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

Richard John Harvey Dallison^{*a}, A. Prysor Williams^a, Ian M. Harris^a,
Sopan D. Patil^a

^a*School of Natural Sciences, Bangor University, Bangor, Wales, UK*

*Corresponding author: Richard Dallison (r.dallison@bangor.ac.uk)

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 could become more unreliable, seasonal, and polluted.

Keywords: hydrological modelling; particle swarm optimisation; trend analysis; UKCP18; water resource management; water supply

1. Introduction

Globally, river catchments are likely to face significant changes due to a variety of factors, including climate change, land use/land cover change, increased population and urbanisation, 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, 2014). 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, 2014). 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.

Several studies have analysed future seasonal and annual average streamflows for the UK, mostly using UK Climate Projections data (UKCIP02, UKCP09 & UKCP18). While less work has thus far been published using the new UKCP18 data, Kay *et al.* (2020) compared estimates of change under both the new and previous (UKCP09) projections and found the results to be similar, but with higher uncertainty in the most recent version. A study using UKCP09 data by Watts *et al.* (2015) suggests that 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, with little change in the annual average. Investigating the impact of these

changes on river flows in the short and long-term respectively, Christensen *et al.* (2012) and Prudhomme *et al.* (2012) both projected annual average 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 (Christensen *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 predict that while UK annual average streamflows will decline, the magnitude of change will be less than that seen seasonally. For Wales specifically, the results of these UK-wide studies, in terms of seasonal streamflow changes, are consistent with the projections of Afzal *et al.* (2021), for the Ebbw catchment in south Wales.

For extreme streamflow events in the UK (large discharge events/flooding and long-term drought), it is likely that climate change will alter their frequency, duration, and severity (IPCC, 2014; Watts *et al.*, 2015; Sayers *et al.*, 2016; Miller & Hutchins, 2017; Lane & Kay, 2021). Extreme streamflow changes are mainly driven by changes in precipitation regime. For example, Hanlon *et al.* (2021) link future daily rainfall levels, using UKCP18 projections, to increasing numbers of flood days, as well as increasing drought severity, by the 2080s under low and high future emissions scenarios. Rau *et al.* (2020) found that extreme hourly precipitation is set to increase under a high future 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.*, 2013), 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). Using UKCP09 data, Afzal *et al.* (2021) also demonstrate an increase in the frequency and severity of drought events under future medium- and high-emission scenarios.

The aforementioned projections for alterations in streamflows will likely often have a deleterious impact on water quality, though the magnitude of these changes will depend on individual catchment characteristics. Whitehead *et al.* (2009a), for example, showed that patterns in future water quality varied greatly across six UK catchments based on the geology, topography, urbanisation, agricultural land use and point source inputs of each catchment. Furthermore, within-catchment variation was also demonstrated, with the River Tweed showing 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 future drivers of water quality changes, including variations in streamflow regime, as well as water temperature alterations. These changes influence stream power, and therefore the erosion and transport of sediment, as well as the dilution and movement of pollutants; instream chemical process rates are also affected by water temperature changes. Delpla *et al.* (2009) found 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 of Ockenden *et al.* (2017), who showed a positive trend between total phosphorous load and annual rainfall, and Ponting *et al.* (2021) in relation to increased organic and inorganic matters reaching rivers through flood events. 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, with some zones already seeing seasonal deficit (DCWW, 2019a). Furthermore, Wales exports large quantities of water to metropolitan areas in central and northern England (Warren & Holman, 2012; DCWW, 2016), 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, especially small run-of-river schemes, which are 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 of 389 GWh, accounting for approximately 1.3% of total electricity generation in the country in 2018, and 5.2% of renewable electricity generation (Welsh Government, 2019). Although a small proportion of overall generation, this is increasing, especially with growing numbers of small-scale development, and equates to enough power for the equivalent of over 100,000 households (Welsh Government, 2019). 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 over £3bn to the Welsh economy in terms of gross value added in 2016 (Welsh Government, 2020), therefore understanding how changes to the natural landscape and resources of the region will impact on tourist appeal is crucial. Finally, any changes in flow characteristics or water quality could have important implications for river ecology and aquatic life in both rivers and coastal waters. A better understanding of potential future changes will aid with designing suitable mitigation measures.

