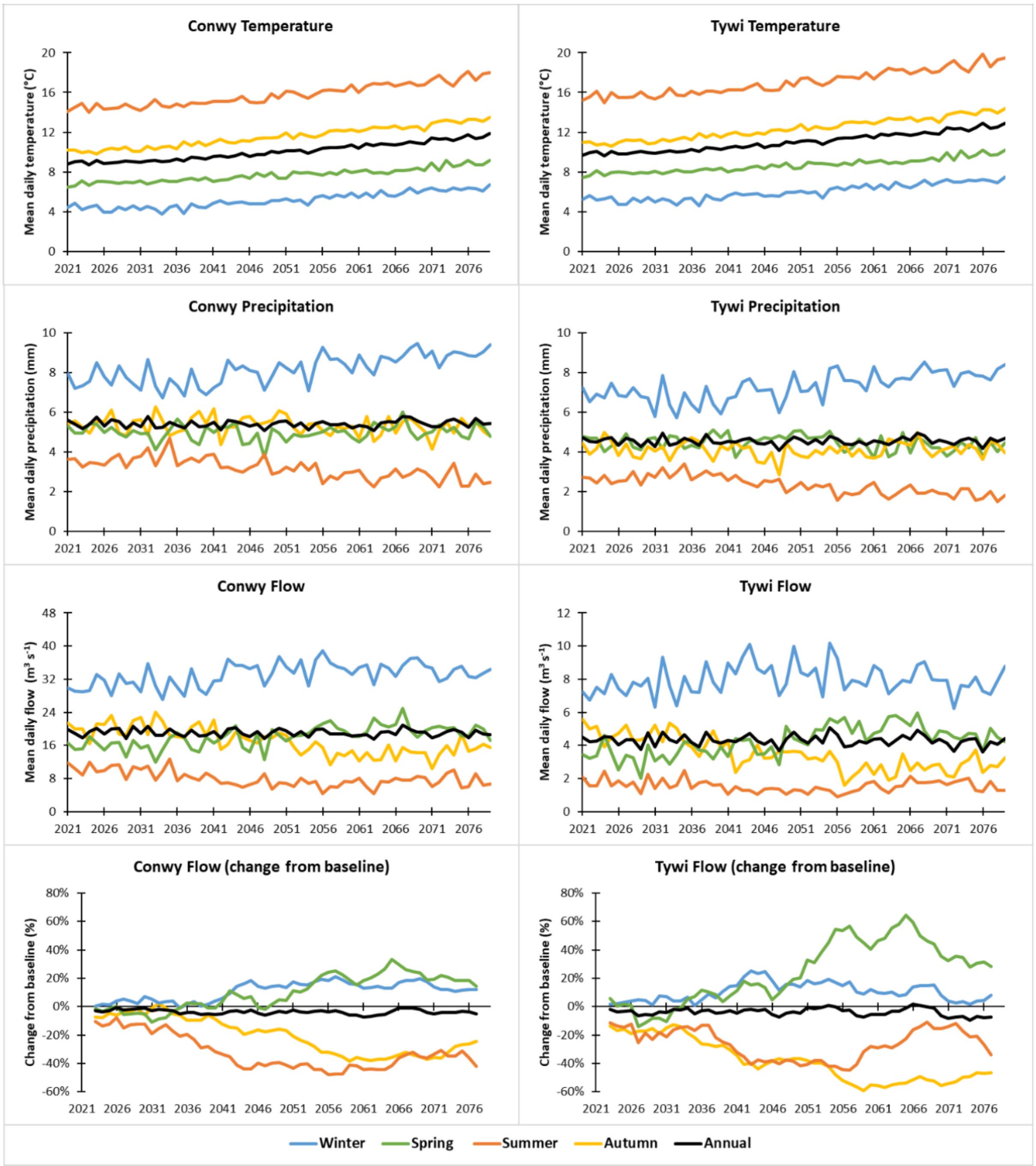

Figure 6.2. Projections for seasonal and annual mean temperature, precipitation and streamflow for Conwy (left) and Tywi (right). Bottom panels shows percentage change from 1990-2010 baseline average for a 5-year moving average of seasonal and annual mean streamflow, at the gauging station locations identified in Figure 6.3.

6.3.3 Hydroelectric power assessment

Assessment of changes in the abstraction regime for HEP locations was undertaken for non-impoundment, run-of-river based schemes only, of which there are a total of sixteen in Conwy, and nine in Tywi. Abstraction locations were obtained from NRW. Due to lack of specific information pertaining to each HEP scheme, such as abstraction licence conditions, scheme layout, generation capacity etc., abstraction conditions were based on general licensing guidelines laid out by NRW (NRW, 2020b). Guidance from the organisation states that for schemes creating a depleted reach (i.e. run-of-river schemes) and that do not operate on rivers supporting salmon spawning or protected species, there are two types of abstraction permitted, Zone 2 (Z2) and Zone 3 (Z3; NRW, 2020). It was assumed for the purposes of this study that all schemes operate under Z2 or Z3; a summary of the conditions placed on abstraction rates of these zones is made in Table 6.2. Schemes are categorised into either zone based on the gradient of the depleted reach, with those below 10% gradient being Z2, and those above being Z3. As information on the actual depleted reach was not available, the average slope of the sub-basin immediately downstream of the abstraction location was taken, and the corresponding zone type applied (Figure 6.3). Under the assumption that each HEP site abstracts the maximum amount of flow available to it, and given daily average streamflow (Q), Equations 6.1 and 6.2 were used to calculate daily average abstraction volume (A_{daily}) at each location in line with abstraction rates dependent on the site zone:

$$Q_{surplus} = Q - HoF \qquad \textbf{(Eq. 6.1)}$$

where HoF represents the compensation hands-off-flow release required to protect low flows and $Q_{surplus}$ is the amount of water available for abstraction, used to calculate A_{daily}:

$$A_{daily} = Q_{surplus} \times Q_{take} \begin{cases} 0, & if\ A_{daily} < A_{start} \\ A_{max,} & if\ A_{daily} > A_{max} \\ A_{daily,} & if\ A_{start} < A_{daily} > A_{max} \end{cases} \qquad \textbf{(Eq. 6.2)}$$

where Q_{take} is the proportion of flow available for abstraction as per the zone conditions, A_{start} refers to the minimum abstraction volume required to start, and for efficient operation of, the turbine, and A_{max} represents the maximum permitted abstraction volume. A further assumption was that an impulse turbine is in use at each site, as is common with small-scale HEP schemes in upper catchment reaches, such as those analysed in this study (Lilienthal *et al.*, 2004; Cobb & Sharp, 2013; Židonis *et al.*, 2015). Impulse turbines have largely high and stable efficiency after approximately 10% of designed flow is achieved (Paish, 2002; Novara & McNabola, 2018; Chitrakar *et al.*, 2020), making them ideal for settings with variable A_{daily} (Cobb & Sharp, 2013). For this reason, A_{start} was set at 10% of A_{max} for each scheme, which is the assumed design flow volume.

Table 6.2. Abstraction conditions as defined by NRW guidelines for Zone 2 and Zone 3 sites (NRW, 2020b).

Condition	**Definition**	**Zone 2**	**Zone 3**
Depleted reach gradient	Gradient of the stream between abstraction point and return flow	<10%	>10%
Hands-off-flow (HoF)	Streamflow rate below which abstraction is not permitted	Q_{95} [a]	Q_{95} [a]
Maximum abstraction volume (A_{max})	Maximum rate of abstraction, above which no additional flow can be taken	1.3 x Q_{mean} [b]	Q_{mean} [b]
Percentage take (Q_{take})	Proportion of flow between HoF and A_{max} permitted for abstraction	50%	70%

[a] Streamflow volume exceeded 95% of the time

[b] Mean annual streamflow volume

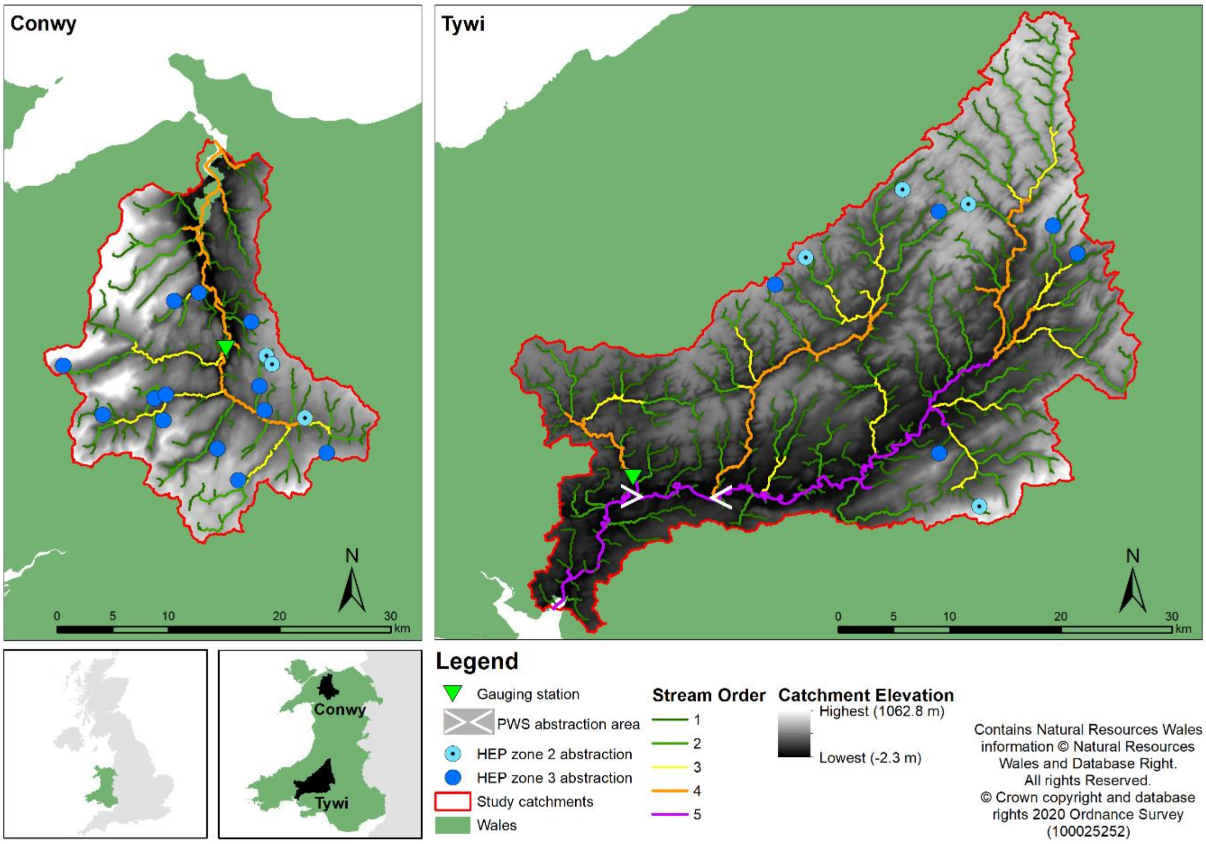

Figure 6.3. Studied abstraction locations for hydroelectric power (HEP) and public water supply (PWS); HEP locations categorised by abstraction regime type. The '>' and '<' markers denote the river section of the PWS abstraction, as to identify the specific location would violate data licence conditions. River network, with stream orders defined by Strahler method, and catchment elevation, based on 5 m resolution OS Terrain 5 DEM from Ordnance Survey, also shown.

6.3.4 Public water supply assessment

Assessment of the impact of future hydrological regime change on PWS was undertaken in the Tywi catchment only, due to the lack of river-based PWS abstraction in the Conwy catchment. The supply-demand balance at the aforementioned single major abstraction location (Figure 6.3) was calculated using the Water Evaluation And Planning (WEAP) system (Raskin *et al.*, 1992; Yates *et al.*, 2005). WEAP is an integrated water resource management model that assimilates the demand and infrastructure management with physical hydrological processes and allows for multiple scenario analysis and comparison (Raskin *et al.*, 1992; Yates *et al.*, 2005). The WEAP model has been used extensively for scenario analysis related to water resource planning and allocation in a variety of contexts, such as the impacts of climate and land use change (Purkey *et al.*, 2008; Joyce *et al.*, 2011; Ashofteh *et al.*, 2013; Esteve *et al.*, 2015; Tena *et al.*, 2019), reservoir and dam operation planning (McCartney & Menker Girma, 2012; Demertzi *et al.*, 2014; Vonk *et al.*, 2014; Azari *et al.*, 2018), ecosystem requirements and environmental protection (Thompson *et al.*, 2012; Fatemi *et al.*, 2013; Flores-López *et al.*, 2016; Momblanch *et al.*, 2020), and population increase and urbanisation impacts (Höllermann *et al.*, 2010; Kumar *et al.*, 2017; Toure *et al.*, 2017; Alamanos *et al.*, 2020). However, WEAP is not designed for detailed optimisation studies, such as that required for HEP (Yates *et al.*, 2005). For this reason, the model has only been used in the PWS analysis for this study.

Future total daily water demand was calculated for three scenarios (Figure 6.4), representing increased, static, and declining abstraction requirement. The increased demand scenario was based on the linear relationship between historical daily temperature and total water abstraction from the location, as presented by Dallison *et al.* (2020). The water abstraction data was provided by DCWW for January 2012 to December 2016 period. The static demand scenario was based on the same 2012-2016 data, with a mean for each day being taken across the 5-year dataset; this year of mean values was then applied every year for the future period. The decreased demand scenario used the same starting base as the static scenario, with demand decreasing linearly by 20% across the period. This decrease is in line with that projected in DCWW's latest water resource management plan (DCWW, 2019a), based on an extensive leakage reduction programme and decreasing domestic water usage, despite a projected increase in the population served. A compensatory HoF was also implemented in WEAP, set at 681.91 million litres per day as laid out in the abstraction license for this location (SWWRA, 1965). Total daily unmet demand (D_{unmet}) was then calculated under each scenario using Equation 6.3:

$$D_{unmet} = Q - HoF - D \qquad \textbf{(Eq. 6.3)}$$

where D is daily total water demand; Q and HoF are defined as Equation 6.1. Due to the aforementioned system of reservoir low flow support by Llyn Brianne, D_{unmet} is therefore also assumed to be equal to the total daily required reservoir release.

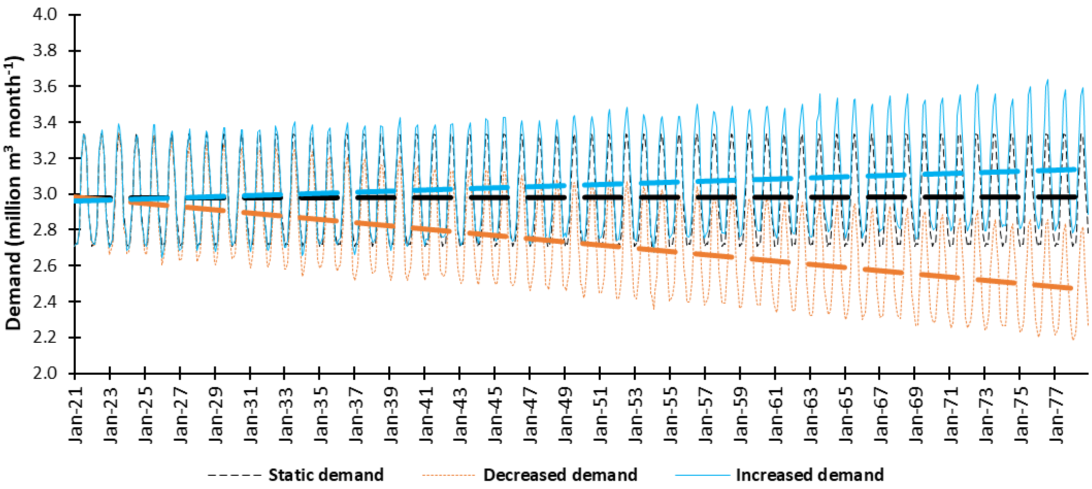

Figure 6.4. Future monthly total water demand at the Tywi public water supply abstraction under the three future water demand scenarios: increased, static, and decreased. Thick dashed lines represent the linear trend of each scenario.

6.3.5 Trend analysis

Trends in the output data from the HEP and PWS calculations were analysed using Mann-Kendall (MK) trend analysis (Mann, 1945; Kendall, 1975), in line with other studies that have analysed data relating to hydrological regime change (Murphy *et al.*, 2013; Mwangi *et al.*, 2016; Mudbhatkal & Amai, 2018; Dallison *et al.*, 2020; Jin *et al.*, 2020). The nonparametric test was deemed suitable due to the nature of hydrological data, which is non-normally distributed and exhibits seasonality. The Hamed & Rao method of auto-correlation correction (Hamed & Rao, 1998) was applied, along with Sen's slope estimator (Sen, 1968), to evaluate the direction and size of detected trends. Trends for all factors were analysed based on seasonal (winter, December to February; spring, March to May; summer, June to August; autumn, September to November) and annual averages (hydrological years), or totals, dependent on the factor. HEP trends for each catchment were analysed separately for the average of all Z2 and all Z3 abstractions. The factors analysed were: (1) number of days where A_{daily} is greater than A_{start}, i.e. number of days generation is possible, (2) number of days A_{max} reached, (3) mean A_{daily} on days generation possible, and (4) total seasonal/annual abstraction. For PWS, total unmet demand, number of days demand unmet, and mean unmet demand, were all analysed under each demand scenario. For both HEP and PWS, MK analysis was applied to the full 2021-2079 (long-term) period, as well as to the end of a medium-term period, 2021-2054. This approach is useful for HEP, as the near future analysis is more in line with the life span of recently installed, and soon to be installed small-scale systems (Hatata *et al.*, 2019; Killingtveit, 2019). For PWS, the near future analysis is a similar period as is currently being planned for, 2050 being the end of the planning period for recently published water resource management plans (e.g. DCWW, 2019). For Wales specifically, DCWW also recently published a vision document to 2050 (DCWW, 2018). HEP and PWS baseline (2021-2030), near future (2045-2054) and far future (2070-2079) decadal averages were also taken seasonally and annually for the same factors as the MK analysis, to enable further visualisation of a potential medium- and long-term planning needs for both industries.

6.4 Results

6.4.1 Hydroelectric power

With regards to change in the number of days annually when A_{start} is achievable, all abstraction locations display a decrease in both the medium-term (2021-2054) and long-term (2021-2079), although these trends are statistically significant for more HEP abstractions in the medium-term analysis than in the long-term (Figure 6.5). Trends in the number of days when A_{max} is reached are more variable, especially in the long-term, with differences seen both within and between the two catchments. The Conwy in this period, for example, exhibits statistically significant increases for all abstractions in the west of the catchment, while those on the eastern side vary, with a statistically significant decrease being present for one location (Figure 6.6). In the medium-term, there is more agreement between abstraction locations, with all but one Z3 abstraction in each catchment seeing an increase in the number of days when maximum abstraction is achieved. The combination of these two broad trends (fewer days of abstraction, but larger abstraction volumes available) causes mean A_{daily} on days when abstraction is possible, to increase for the vast majority of locations in both time periods, but especially so in the medium-term (Figure 6.7). However, when observing the change in total volume abstracted per year, a decrease is displayed in all locations, for both time periods (Figure 6.8). Notably in the medium-term trends for total abstraction, all Z3 abstractions had statistically significant ($p < 0.05$) decreases in volume, while all Z2 locations decline without statistical significance (Figure 6.8), the only factor which showed such a split.

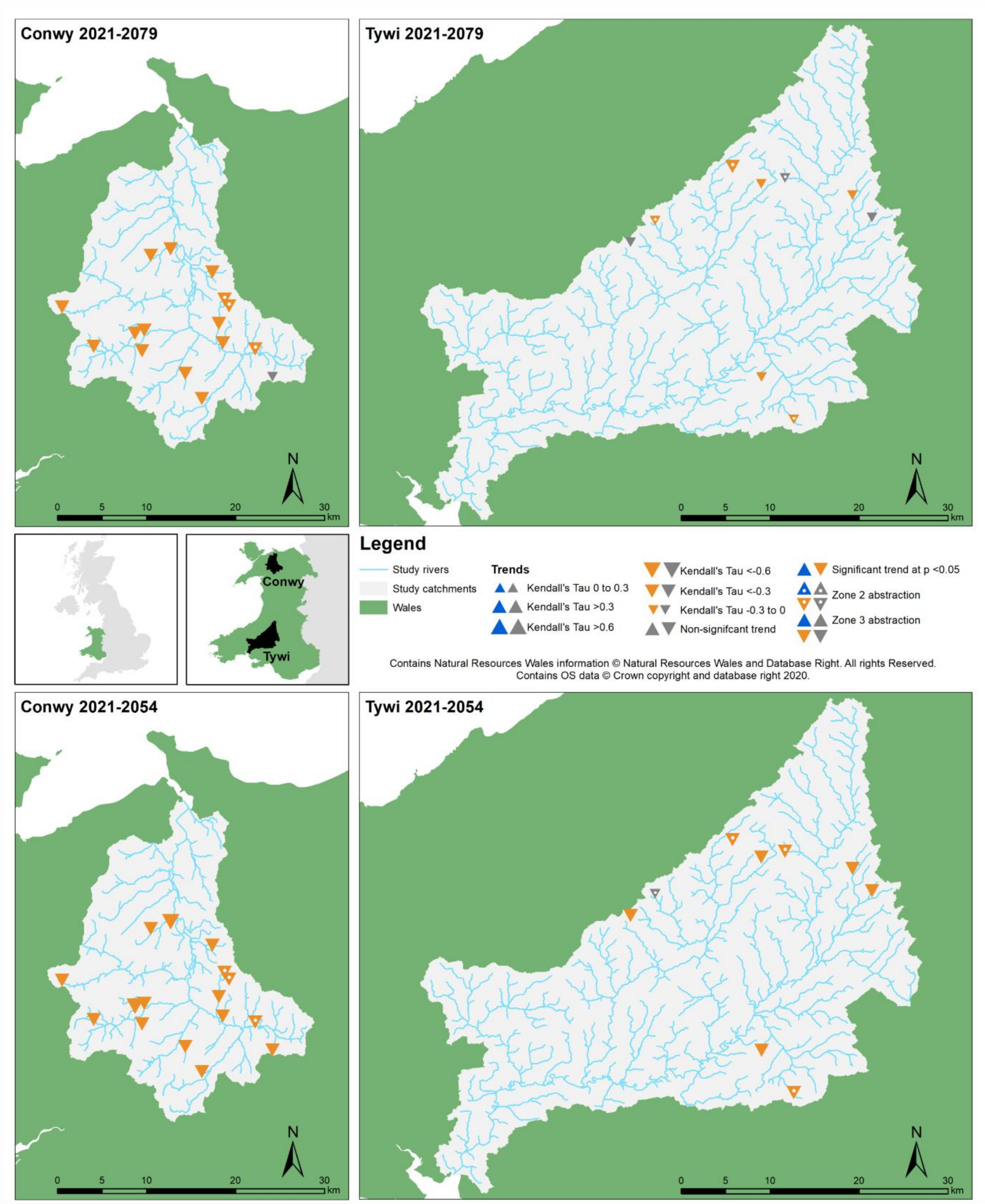

Figure 6.5. Overview of the direction, magnitude and significance of annual trends in number of days A_{start} achieved for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

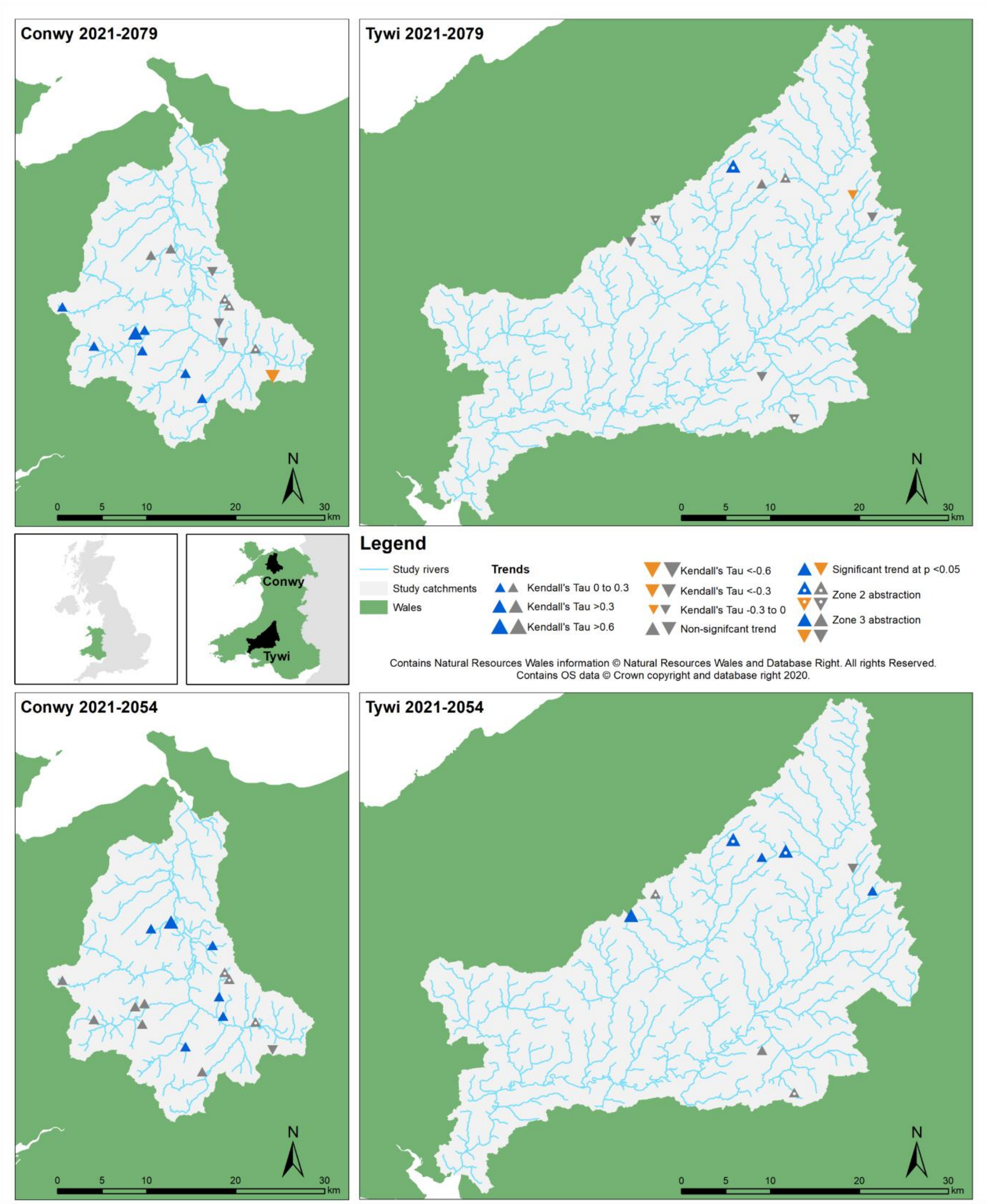

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Figure 6.6. Overview of the direction, magnitude and significance of annual trends in number of days A_{max} reached for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