2. Data and methods

2.1. Study catchments

Our study focusses on five catchments in Wales: the Clwyd, Conwy, Dyfi, Teifi, and Tywi (Figure 1). These catchments have been selected for study due to the variety of different characteristics displayed, in factors such as topography (Figure 1), land use/land cover (LULC), and soil types (Figure 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 1. In addition, the catchments are important economically, socially, and environmentally, in line with the reasons for selecting Wales as a study region. For example, they directly contribute to the water supplies of over 975,000 people (derived from DCWW, 2019b), as well as over 70 run-of-river hydroelectricity scheme abstractions (derived from NRW, 2019a). From an environmental perspective, they include various land protections and designations, 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).

The catchments range in size from Dyfi at 507 km² to Tywi at over two and half times the size (1365 km²). 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 proportions 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 catchments, tending 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.

2.2. 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, 2018). 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. This 12 km gridded version of the dataset provides an ensemble of twelve regional climate model (RCM) projections derived and, dynamically downscaled, from twelve of the fifteen members of the 60 km HadGEM3-GC3.05 global coupled model (GCM) perturbed parameter ensemble (Murphy *et al.*, 2018). The climate projections are based on a scenario of no downturn in global greenhouse gas

emissions, using 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 perturbed parameter ensemble members, as well as natural climate variability between the members (being based on a range of plausible climate storylines), cause the 12 RCM ensemble member outputs to differ when downscaled (Kendon *et al.*, 2019). For greater detail on the UKCP18 data used in this study, we direct the reader to Murphy *et al.* (2018) for a comprehensive overview. 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, thirteen were selected as pseudo-meteorological stations (Figure 3).

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. In addition, to provide the best level of coverage using the least stations, in neighbouring catchments (Clwyd and Conwy; Teifi and Tywi) all pseudo-meteorological stations in both catchments were made available as inputs to each individual catchment model, to efficiently provide additional weather data.

2.3. Hydrological modelling

In this study, we have used SWAT 2012 (Soil and Water Assessment Tool) revision 670, a quasi-physically based, semi-distributed hydrological model developed by the US Department of Agriculture's Agricultural Research Service (Arnold *et al.*, 1998). When selecting a hydrological model, several factors were taken into consideration. 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 with

maintained representation of catchment characteristics (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 SWAT after a review of 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.

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; Dallison *et al.*, 2021), 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), Jilo *et al.* (2019) and Hosseini & Khaleghi (2020) studying sediment yield in catchments in Greece, Ethiopia, and Iran, respectively. In addition, Pesce *et al.* (2018) investigated nitrogen, phosphorous and dissolved oxygen in a catchment in Italy, and Yang *et al.* (2017) studied 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, validated, and run separately. The key inputs to the SWAT model are elevation, soil type, LULC, and weather data. The 5 m resolution OS Terrain 5 DEM from Ordnance Survey (2020) was used alongside soil data from the EU soil database version 2.0, specifically the 1:1,000,000 scale Soil Geographical Database of Eurasia (European Commission, 2004). LULC input data were obtained from the CORINE Land Cover dataset (Copernicus Land Monitoring Data; EEA, 2012), accurate spatially to within 25 m, with a minimum mapping unit of 25 hectares for areal features and width of 100 m for linear features (EEA, 2017). 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 were obtained from CEH's National River Flow Archive dataset (NRFA, 2020) for one gauging station in each catchment, with as close to natural flow regime as possible (station details and locations shown in Figure 1). In terms of potential evapotranspiration (PET) calculation, this is inbuilt within SWAT and is based on the weather data provided, with the modeller having the choice of three calculation methods: Priestly-Taylor, Penman-Monteith, and Hargreaves. Given that the data required were available, the widely used Penman-Monteith method was implemented. This method was chosen as it is the sole standard method recommended by the Food and Agriculture Organization of the United Nations, due to its proven applicability to catchments of all types (Allen *et al.*, 1998). In addition, Prudhomme & Williamson (2013) also recommend the use of the Penman-Monteith method for PET estimation specifically for hydrological climate change impact analysis in Great Britain, such as that completed in this study. Furthermore, it is suitable for use at a daily timestep, unlike the Hargreaves method which Hargreaves and Allen (2003) recommend using only at five-day or longer time steps.