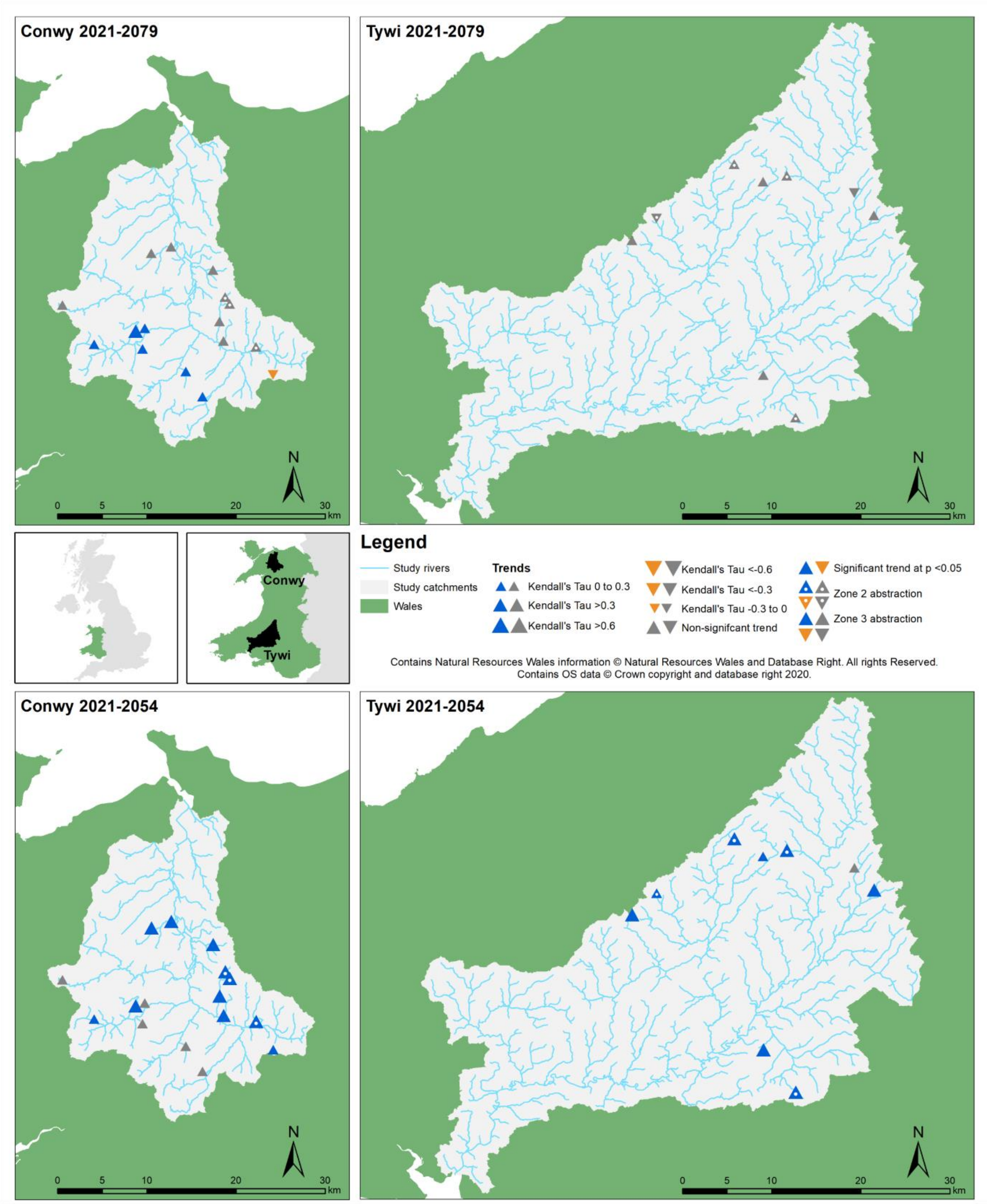

Figure 6.7. Overview of the direction, magnitude and significance of annual trends in mean A_{daily} for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

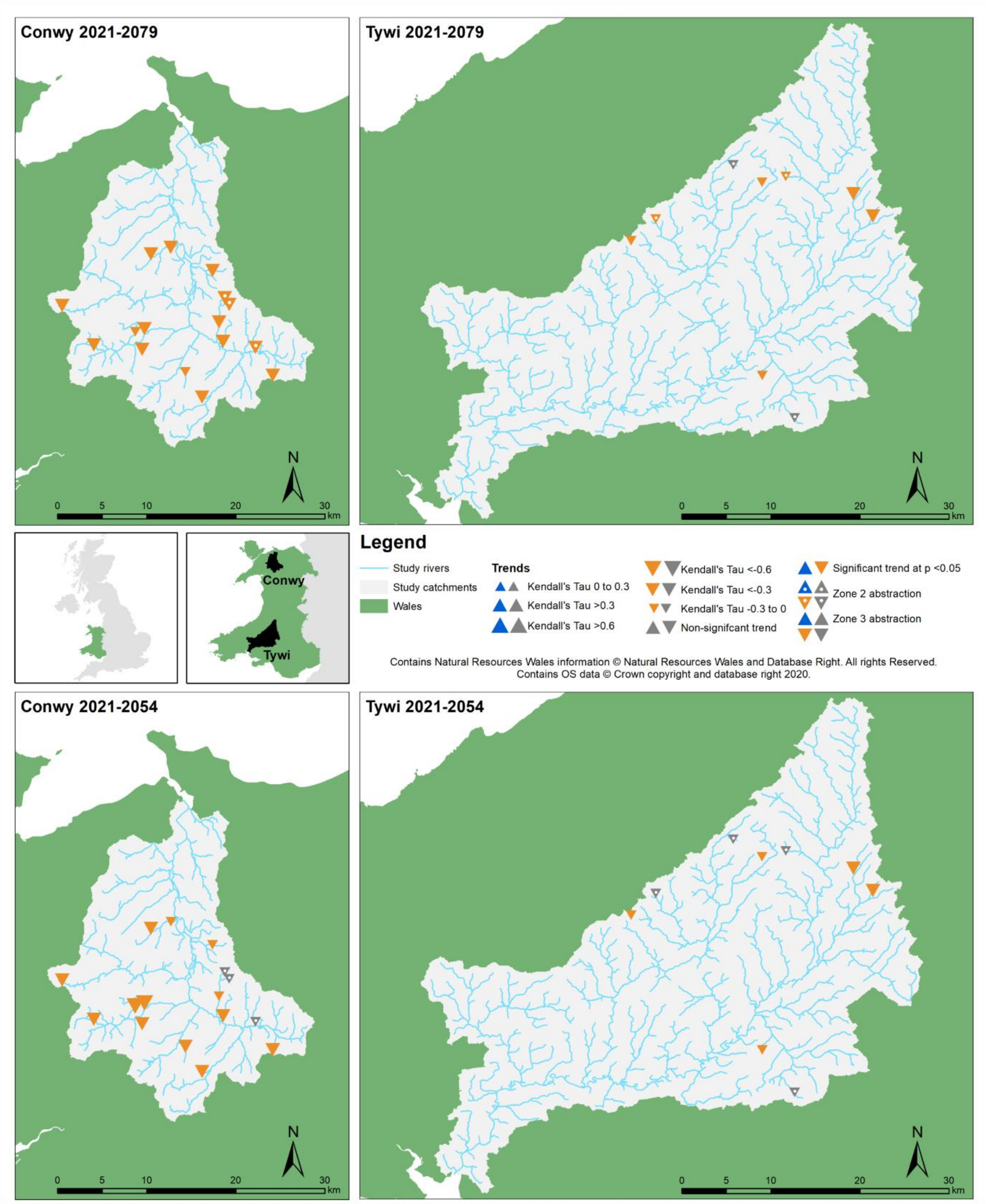

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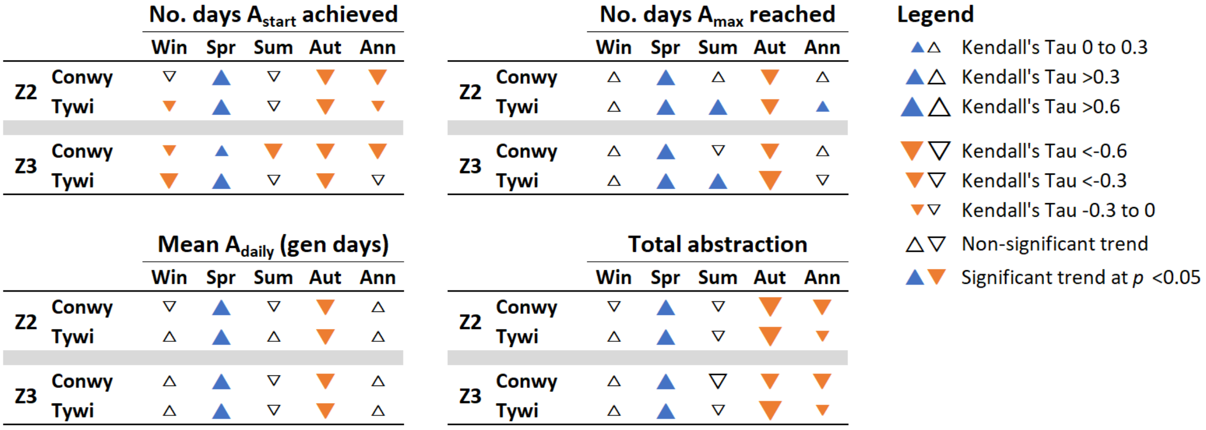
Figure 6.8. Overview of the direction, magnitude and significance of annual trends in total abstraction for the periods 2021-2079 (top) and 2021-2054 (bottom). Trends detected by Mann-Kendall trend analysis for individual hydroelectric power abstraction locations.

Figures 6.9 and 6.10 provide more details on the seasonal trends observed in the four factors studied, for long-term and medium-term respectively. Examining the trends taking place in the 2021-2079 period, it can be seen that the most significant change generally occurs in the spring and autumn, with small declines in annual total abstraction and number of days A_{start} is achieved. In the medium-term, a greater number of statistically significant trends are seen in winter and summer, with increases in annual mean A_{daily} also being statistically significant. Total abstraction also varies considerably between the two periods, with significant increases seen across both catchments and abstraction zones in winter and spring, and decreases in summer and autumn, leading to an overall decrease annually at the Z3 abstractions in the medium-term analysis. Little difference can be seen between the corresponding trends for the two catchments, with trend direction agreeing in all but three occasions, and few occasions of varying magnitude of change. In terms of difference between the two abstraction types, once again little variation is seen. However, when studying the percentage change from the baseline (2021-2030) annual average, with the near and far future decadal annual averages (Table 6.3), large differences in the number of days A_{max} is reached are shown between the zones. In the far-future average, the Z3 abstractions display a 9% decline in Tywi and stay stable in Conwy. Nonetheless, the Z2 abstractions increase quite significantly in both catchments, 32% and 18% respectively. Few differences are seen between the zones, catchments or time periods for the other factors studied. With the exception of total abstraction, the magnitude of change from the baseline is greater for the near-future than far-future.



No. days A_{start} achieved

		Win	Spr	Sum	Aut	Ann
Z2	Conwy	▽	▲	▽	▼	▼
	Tywi	▾	▲	▽	▼	▾
Z3	Conwy	▾	▴	▼	▼	▼
	Tywi	▼	▲	▽	▼	▽

No. days A_{max} reached

		Win	Spr	Sum	Aut	Ann
Z2	Conwy	△	▲	△	▼	△
	Tywi	△	▲	▲	▼	▴
Z3	Conwy	△	▲	▽	▼	△
	Tywi	△	▲	▲	▼	▽

Mean A_{daily} (gen days)

		Win	Spr	Sum	Aut	Ann
Z2	Conwy	▽	▲	▽	▼	△
	Tywi	△	▲	△	▼	△
Z3	Conwy	△	▲	▽	▼	△
	Tywi	△	▲	▽	▼	△

Total abstraction

		Win	Spr	Sum	Aut	Ann
Z2	Conwy	▽	▲	▽	▼	▼
	Tywi	△	▲	▽	▼	▾
Z3	Conwy	△	▲	▽	▼	▼
	Tywi	△	▲	▽	▼	▾

Legend

▴△ Kendall's Tau 0 to 0.3
▲△ Kendall's Tau >0.3
▲△ Kendall's Tau >0.6

▼▽ Kendall's Tau <-0.6
▼▽ Kendall's Tau <-0.3
▾▽ Kendall's Tau -0.3 to 0

△▽ Non-significant trend
▲▼ Significant trend at p <0.05

Figure 6.9. Overview of the direction, magnitude and significance of annual and seasonal trends in future hydroelectric power characteristics for the period 2021-2079, as detected by Mann-Kendall trend analysis. Based on the average of all Zone 2 (Z2) and Zone 3 (Z3) abstractions in each catchment with the exception of total abstraction, which is based on the sum of the total abstraction of all locations in each respective zone.