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 1) was used as the goodness-of-fit metric for model calibration (Gupta *et al.*, 2009):

$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (\text{Eq. 1})$$

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 2, with a hydrograph of observed and simulated flow for the calibration and validation periods of each catchment shown in Figures S1 and S2 of the Supplementary material, respectively. A total of 17 parameters were used in the calibration, the details of these are provided in Table 3. These parameters were selected based on a combination of a literature review of studies of similar catchments (size, climate, and topography), after consultation with experienced SWAT modellers, and following a global sensitivity analysis. Groundwater parameters were found to be particularly sensitive across all catchments, but especially so in the Clwyd and Conwy, hence the abundance of groundwater related parameters calibrated (Table 3). All 17 parameters were found to be sensitive ($p < 0.05$) in at least one of the five catchments.

Due to the lack of sufficient historical sampling data, water quality parameters were not calibrated, with the default SWAT water quality parameters being used, after a review of their suitability for the study area. 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). Sampled data from a single water quality monitoring location in each catchment was used for the validation, the location of these are shown in Figure 1. 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 4). The modelled TP, TN and SS output do all correlate well with modelled streamflow however (Table 5), suggesting that this is the key driver of change in the uncalibrated model.

Future runs of the calibrated and validated SWAT model were completed for the hydrological years 2021 to 2080, where a hydrological year runs from 1 October to the following year's 30 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. 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, in this way individual dataset continuity was prioritised above overall approach consistency. 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. Each individual catchment model was run for each of the twelve RCM ensemble members, the mean of all twelve streamflow and water quality outputs for each catchment was then taken and has been analysed as detailed below.

2.4. 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 on the mean of the 12 model runs for each catchment, for both streamflow volumes (at the gauging station location in each catchment) and water quality factors (measured at the water quality monitoring location in each catchment), was 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 where 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 2, to subsequently enable the calculation of baseflow:

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

where Q_{Dt} is direct runoff at a given timestep, c is a constant with value 0.925, Q_{Dt-1} is direct runoff at the previous timestep (at timestep $t = 0$, Q_D is assumed to be 0) and Q is total streamflow. Baseflow (Q_{Bt}) for the same timestep was then calculated using Equation 3:

$$Q_{Bt} = Q_t - Q_{Dt} \quad (\text{Eq. 3})$$

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.

3. 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.

3.1. Climate projections

When looking at the mean of all 12 RCM outputs, 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 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.

3.2. Streamflow

3.2.1. Long-term averages

Long-term trends are seen both annually and seasonally in the catchments when analysing future streamflows (based on the average of all 12 model runs for each catchment), however, the direction and statistical significance of these vary between catchments. Seasonal and annual streamflow output, based on a five-year moving mean, for each of the 12 model runs for each catchment can be found in the Appendix, with the mean of this ensemble (used for the presented analysis) also shown. Using the 1990-2010 period average as a baseline, it can be seen that in most cases there is consistency between catchments (Figure 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 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 ($p < 0.01$).

3.2.2. *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 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 7).

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 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 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 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.

3.2.3. 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 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.

3.3. *Water quality*

As can be seen in Figure 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.

4. Discussion

4.1. 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, 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 in the UK, such as UK CEH (2012) and Kay (2021). 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.

In terms of the magnitude of large streamflows, the catchments fall into two clusters. Once again, the Conwy and the Dyfi catchments are similar to one another, while the Clwyd, Teifi, and Tywi all show similar responses. This can be seen for the annual data, when looking at Figure 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 (Hornberger *et al.*, 2014). 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 exacerbated by soil characteristics, 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 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 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 8); this is likely due to the statistically significant declines seen in summer and autumn average flows into the future (Figure 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. In addition, research by Dobson *et al.* (2020) for England and Wales draws similar conclusions, with the yearly probability of water-use restrictions due to extreme drought projected to double by 2050.

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). In addition, Lane & Kay (2021) forecast, using UKCP18 projections, large reductions in summer low flow volumes by the 2080s, this is combined with simultaneous increases in winter high flow volumes, in line with our results. 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. This conforms with the results of work by Kay *et al.* (2021), which demonstrates peak river flows to be increasing in magnitude for a studied region covering west Wales.

4.2. Water quality trends

Unlike the streamflow trends discussed, the results of the MK trend analysis of water quality factors are 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 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, 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; Varvani *et al.*, 2019; 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 very 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 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 oxygen solubility 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.