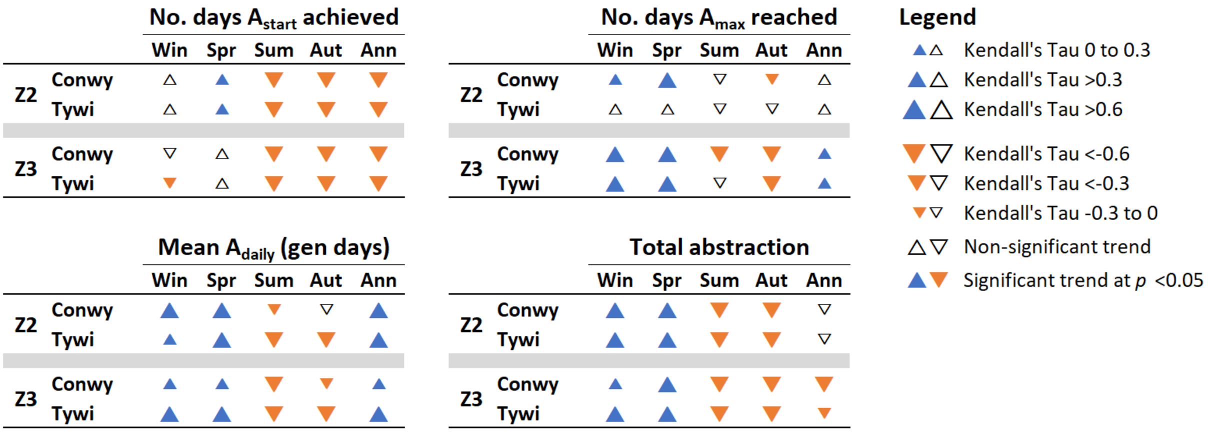


Figure 6.10. Overview of the direction, magnitude and significance of annual and seasonal trends in future hydroelectric power characteristics for the period 2021-2054, as detected by Mann-Kendall trend analysis. Based on the average of all Zone 2 (Z2) and Zone 3 (Z3) abstractions in each catchment with the exception of total abstraction, which is based on the sum of the total abstraction of all locations in each respective zone.

Table 6.3. Percentage change in annual hydroelectric power characteristics when comparing far (2070-2079) and near (2045-2054) decadal averages with a baseline decade of 2021-2030.

			A_{start} achieved	A_{max} reached	Mean A_{daily}	Total abstraction
Z2	**Conwy**	2070-2079 average	-13%	+18%	+1%	-11%
		2045-2054 average	-15%	+54%	+12%	-5%
	Tywi	2070-2079 average	-9%	+32%	+1%	-7%
		2045-2054 average	-11%	+47%	+8%	-2%
Z3	**Conwy**	2070-2079 average	-11%	0%	+3%	-9%
		2045-2054 average	-12%	+11%	+5%	-8%
	Tywi	2070-2079 average	-7%	-9%	-1%	-8%
		2045-2054 average	-13%	+11%	+5%	-7%

6.4.2 Public water supply

Under all three demand scenarios, in both the medium- and long-term, we observe an increase in the number of days annually when streamflow is not sufficient to satisfy demand, as well as an increase in the mean and total unmet demand volume (Figure 6.11). These trends are larger in magnitude for the 2021-2054 period and are also statistically significant for this study period (p <0.05), with the exception of mean unmet demand in the decreased demand scenario (Figure 6.11). No unmet demand is recorded at any point in the winter months under any scenarios, whereas Kendall's Tau results suggest a decrease in unmet demand in spring, especially in the medium-term analysis, although this is not statistically significant. Autumn displays the most consistency in trends across both time periods and the three demand scenarios, with large magnitudes of change seen in total unmet demand and number of days demand unmet.

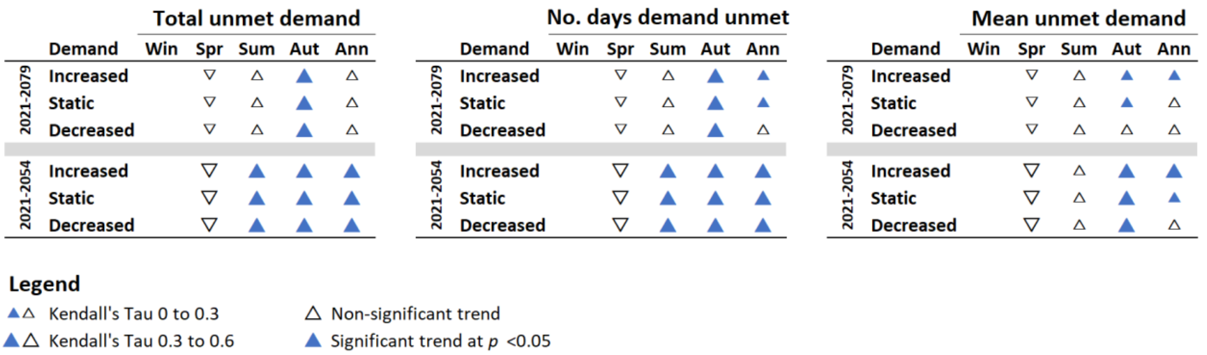


Figure 6.11. Overview of the direction, magnitude and significance of annual and seasonal trends in future public water supply unmet demand characteristics for the periods 2021-2079 and 2021-2054, as detected by Mann-Kendall trend analysis. No unmet demand is recorded in winter throughout the future period; therefore, no trends are displayed.

Further analysis (Table 6.4) reveals that for all factors considered, and under all demand scenarios, the degree of change between the annual averages of the baseline and near future, is much greater than that between the baseline and far future. For example, under the increased demand scenario, total unmet demand is 167% higher than the baseline in the near future, whereas the far future period is only 84% higher. Similarly, for the number of days demand is not met in the static demand scenario, the near future average is 151% higher than the baseline at 43.4 days per year, compared to only 30.7 days per year in the far future period, a 77% increase on the baseline of 17.2 days (Table 6.4). The same is true for mean unmet demand in the decreased demand scenario, with the near future period being 49% higher than the baseline, and the far future being only 10% greater.

Table 6.4. Percentage change in annual public water supply unmet demand characteristics when comparing near (2045-2054) and far (2070-2079) future decadal averages with a baseline decade of 2021-2030.

		Increase demand		Static demand		Decreased demand	
		Value	% change from baseline	Value	% change from baseline	Value	% change from baseline
Total unmet demand (million m^3)	2021-2030	1.55		1.53		1.51	
	2045-2054	4.12	+167%	3.95	+159%	3.60	+138%
	2070-2079	2.84	+84%	2.58	+69%	2.11	+40%
Days demand unmet	2021-2030	17.2		17.3		17.2	
	2045-2054	43.9	+155%	43.4	+151%	42.8	+149%
	2070-2079	31.4	+83%	30.7	+77%	28.6	+66%
Mean unmet demand (m^3)	2021-2030	57,015		55,893		55,639	
	2045-2054	93,162	+63%	90,232	+61%	83,140	+49%
	2070-2079	73,506	+29%	68,721	+23%	61,351	+10%

6.5 Discussion

6.5.1 Hydroelectric power

The results of the MK trend analysis conducted on HEP abstraction characteristics display a range of changes, with most variation seen between the seasons and time periods studied, rather than between catchments or abstraction zones. These patterns are driven by the streamflow changes shown in Figure 6.2. An example of this are the declines seen in spring and summer flows in Conwy and Tywi up to the late 2050s, followed by an increase in summer flows to the end of the study period for Tywi and a plateau for Conwy. Autumn flows plateau after this point for both catchments. These seasonal streamflow changes lead to the differences in trends observed in the MK analysis, with larger and more statistically significant results being seen in the medium-term than long for declines in mean abstraction, number of days A_{start} achieved, and number of days A_{max} reached. Changes in these factors in summer in particular are only significant in the medium-term analysis, due to the levelling off (Conwy) and increase (Tywi) seen in streamflow after this period. This observed shift towards less days and volume of abstraction in the summer and autumn, and an increase in the winter and spring is in line with previously published research for Wales and the UK. To our knowledge, the only previous study that has investigated climate change impacts on hydropower in Wales specifically is the aforementioned work of Carless & Whitehead (2013). Their research presents trends in streamflow and potential HEP output for streams in the upper Severn catchment, similar in nature to the abstraction locations studied in the present research. A baseline, 2020, and 2050 scenarios are considered, with a marked decline in flow and power output in summer and early autumn months displayed in 2050 (Carless & Whitehead, 2013). Winter and early spring months show a smaller magnitude increase for the same period, leading to a stable situation annually (Carless & Whitehead, 2013). These results align well with that of our study's medium-term trend analysis for total abstraction. While no further studies use Wales as a region of focus specifically, other research based on the UK, or regions thereof, seems to be consistent with our results; Scotland for example, which is comparable to Wales due to the similar nature of catchments and also due to the high uptake of HEP in the country. Sample *et al*. (2015) summarises the research on the potential impacts of climate change on Scotland's HEP. It is suggested that run-off, which is highly sensitive to climate change, is closely linked to generation potential. This relationship, in line with the results of this study, is projected to cause a decline in summer generation potential; although this is likely to be offset in the winter, HEP schemes may be unable to make use of the higher flows due to design limitations (Sample *et al.*, 2015). Further work in Scotland by Thompson (2012) on the impacts of climate change on streamflow also lend weight to the findings of this research, once again suggesting an accentuation of low summer flows and high winter flows in the future. These trends are also echoed on a UK-scale by research such as UK CEH (2012) and Kay *et al*. (2020) both corroborating the seasonal and annual driving streamflow trends observed in the study catchments of this research.

Furthermore, the trends observed of mean abstraction volume increasing, while total abstraction volume is decreasing, suggests that there will be fewer days of abstraction in the future, but with a greater abstraction per day. This trend also fits with the observed decrease in the number of days A_{start} is reached, and the increases seen in the number of days A_{max} is achieved. Once again, this is particularly pronounced in the medium-term analysis and is supported by research on low and high flows in Wales. Collet *et al*. (2018), Marx *et al*. (2018), Thober *et al*. (2018) and Visser-Quinn *et al*. (2019) all suggest that for Wales, in the future, the magnitude, duration and frequency of extreme high and low streamflows will increase.

In terms of observed differences between Z2 and Z3 abstraction types, a smaller magnitude of decline is observed for change in total abstraction in Z2 abstractions compared to Z3 in the medium- and long-term, as well as lack of statistical significance. This suggests that Z2 abstractions are potentially more resilient to climate-induced streamflow change in terms of annual total generation potential. This is possibly caused by the greater volume of water that it is allowable to abstract at these locations, being 1.3 times Q_{mean}, as opposed to Q_{mean} only in Z3 abstractions. This difference allows for Z2 abstractions to make greater use of larger magnitude flows and the observed increases in number of days A_{max} is reached annually. This is further exemplified in the fact that Z2 abstractions on average in both the medium- and long-term have a larger increase in the number of days A_{max} is reached, than Z3 abstractions.

While differences are seen for certain aspects between the two abstraction conditions zone types, little difference in observed trends is seen when comparing the two catchments. This lack of variation is likely due to the fact that the vast majority of the currently operating schemes, and therefore those studied, are located in the uppermost reaches of the catchments, predominantly on first order streams. This positioning leaves little time for LULC differences to cause impact to run-off generation and streamflow significantly between catchments. The same is true for topographical characteristics, with the majority of abstractions being located in topographically homogenous areas across the two catchments. While all four of the factors studied are important for HEP scheme design, perhaps the most important in terms of future profitability is total abstraction. For all time periods, catchments and abstraction zones, a decline is observed, suggesting less generation output in the future.

6.5.2 Public water supply

When viewing the unmet demand trend analysis results with the streamflow and demand trends, it can be seen that streamflow is the major factor, rather than water demand. In particular, large declines observed in summer and autumn streamflow lead to continued shortages of water, even in the reduced demand scenario. Similarly to HEP, the characteristics of future streamflow change also correspond with the difference seen between the medium- and long-term trend analysis conducted for PWS unmet demand. Spring streamflows increase considerably from the mid-2040s, while winter flows display a small increase; annual streamflow volume remains relatively stable throughout. Increases in winter and spring streamflows however do not factor into annual mean and total unmet demand, as streamflow is continually sufficient during these seasons. This means there is no offset for the increased demand and decreased streamflow seen in summer and autumn, leading to an increase annually in the number of days and volume of unmet demand under all scenarios. This problem is particularly pronounced in the medium-term, with both summer and autumn streamflow declining most steeply up to the mid-2050s. These results agree with published literature, with studies such as Sanderson *et al*. (2012), Henriques *et al*. (2015), and Afzal & Ragab (2019) projecting large decrease in water availability by the 2050s and beyond for the UK, and Wales specifically. Furthermore, the findings are commensurate with reports from organisation such as the ASC (2016a, 2016b), stating more action is needed to tackle future water supply security; Welsh Government (2015b), detailing the necessary steps for resilience in Welsh water supply; and, for catchments reliant on river-based abstraction such as Tywyn Aberdyfi and Pembrokeshire, DCWW (2019a). Imbalances observed could lead to problems for water supply, especially in times of prolonged drought, as increases in winter and spring flow will do little to combat summer and autumn shortages if reservoirs are already full.

6.5.3 Study implications

With regards to HEP abstractions, due to lack of scheme specific data, the results represent an indication of future change in generation potential and timing for the study catchments, and more broadly for catchments across Wales, and the 364 HEP projects there within (Welsh Government, 2019b). For example, seasonal shifts in streamflow, and therefore generation capacity, will likely still impact on specific scheme layouts in a similar way to that that has been assumed in this study. The results are therefore helpful in planning future schemes and more generally, alteration in UK energy mix. Significantly less generation is expected to be possible in the summer and autumn in the future, which will be important to consider when planning the future resilience of the energy network. Overall, the results show that in the medium-term (2021-2054), abstraction characteristics and potential at installed HEP generation sites is likely to change greatly compared to the baseline; this is significant as this period falls at the end of the general lifespan of small hydroelectric projects (~40 years) being built in the last and upcoming five years (Hatata *et al.*, 2019; Killingtveit, 2019). For those sites under development in the next five years, it may be beneficial to review scheme design in view of future flow conditions, for example by installing a larger turbine to make more use of increases in high flows, thus maximising generation potential over the lifetime of the project. In the longer-term, the magnitude of observed changes is smaller for all factors except total abstraction, than the medium-term. Therefore, when site redevelopment and replacement opportunities arise in the future, it will be important to once again looking at future projected change to best determine the most efficient scheme upgrades and alterations.