4.3. 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 one 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, 2019a), 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. These problems could be further exacerbated given the lower summer flows projected in particular, especially downstream of consented discharges from sites such as wastewater treatment works, as well as diffuse pollution sources. Lower streamflows provide less dilution potential; this, combined with higher water temperatures, has the potential to seriously impact on overall water quality.

5. 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.

It is important to note that this work takes a worst-case approach in terms of future climate change, so the streamflow and water quality results presented are at the highest-end of potential future change. Therefore, we suggest further hydrological modelling, using more optimistic projections for future emissions, such as RCPs 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 by water users. 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. In addition, further investigation of the impact of streamflow changes on water abstractors is required. For example, implications for the output generation potential of hydroelectric schemes is needed at a

national level, to enable robust planning across the country, ensuring stability in the national electricity grid. Furthermore, 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. Finally, initial investigation of future water quality alterations due to climate change have been presented in this paper. There is scope for future to work to build on the results presented here and provide greater clarity on likely changes, for both the quality factors studied here, and other important water quality parameters, such as microplastics, pharmaceuticals, heavy metals, and bacteria.

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Appendix: Ensemble projections for seasonal and annual streamflow

Figure A1.

Figure A2.

Figure A3.

Figure A4.

Figure A5.

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Table 1. Key study catchments details; catchment area is 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

Table 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 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

Table 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	<u>0.200</u>	-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. 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	<u>0.033</u>	<u>0.035</u>	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

Figure captions

Figure A1. 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. 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 A3. 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 A4. 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 A5. 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.

Figure 1. Study catchments as delineated in SWAT. **(a)** Streams and stream orders (derived by Strahler method), streamflow gauging stations (blue X) and water quality monitoring locations (orange +). **(b)** Catchment elevation and streams (third order and larger).

Figure 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).

Figure 3. Pseudo-meteorological stations used in SWAT future weather input, labelled with station name and elevation.

Figure 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 13-station mean also shown, bold p values are significant at <0.05 .

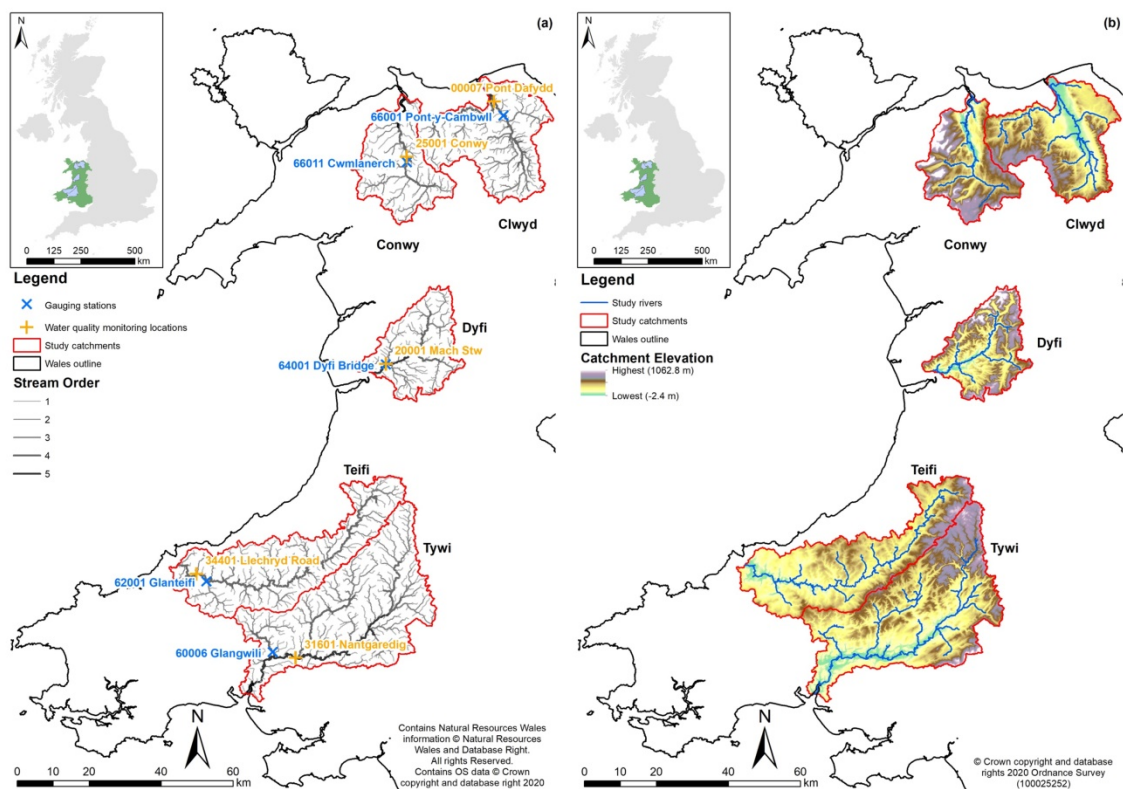
Figure 5. Percentage change from the 1990-2010 baseline average (y-axis) for a 5-year moving average of 2021-2080 future streamflow data (x-axis). Seasonal and annual averages shown for each catchment. Please note that the y-axis scale on the annual average graph (bottom) is a factor of two smaller than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