In terms of PWS, while the specific abstraction studied may be relatively resilient to future changes in streamflow, due to the supporting flow provided by the large upstream reservoir, the results of this work could have important implications for other, non-supported, direct river abstractions. The changes in streamflow and results on unmet demand demonstrated in this study, if applied to other catchments in Wales and the UK, could have major implications for future water supply sustainability. The increases in unmet demand that have been observed, even under a decreased demand scenario, clearly suggests that the pace of change in reduction of water demand by processes such as leakage reduction and domestic water use education and awareness raising, needs to be implemented as soon as possible. These measures should certainly be the first step in ensuring future water supply security, rather than large infrastructure projects to increase supply, in all but the most pressing of cases.

The results and implications of this work can also be paralleled to other large water abstractors in the region which will be operating under the same streamflow regime changes. Industrial and agricultural users in particular could face challenges, causing alterations in operation practices and timing, due to lack of available water, especially for those abstracting directly from rivers and streams. The abstraction location and use data used to identify run-of-river HEP schemes for this study details over 217 surface water-based abstractions used for industrial and commercial purposes, and a further 444 used for agriculture across Wales. These numbers highlight the potential scale of impact of future hydrological regime changes, and the need to act now to ensure resilience to such changes.

6.6 Conclusions

This research has demonstrated clear trends in future availability of water for the HEP locations studied in the Conwy and Tywi catchments, as well as the major PWS abstraction in the Tywi. Our results highlight that spring and autumn are the key change seasons long-term in terms of water availability, while winter and summer are more impactful in the medium-term. The results also demonstrate the need for action now, especially in terms of the planning and design of HEP installations. Schemes and turbines must be designed with future streamflow patterns in mind, in particular increasing winter and spring flows, rather than decreasing summer and autumn flows, thus allowing for the maximisation of power generation over the course of a year. Additionally, regardless of future demand decline, increased pressure is likely to be placed on PWS due to large declines seen in future streamflows, therefore careful planning is also required here in order to ensure continued water supply.

Finally, we suggest avenues of future research. Firstly, the impact of different climate change/emissions scenarios on future HEP output and PWS availability is required at a national-scale. While a worst-case scenario approach has been taken in this study, it is paramount to consider the range of potential outcomes under different emissions pathways, to ensure that the most proportionate future planning and adaptation measure are undertaken. Furthermore, research on specific HEP schemes, with historical generation data, would be highly beneficial as this would allow future climate change scenarios to be tested after calibration with actual data, giving a better understanding of how future hydrological regime change will impact on generation potential. Secondly, further research taking a holistic view of all catchment abstractions is needed, including industrial, commercial, and agricultural purposes, as well as PWS and HEP. This approach would give greater insight to how total catchment water demand will impact on individual water users, as well as the catchment as a whole. In addition to this, the inclusion of impacts of other climate change mitigation measures, such as upland management for flood control, would give a complete picture of future potential alterations. This holistic catchment level approach would give the best chance of ensuring fair and equitable distribution of changing future water resources.

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CHAPTER 7: DISCUSSION

7.1 Hydroclimatic trends and implications

While a discussion on the findings of each study is found in each of the study chapters, here we will discuss the results in relation to each other, and their applicability at a larger scale. When the results of all three studies (Chapters 4, 5, and 6) undertaken in thesis are viewed together, or as a subset thereof, several aspects become clear. First, it is evident that observed historical changes in hydroclimatology are indicative of the beginning of what could be much larger change for Wales in the future. For example, in the analysis of the 34 years of historical data, only small change is seen for the most part in seasonal and extreme streamflow, however, much greater change is projected for the future, as increasing global greenhouse gas concentrations continue to take greater effect on the global climate system (IPCC, 2013). It is also notable that those statistically significant trends seen in the historical data continue into the future; the observed trend of increased average autumn temperatures, for example, continues for all catchments to 2080 (Section 5.4.1). This trend also follows the expected acceleration of global temperature changes over the next 60 years (IPCC, 2018), with the average rate of change across all five catchments between 1982-2015 being 0.039°C per year, compared to 0.062°C per year between 2021-2080. Additionally, trends observed in both Study 1 and Study 2 demonstrate a greater degree of change in extreme events than seasonal and annual averages; historically, this change is in agreement with work for the UK such as Hannaford & Buys (2012), Hannaford (2015) and Watts *et al*. (2015a). Accentuation of streamflow seasonality is most pronounced in the future average and extreme trends presented in Study 2 (Section 5.4.2), with winter and spring set to get wetter, and summer and autumn drier, in line with accepted projections for the UK (Prudhomme *et al.*, 2012; Suggitt *et al.*, 2015; Garner *et al.*, 2017; Lowe *et al.*, 2018).

The results shown in Studies 1 and 2 are also indicative of the results found at a European scale. Stahl *et al*. (2010), for example, when studying 441 near-natural catchments across Europe for the period 1962-2004, presented similar trends to those found in Study 1 for Wales. This similarity in changes shown for Wales is especially true for trends in seasonality, with these in turn being very similar to the magnitude of change presented for other Atlantic-influenced western European countries (Stahl *et al.*, 2010). In addition, Forzieri *et al*. (2014) found similar future seasonal shifts for non-snow influenced catchments in Europe as are presented in Study 2 of this thesis. The 7-day average streamflow of a control period (1961-

1990) was compared with projected streamflow in the 2080s under the SRES A1B scenario (equivalent to between Representative Concentration Pathways (RCP) 6.0 and 8.5) from the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC). Of the twelve catchments studied, those in western and central continental Europe in particular (especially France, Italy, and the Czech Republic) show the same accentuation of winter high flows and summer low flows (Forzieri *et al.*, 2014) as projected in the results of this research (Section 5.4.2.3). In addition, the work of Schneider *et al*. (2013) shows trends for decreases in annual 1-day minimum flow, and increases in 1-day maximum flow in temperate oceanic Europe, when comparing a baseline period of 1971-2000 with modelled data for 2041-2070. Their trend observations clearly correlate with those shown in Section 5.4.2.2 of this thesis, being similar in magnitude as well as direction.

The benefit of conducting climate change evaluation studies and impact assessments at a catchment scale is highlighted in particular in Studies 1 and 2. The results of both chapters demonstrate how factors such as physical geographic location, as well as catchment characteristics can impact on the influences of nationwide climatic forcing. The streamflow results presented in Study 1 (Section 4.4.1.3), for example, show how the catchments in the north of Wales display different trends to those in the south, due to the impact of the North Atlantic Oscillation, as evidenced in earlier research by the likes of Dixon *et al*. (2006), Beranová & Huth (2007), and Osborn (2011). Furthermore, Study 2 describes how different and individual catchment characteristics such as underlying soil type, topography, and land cover can influence the responses of a catchment to long-term changes in climate. This is particularly well demonstrated by the Conwy and the Dyfi, which display similar changes in streamflow characteristics, aside from low flows in winter and spring, as well as annual average flow (Section 5.4.2). These differences are chiefly caused by variation in land cover characteristics, in particular a greater proportion of coniferous forest in the Dyfi which has been shown by Robinson *et al*. (2003) to help maintain baseflow conditions. This difference is the key driver of the distinct opposition of trends seen in terms of future total phosphorous (TP) and total nitrogen (TN) concentrations in winter and annually in particular, with the Dyfi showing a decline, and the Conwy an increase (Section 5.4.3). Both TP and TN are shown to correlate with streamflow statistically significantly in the modelling, explaining the discrepancies between the two catchments, despite the broadly similar hydrological response overall. These findings correspond with the findings of Dearmont *et al*. (1998) and Price & Heberling (2018) who detail decreases in overall water quality, including nutrients, with increased streamflow. Furthermore, a study by Whitehead *et al*. (2009b) also reports a decline in water quality linked with climate change influenced alterations in streamflow. Dissolved oxygen (DO) and TP concentrations in particular are shown to be highly sensitive to streamflow (Whitehead *et al.*, 2009b), once again demonstrating that a catchment approach, taking account of local streamflow conditions, is key for robust projections of future water quality changes.

Moreover, results presented in Study 3 show how even within catchments, hydrological responses can vary (Section 6.4.1). The Conwy catchment in particular displays significant trends only in the most westerly hydroelectric power (HEP) abstraction sites for long-term (2021-2079) changes in the number of days maximum abstraction volume is achievable, and the mean annual abstraction of water (Section 6.4.1). This finding of intra-catchment variation corresponds with those of Coulthard *et al*. (2005), who linked within catchment variation in erosion and deposition phases with local discharge distinction in the River Ouse, Yorkshire. Similarly, Tetzlaff *et al.* (2007) showed that differences in soil type was the key driver of intra-catchment variability in streamflow for a 223 km^2 case study catchment in Scotland. Additionally, changes in HEP generation characteristics seen in this thesis, such as a decrease in the number of days per year when generation is achievable, link well with alterations in extreme streamflow characteristics detailed in Study 2 (Section 5.4.2.2). In this case a decline in minimum flow volumes and an increase in number of low flow days is the driving cause; consistent with the findings of Carless & Whitehead (2013) for the River Severn. Furthermore, nuances in the few differences between the HEP results for each catchment also link to variation in extreme streamflows. Taking the number of days maximum abstraction is achievable in summer for Zone 3 abstractions in the long-term, as an example, it can be seen that the opposing trends (decrease in Conwy, increase in Tywi) correlate with the corresponding opposing trends for both catchments in 1-day maximum flow, and to a lesser extent, number of high flow days. This high sensitivity of HEP schemes to small changes in streamflow trends is mirrored by the findings of Sample *et al*. (2015), for Scotland, who found generation potential, and therefore profit margin to be highly sensitive to changes in precipitation and streamflow. Furthermore, one of the first papers to look at climate change impact on HEP in the UK, Harrison (2006), found that decreases in generation potential in summer months are likely to outweigh the increases in winter months, due to design limitations of installed infrastructure. Relatively little work has been completed either nationally, regionally, or globally on the impact of climate change on HEP generation, the findings presented here go some way to starting to address this for small scale HEP, with the results being more widely applicable than the area studied. Small-scale HEP technology is broadly standard globally, and while clearly different countries will have different regulations in terms of abstraction licence conditions, the results presented here can still be generalised to similar catchments in other regions. Indeed, with both the historical and future streamflow patterns presented in this thesis corresponding well with the trends seen in northern and central Europe in other work, as discussed earlier, it is reasonable to assume that HEP results presented in Study 3 are also indicative of likely change in abstraction and generation potential for those areas.

Study 3 also highlights the importance of study length when conducting impact assessments, with considerable differences being observed in the trends displayed for medium-term (2021-2054) and long-term (2021-2079) analysis periods (Section 6.4). Therefore, it is crucial that impact assessment studies take account of this, to ensure that projected future trends, and consequently their impact, are realistic and useful to the industry being studied. In this instance, the medium-term scenario is particularly applicable to HEP as it falls within the initial expected generation lifespans of schemes installed recently, giving important insight into the potential changes in generation regime. For public water supply (PWS), both future periods studied are useful, allowing for medium- and long-term planning to be implemented.

7.2 Future water quality implications for abstractors

One key relationship that has not previously been discussed in this thesis is the impact of the water quality findings presented in Study 2 (Section 5.4.3), in relation to the results of Study 3 (Section 6.4) for both PWS and HEP. For HEP, changes in suspended sediment (SS) loads are likely to have a deleterious impact on infrastructure, in particular the turbine blades and casing. Changes in SS loads are expected to cause additional abrasion, scouring and pitting, especially when considering that some of the largest increases in SS loads are seen in the periods of heaviest streamflows, and therefore greatest throughput of water and sediment through the HEP system. Indeed, Padhy & Saini (2008) conclude that sediment concentration, flow velocity, grain size, and grain hardness are the key determinants of abrasion potential of suspended sediments on HEP turbines. Work by Naidu (1999) supports this, describing how a 10% increase in water velocity (analogous to sediment velocity here) increases erosion capability by 27%, while Neopane (2010) describes a directly proportional relationship between erosion potential and particle concentration. Under the future projections made in Studies 2 and 3, both of these factors increase, with greater concentrations of SS shown to be likely during the main generation seasons, as well a larger proportion of time that HEP schemes are running at maximum capacity, and mean abstraction on generation days becoming larger. In addition, while we can assume that grain hardness remains constant over the period of study, larger flow velocities such as those projected in this work also have the ability to suspend larger particles, thereby further increasing the abrasion potential. The findings of Worster & Denny (1955) demonstrate that when considering erosion caused by sliding and grazing, particle size is directly proportional to amount of wear. Although, further findings by Padhy & Saini (2011) showed that fine sediments can also be highly damaging to turbines, especially in systems with high head.

The multi-faceted change in abrasion potential clearly have implications for the maintenance and life-span of HEP schemes, even despite the projected overall decrease in future total abstraction potential. These changes could impact on their viability, productivity, and overall output of schemes, further confounding pressures already faced by small-scale HEP such as business rate increases and the curtailment of feed-in-tariffs, as detailed in Section 1.2. Careful consideration should therefore be given to this area during the design, construction, and operation phases of new HEP schemes, in order to ensure that either greater protections are made (e.g. finer screens on intake weirs, or sediment bypass systems) or more regular servicing of parts is completed. For schemes that are already in operation, greater monitoring should be undertaken, to guard against component failure or system damage, and in some cases, upgrading of parts or retrofitting of systems may be needed (Hauer *et al.*, 2018).

In addition, the impact of the studied water quality parameters on PWS is likely to be large, not just due to the four factors themselves, but also due to knock-on impacts, such as higher TN and TP levels giving rise to greater eutrophication. These alterations are likely to lead to an increase in required treatment to maintain drinking water standards, this has economic and operational efficiency impacts, and consequently an environmental toll. The link between raw water quality and treatment cost has long been established, with Dearmont *et al*. (1998), for example, showing that for twelve water treatment works in Texas, a 1% increase in SS concentrations increases chemical costs by 0.25%. This increase in cost is not just related to the removal of sediments however, as SS can be seen as an indicator of wider water quality, which also requires greater treatment (Dearmont *et al.*, 1998). Indeed, SS is an important transport medium for various pollutants which can become adsorbed to sediment grains (Dearmont *et al.*, 1998), including phosphorus (House *et al.*, 1998), heavy metals, and bacteria (Loperfido, 2014). This clearly makes SS a highly influential water quality parameter, with increases in concentrations bringing a variety of challenges for water treatment facilities, likely increasing costs and chemical requirements, and lowering treatment capacity.

A review by Price & Heberling (2018) investigated the impacted of changes in water quality parameters on the operation and maintenance (O&M) cost of water treatment plants. Along with sediment, nutrients and pesticides (TP, TN and nitrates) were found to be among the key drivers of O&M cost increases induced by lower raw water quality (Price & Heberling, 2018). Various studies support this conclusion, Forster & Murray (2007), for example, found a 0.08% increase in O&M cost per 1% increase in total pesticide load, when studying the agricultural Maumee Catchment in Ohio. These results correspond with the results of Murray (2001) and Fiquepron *et al*. (2013) who found 0.12% and 0.01% increases in O&M costs per 1% increase in total pesticide load, in water taken from the Great Lakes and catchments across France respectively. Also looking at nitrogen loads individually, Fiquepron *et al*. (2013) demonstrated a 0.05% O&M cost increase, while Mosheim & Ribaudo (2017) found the value to be 0.06%, both results are relative to 1% increase in total nitrogen concentrations. For phosphorous individually, the results are similar, McDonald & Shemie (2014) reporting a 0.19% increase per 1% concentration increase, and Heberling *et al*. (2015) suggesting a value of 0.06%.

When considering the wastewater treatment side of the water supply process, Astaraie-Imani *et al*. (2012) found that future climate change will reduce water quality downstream of wastewater treatment works in the UK. This is caused by more frequent releases from storm tanks and combined sewer overflows due to increases in the frequency and magnitude of extreme precipitation events (Astaraie-Imani *et al.*, 2012), as also demonstrated in Section 5.4.2.2. These projections are supported by the work of Abdellatif *et al.* (2015) for the northwest of England, who project a 37% increase in total combined sewer overflow spill volume and a 32% increase in total spill duration, when comparing 1961-1990 with 2070-2099 under a future emission scenario equivalent to RCP8.5. These results are congruous with those of Tait *et al*. (2008) who indicate a combined 40% increase in sewer overflow and flood tank spill volume by 2080 for an urban catchment in the UK. The most prominent water quality implications of these changes are declines in dissolved oxygen (DO) concentrations, increases in nutrient levels and the release of harmful bacteria to waterways (Astaraie-Imani *et al.*, 2012). These changes have important implications for downstream ecology, as well impact on bathing waters and shellfish harvesting. Given that combined sewer systems are common in Wales and the UK, and that coastal waters support a variety of industries, not least of all tourism and fishing, this is clearly an area of concern for the region, and nation.

In light of the findings presented above, and given the degree of projected water quality change in Study 2, it is clear that water service providers could face substantial challenges in maintaining both acceptable future water supply quality and water quality downstream of wastewater treatment facilities. In terms of drink water supply, the first steps in trying to ensure output quality could be to lengthen retention times in the different treatment processes or altering the dosing of chemicals used, followed by changing treatment processes if needed. Both of these options are likely to decrease the volume of water that is possible to treat in a given timeframe, therefore effecting plant efficiency, expenditure per litre treated, and the environmental impact in terms of additional chemical use. It is also possible that such changes would not be sufficient to maintain drinking water standards, therefore investment in both new treatment infrastructure, as well as new water sources may be necessary to ensure the safety and continuity of supplies (Jones *et al.*, 2007; Hanson *et al.*, 2016).

7.3 Summary

Overall, this work has shown that catchments in Wales have already undergone alterations due to climate change, and that these alterations will continue into the future, likely at an expedited rate compared to that already seen. Such changes in average and extreme streamflows, demonstrated in this thesis, will have wide-reaching consequences. Firstly, river systems themselves will alter due to changing flow regime as a consequence of altered precipitation input. This will be especially felt in terms of decreased water quality and likely changes in aquatic life and geomorphological characteristics. Furthermore, catchments as a water resource, it has been shown, will alter, with changing timing, quantity, and quality of water available for abstraction or use. Given the reliance on surface waters in Wales, this could have significant impacts in terms of agricultural productivity, energy generation, manufacturing activity, the leisure and tourism industry, and PWS; consequently, these changes could have a large impact on the economy of the nation.

In addition, the trends observed in this research appear also to be relevant to a wider region than that focussed on in this thesis. Several studies that have examined the whole of Europe, and that have been presented in this discussion (Stahl *et al.*, 2010; Schneider *et al.*, 2013; Forzieri *et al.*, 2014; Papadimitriou *et al.*, 2016), have shown that the magnitude and direction of trends seen in Wales, generally corresponds with other northern and western European areas where the climate is also influenced by the Atlantic. The results of this research can therefore be seen as also adding value to the knowledge base of this wider region, and not just those catchments and the area specifically studied. It should also be kept in mind, that the projections shown in this work offer a worst-case scenario of the future, based on high future global greenhouse gas emissions. Therefore, while planning for the future impacts of climate change is highly important, and these results do offer crucial insight, it is likely that the magnitude of changes seen, and therefore impacts, will be reduced. Nonetheless, robust planning for future water resource allocation is critical, therefore, the new findings and conclusions drawn from this thesis and the research within are important and useful.

CHAPTER 8: CONCLUSIONS

8.1 Final conclusions

The research presented in this thesis has been undertaken to further our knowledge in the field of catchment level hydroclimatic changes in Wales, and the impacts of such changes on the exploitation of surface water resources. Through worst-case future emission scenario hydrological modelling it has been shown that Wales could potentially face substantial challenges in the future in terms of supply-demand balance, not just for public water supply (PWS), but for all sectors that make use of surface water resources. Increased future hydrological seasonality has been shown, with spring and autumn being the most susceptible to change both in terms of average flows and extreme events. Furthermore, significant potential future challenges in terms of water quality have been identified, which will impact on those tasked with managing surface waters in Wales, as well as any users or abstractors of the resource in the region. Two sectors have been explored in terms of the changes identified, PWS and small-scale hydroelectric power (HEP). Both sectors face the need for adaptation in order to cope with changes in the timing, quantity, and quality of surface water resources in the medium- and long-term.

Overall, this thesis has been successful in achieving its aim of an assessment of the impact of future climate change on the streamflow characteristics of catchments in Wales, and an evaluation of the effect of such changes on the abstractable water resource (as laid out in Section 1.3). Historical changes in daily temperature, precipitation and streamflow have all been analysed for the period 1982-2015, as well as corelated with total water demand for 2012-2015, giving new insight into water use under changing weather conditions in the region, and addressing objectives I and II of this thesis. Objectives III and IV were achieved with five induvial hydrological models being set-up, calibrated, validated, manipulated, and implemented with future worst-case emissions scenario climate data, allowing for an analysis of future hydrological regime and water quality change. Finally, objective V has been addressed in terms of a projection of future unmet demand for a key river-based PWS abstraction location under three demand scenarios, as well as future abstraction potential for 25 HEP installations in two catchments.

The future hydroclimatic picture for Wales is complex and potentially faces major change, but that is not to say it is without hope, especially with studies such as those presented in this thesis providing valuable insight into the future planning, management and adaptation need. A significant proportion of future Welsh prosperity and development could be linked to the important surface water resource. Therefore, further study focussing on Wales specifically and the challenges it faces, in the manor outlined above, is essential. As aforementioned, the study has also highlighted the importance of local-scale study, as well as national level analysis, with each scale important for different purposes and a combination of the two approaches required to best plan for the future management and use of water resources.

8.2 Recommendations for further work

While the findings of this research have addressed knowledge gaps surrounding the impacts of climate change on the hydrology of Wales, and water resource use thereafter, further research is still required, especially around impact assessment. It is clear from the results of this work for example, that extreme high and low streamflow events are increasing in terms of frequency and magnitude (Chapters 4 and 5). While Chapter 6 goes someway to address the implications of these changes on PWS and HEP, more work is required to fully understand the nature of these changes, especially the duration of drought periods, which could have potentially large consequences for all water users, but PWS especially. In terms of extreme high flow events, this work provides background for further study on areas such as fluvial flooding, with modelling at a finer temporal and spatial resolution required to develop the most informed future planning strategies. Furthermore, the relationship established in Chapter 4 between prevailing weather conditions and overall water demand is an important first step in better managing the future supply-demand balance in Wales. This work could be continued further by the implementation of a component analysis, to give a better understanding of how different user groups (agriculture, domestic, industry, etc.) respond to changes in factors such as air temperature. Analysis of this kind would enable a more rounded picture of future water demand to be achieved, enabling robust water resource planning.

The results presented in Chapter 6 represent an overview of the likely impacts of hydroclimatic change on the two industries studied. While PWS impacts have been studied and shared by Dŵr Cymru Welsh Water (DCWW) in the form of their water resource management plan (DCWW, 2019a) and drought plan documents (DCWW, 2019b), little work has been completed for other industries, especially with a focus on Wales. HEP may play a relatively small role in the overall energy portfolio of Wales, but the projected changes in the seasonality and performance of the sector could have significant implications for HEP schemes, both locally and nationally. It is therefore crucial that further research be completed for the whole of Wales, and more broadly the UK, to fully understand the significance of such changes for the energy provision mix of the nation. On a more localised level, it is important that research be carried out on individual HEP schemes, to ensure optimised operation for the future. Looking more broadly than those industries studied in this research, the impact of projected hydroclimatic changes on sectors such as heavy industry and agriculture are also important to understand, especially for the latter, given the increasing pressure on global and local food systems. Clearly, further work is needed to fully understand the risks posed by future hydroclimatic changes on the overall exploitation of water resources in Wales, and the potential economic and environmental impacts of any changes.

Moreover, Chapter 5 indicates the potential changes in four water quality variables, linked to changing hydroclimatic factors, with substantial alterations likely for all four as well as water quality more generally. Once again, the implications of these changes in Wales has received little attention thus far, clearly making this a key area of future research. Various elements would benefit from further work in this regard: in-stream ecology risks; eutrophication changes; the impact on drinking water treatment plant processes, efficiency, and finances; suspended sediment load changes and implications for HEP; and future compliance with environmental regulations, to name just a few. Furthermore, it has been shown that changes in water temperature are very likely given projected changes in air temperature and the known relationship between the two (Crisp & Howson, 1982; Erickson & Stefan, 2000; Morrill *et al.*, 2005; Hannah & Garner, 2015). It is therefore suggested that an area for future research should be the impact of increased water temperatures for Wales, which has the potential to impact not only in-stream processes, and therefore overall water quality, but also processes and chemical reactions in environments such as drinking water treatment plants.

8.3 Final summary

This thesis has provided a grounding knowledge of spatial and temporal changes in Welsh hydroclimatology, giving insight into the future environment that abstractors, water resource managers, and water users will be operating in. The thesis also presents the need for greater work at a catchment level, with Chapters 4 and 5 in particular demonstrating how significant change can occur between catchments even over small distances, due to factors such the topographical characteristics of the catchment and its surrounds. Indeed, Chapter 6 highlights that variation in streamflow response can be found even within catchments. This underscores the need for awareness of small-scale studies and local management plans in the future, especially when working to address or mitigate against the impacts of future climate change.

Several knowledge gaps have been addressed, as well as novel research methods used, through the course of the thesis. First, a daily and monthly relationship between total water abstraction and three hydroclimatic factors has been established for the first time for Wales, allowing, as conducted in Study 3, for projections of future abstraction requirements for PWS to be made. In terms of Study 2, the research conducted is some of the first to make use of the latest UK climate projections (UKCP18), with little peer-reviewed literature having been published using this data at the time of writing. This is especially true when considering both the study area and research topic, with no articles having been published using the data for Wales, or in reference to future water resource use. Furthermore, the use of the Soil and Water Assessment Tool (SWAT) for modelling of streamflow and water quality is one of the first for Wales, with the future water quality analysis itself being previously sparsely published on for the region specifically. Finally, Study 3 develops for the first time a method for assessing the impacts of streamflow changes on the abstraction potential of multiple individual HEP schemes, where the abstraction licences conditions are unknown. This represents a methodological advancement, allowing for large-scale assessments of the impact of climate change on HEP generation potential, this has previously not been available.

Overall, the research conducted has been successful in addressing the objectives of the thesis and, therefore, achieving the overarching aim laid out at the start of project. Furthermore, the work presented represents an advancement of knowledge for the field, as set-out above, by addressing knowledge gaps in relation to the hydroclimatic character of catchments within Wales and implications for water resource use. It is hoped that the findings of this research will be used to inform future multi-sector water resources management planning, as well as being useful to the specific sectors studied and more, with the results being applicable to a variety of stakeholders. In this manor it is hoped that the findings of the thesis will help towards ensuring long-term sustainability of water abstraction and use in Wales, and beyond.