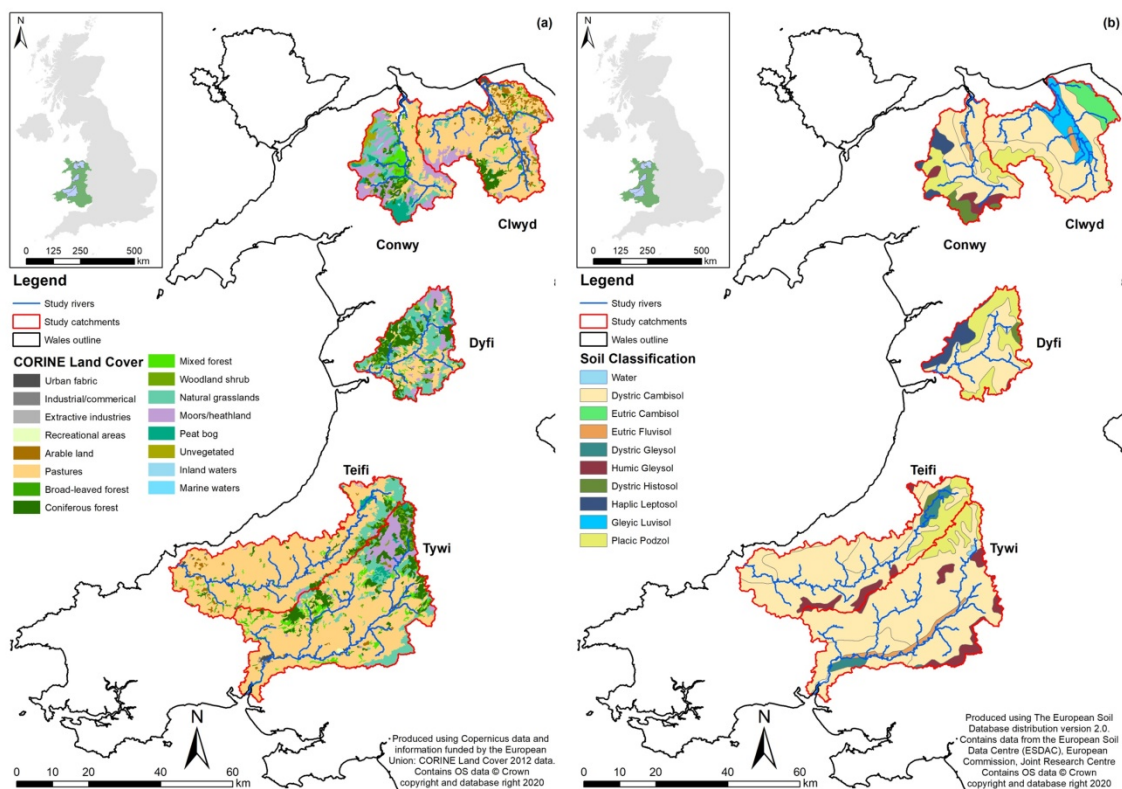
Figure 6. Overview of the direction, magnitude and significance of annual and seasonal average trends in projected future (2021-2080) average streamflow, as detected by Mann-Kendall trend analysis, based on the average of all 12 RCM model outputs.