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APPENDICES

Appendix 1: SWAT model calibration charts

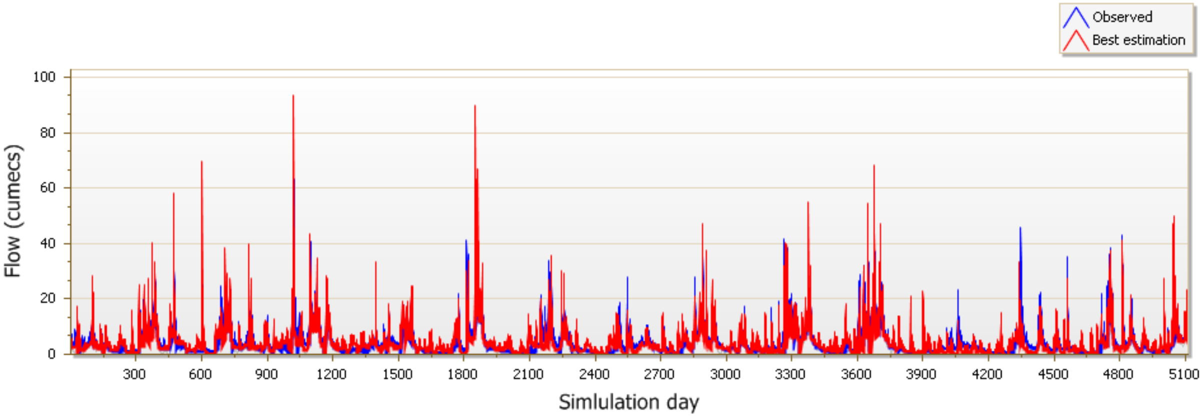

Figure A1.1. Observed streamflow (blue) compared to the best simulation (red) for the Clwyd catchment, following calibration for the period 1st January 1985 to 31st December 1998; KGE = 0.810.

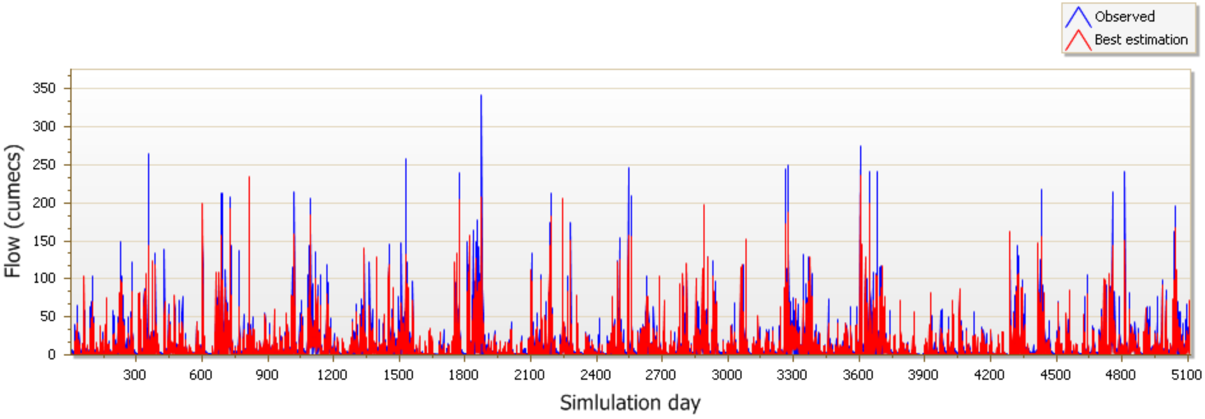

Figure A1.2. Observed streamflow (blue) compared to the best simulation (red) for the Conwy catchment, following calibration for the period 1st January 1985 to 31st December 1998; KGE = 0.770.

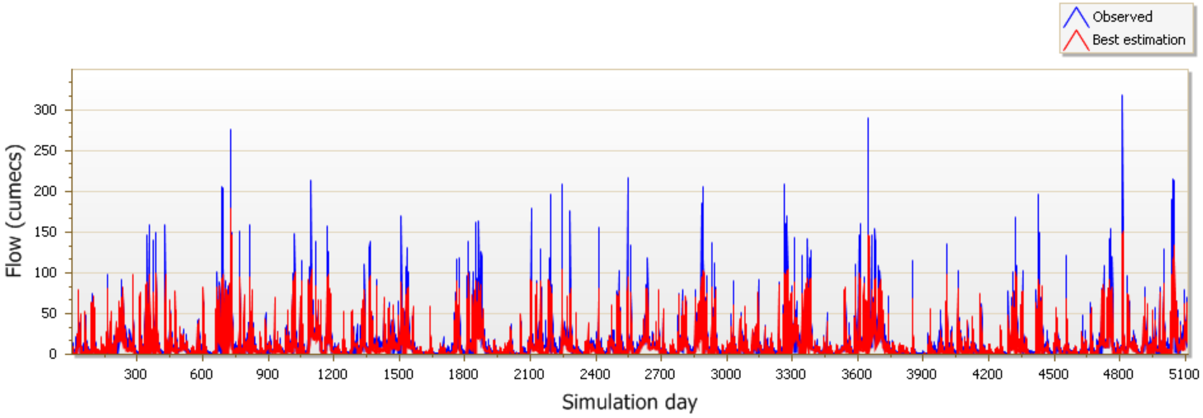

Figure A1.3. Observed streamflow (blue) compared to the best simulation (red) for the Dyfi catchment, following calibration for the period 1st January 1985 to 31st December 1998; KGE = 0.788.

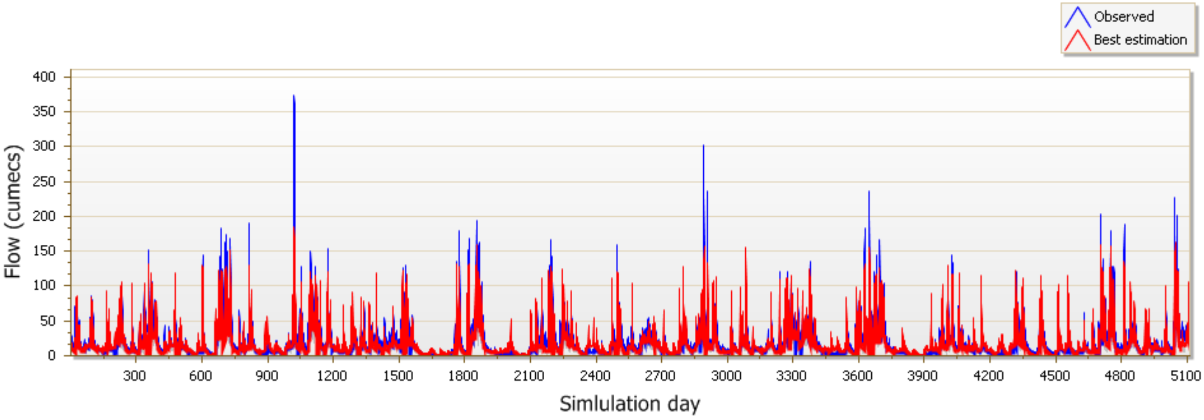

Figure A1.4. Observed streamflow (blue) compared to the best simulation (red) for the Teifi catchment, following calibration for the period 1st January 1985 to 31st December 1998; KGE = 0.851.

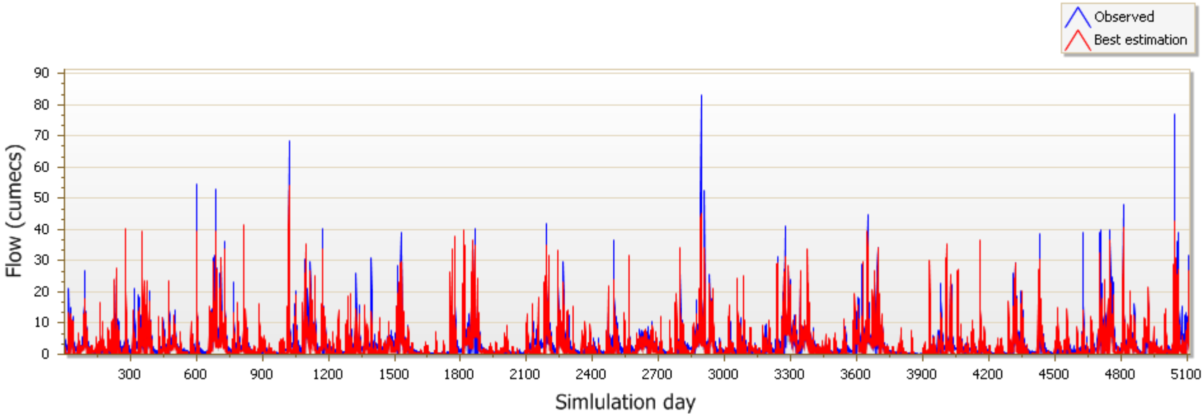

Figure A1.5. Observed streamflow (blue) compared to the best simulation (red) for the Tywi catchment, following calibration for the period 1st January 1985 to 31st December 1998; KGE = 0.841.

Appendix 2: Ensemble projections for seasonal and annual streamflow

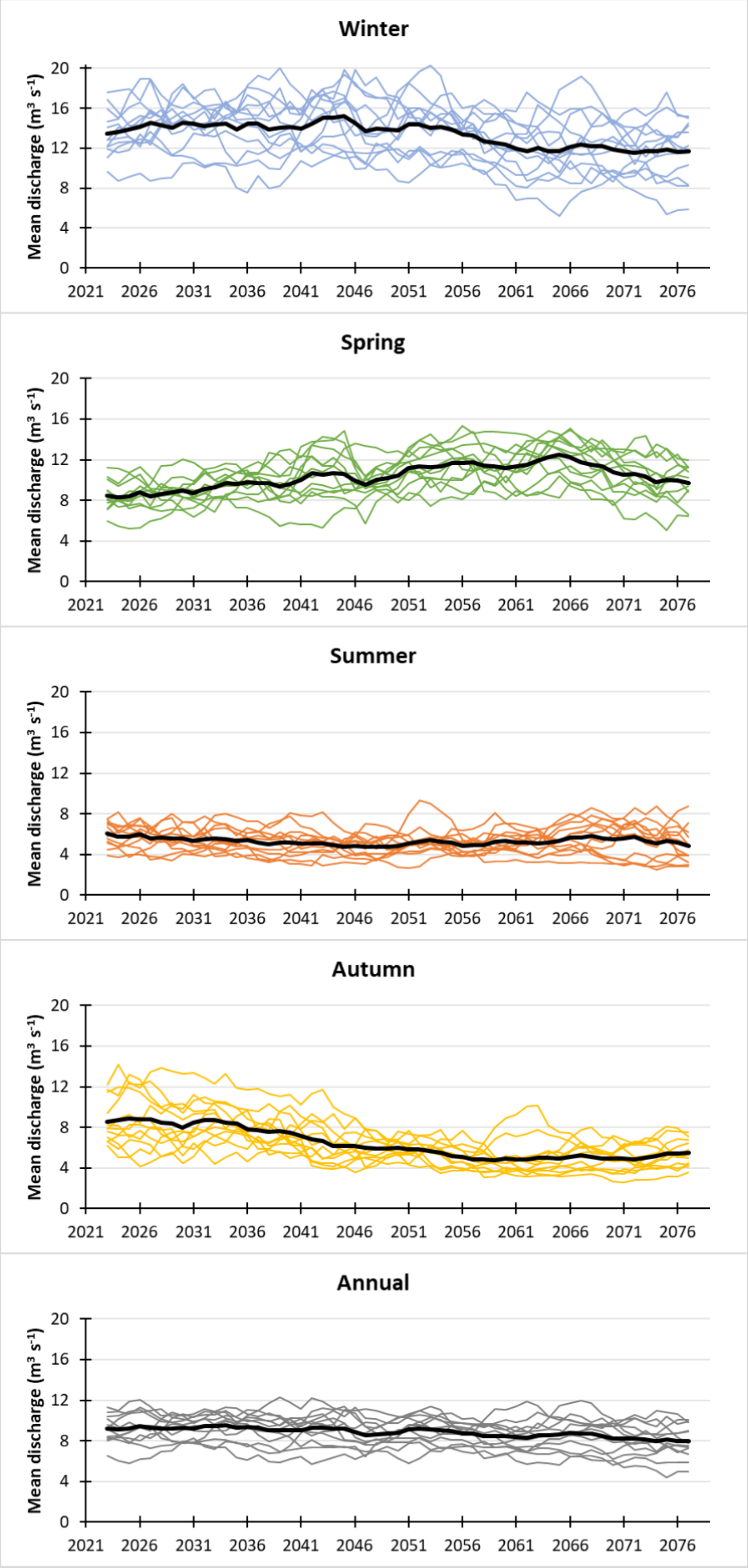

Figure A2.6. Seasonal and annual future streamflow projections for the Clwyd based on a 5-year moving mean; coloured lines represent individual model runs from the 12-member ensemble, black line is the ensemble mean.

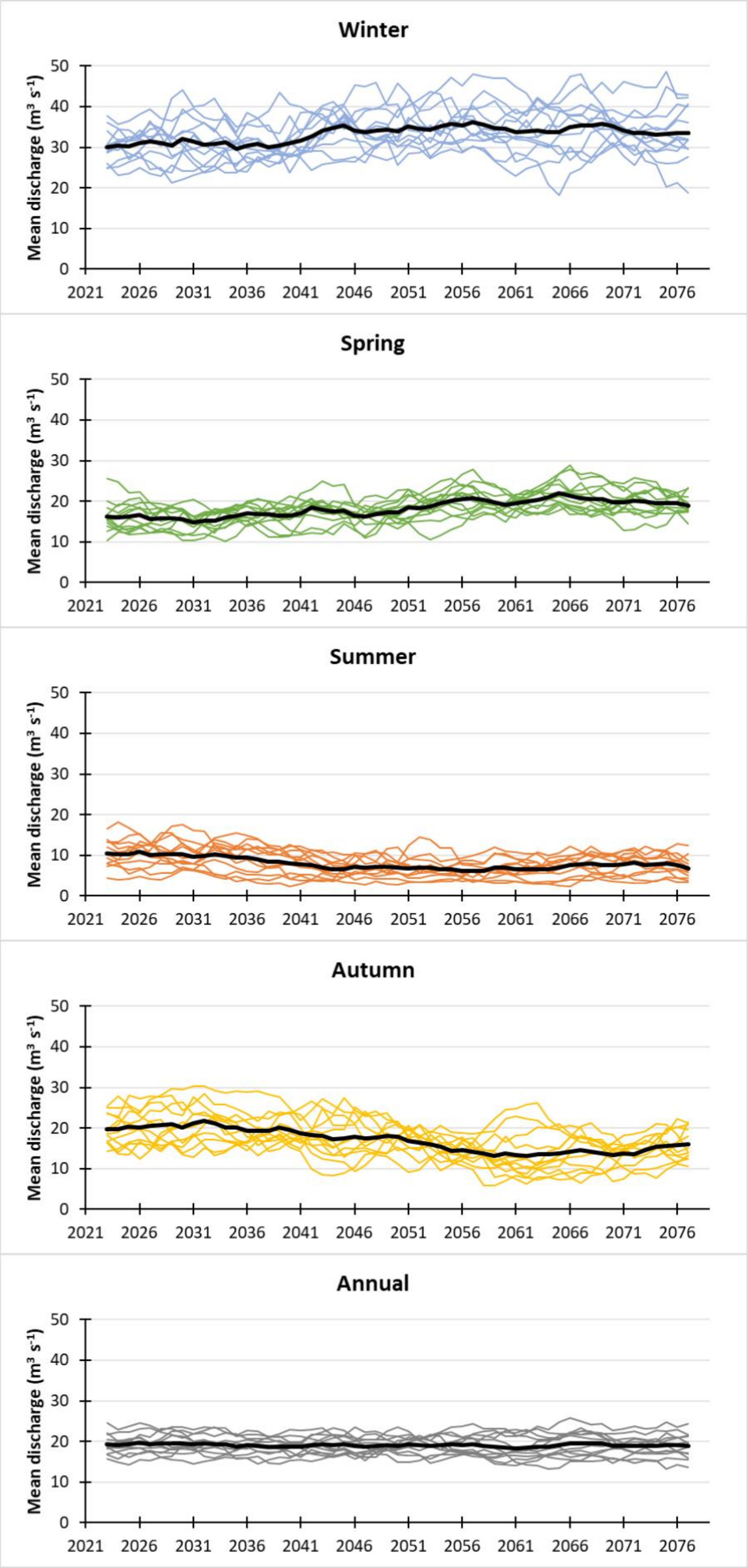

Figure A2.7. Seasonal and annual future streamflow projections for the Conwy based on a 5-year moving mean; coloured lines represent individual model runs from the 12-member ensemble, black line is the ensemble mean.

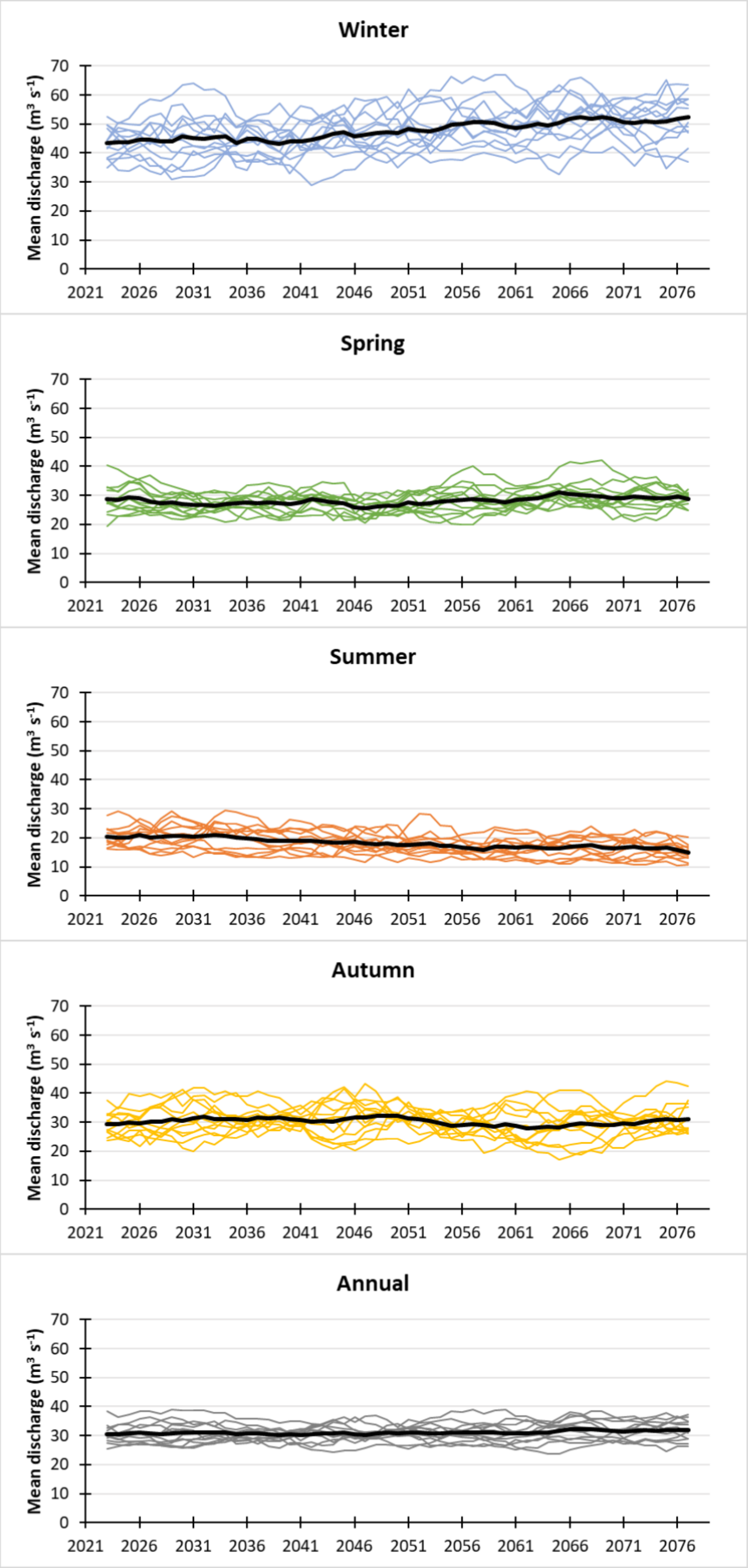

Figure A2.8. Seasonal and annual future streamflow projections for the Dyfi based on a 5-year moving mean; coloured lines represent individual model runs from the 12-member ensemble, black line is the ensemble mean.

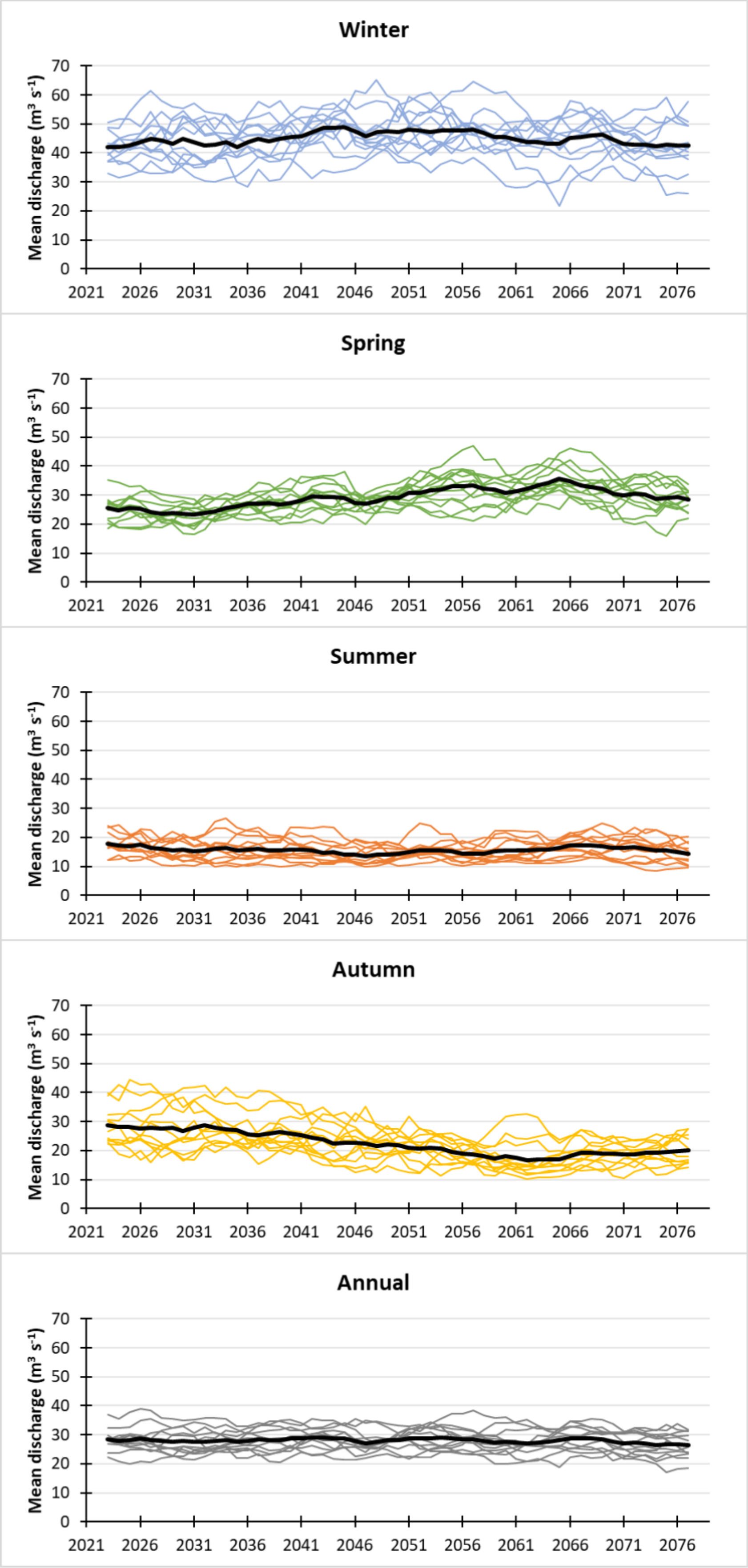

Figure A2.9. Seasonal and annual future streamflow projections for the Teifi based on a 5-year moving mean; coloured lines represent individual model runs from the 12-member ensemble, black line is the ensemble mean.

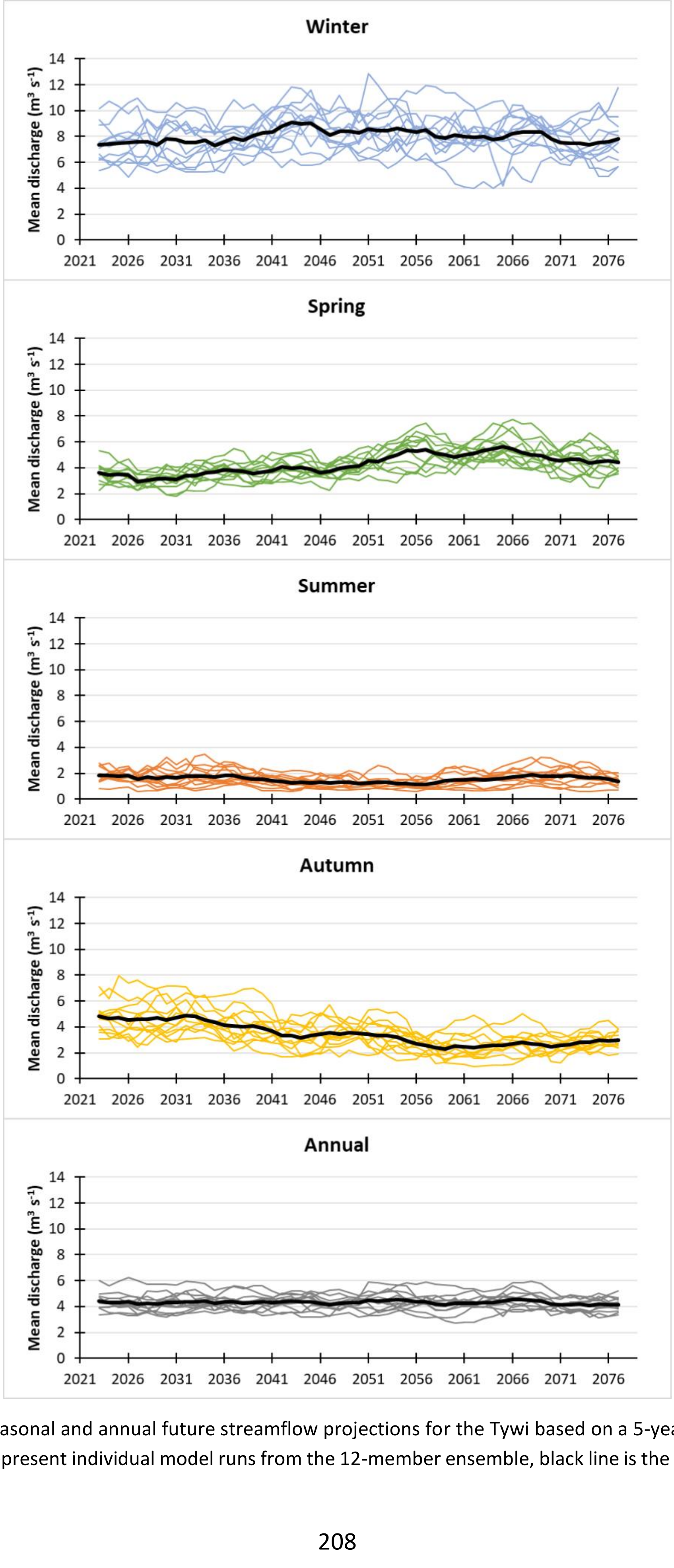

Figure A2.10. Seasonal and annual future streamflow projections for the Tywi based on a 5-year moving mean; coloured lines represent individual model runs from the 12-member ensemble, black line is the ensemble mean.