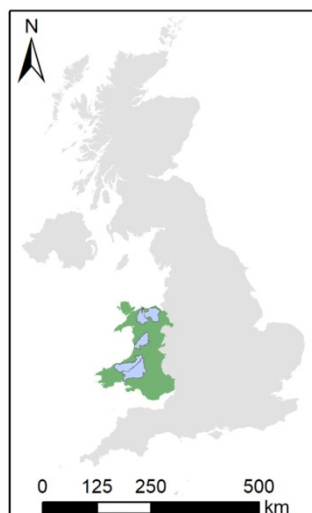
Figure 7. Overview of the direction, magnitude and significance of annual and seasonal trends in projected future (2021-2080) extreme streamflows, as detected by Mann-Kendall trend analysis, based on the average of all 12 RCM model outputs.

Figure 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.

Figure 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.

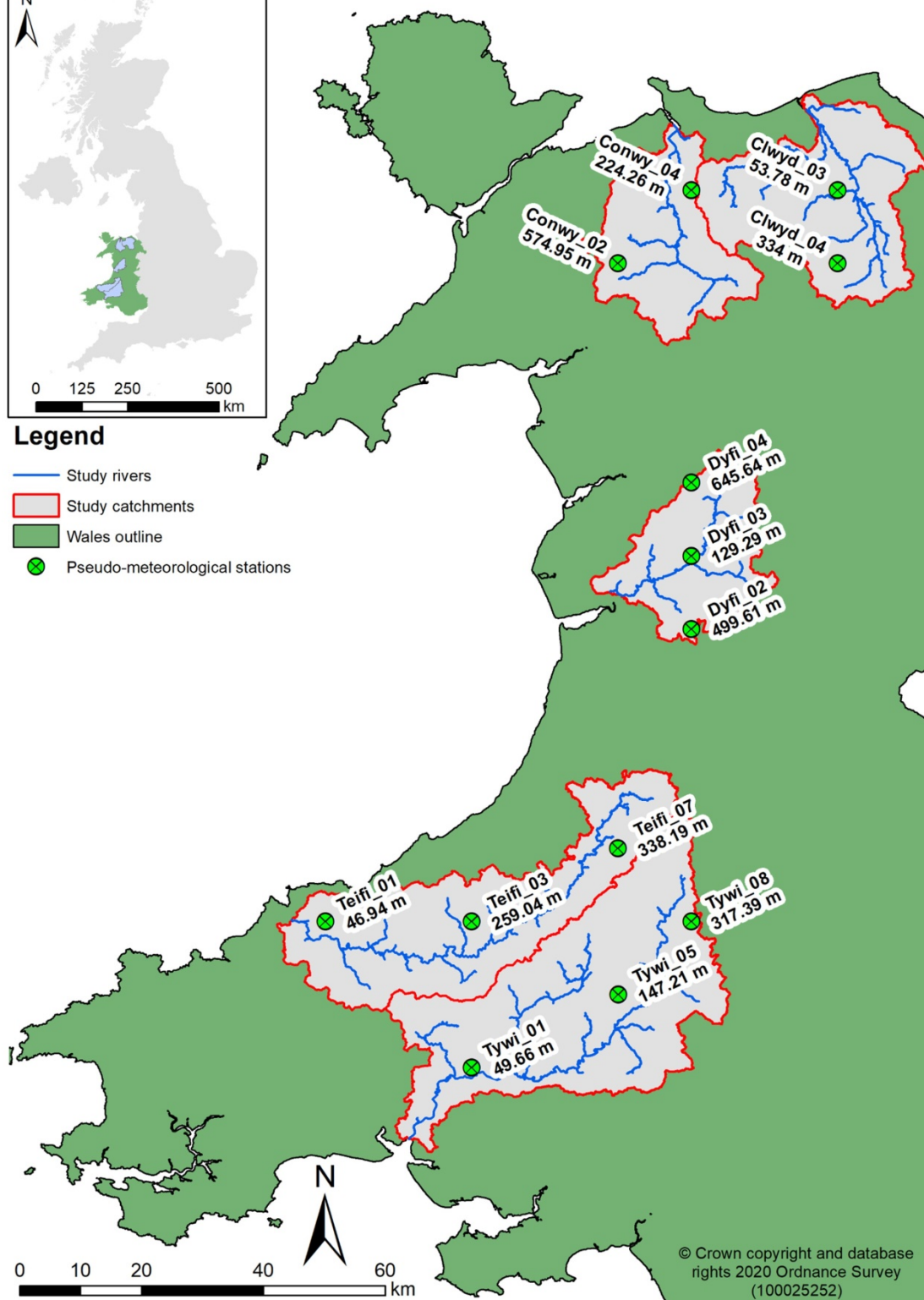




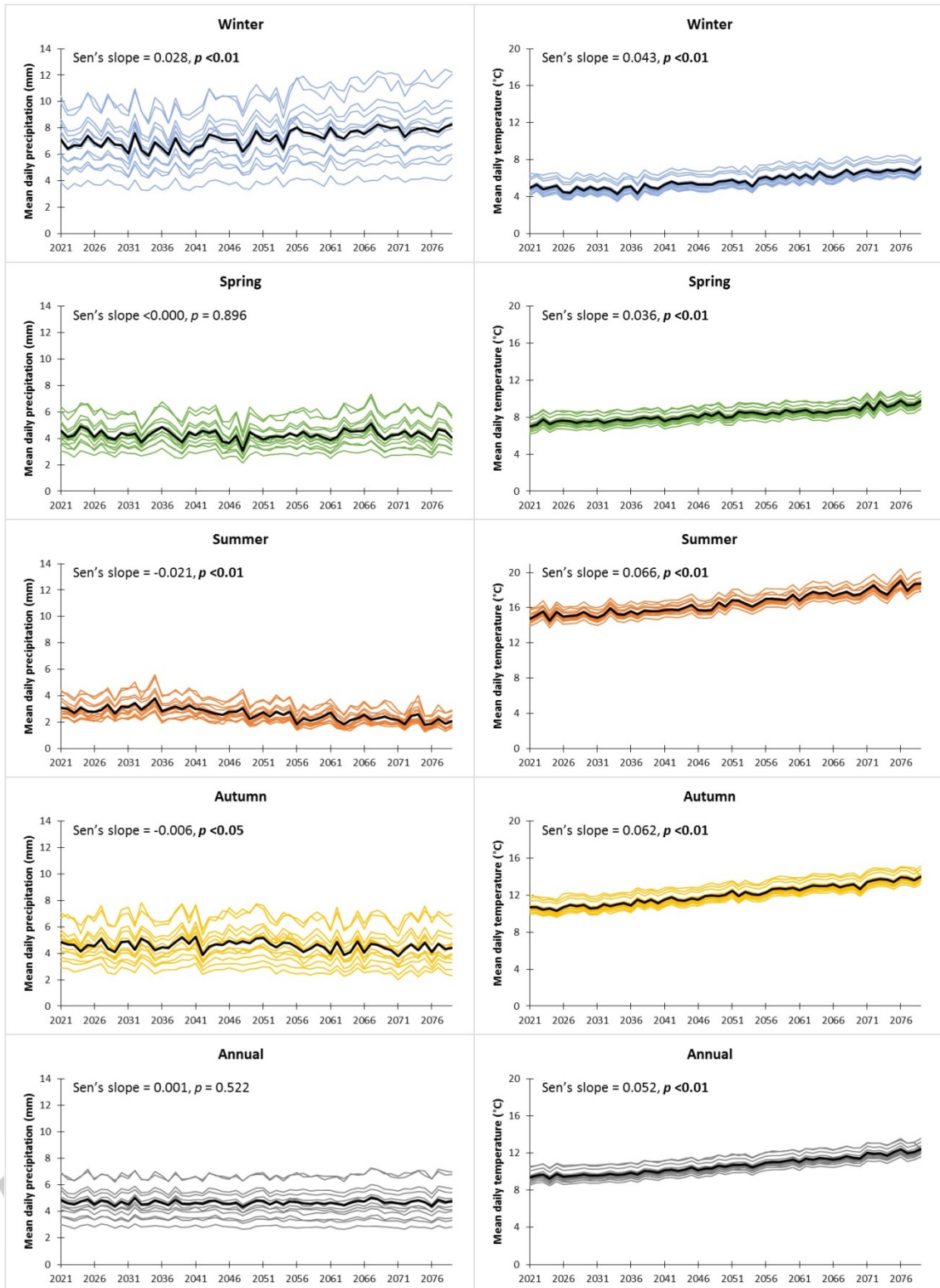


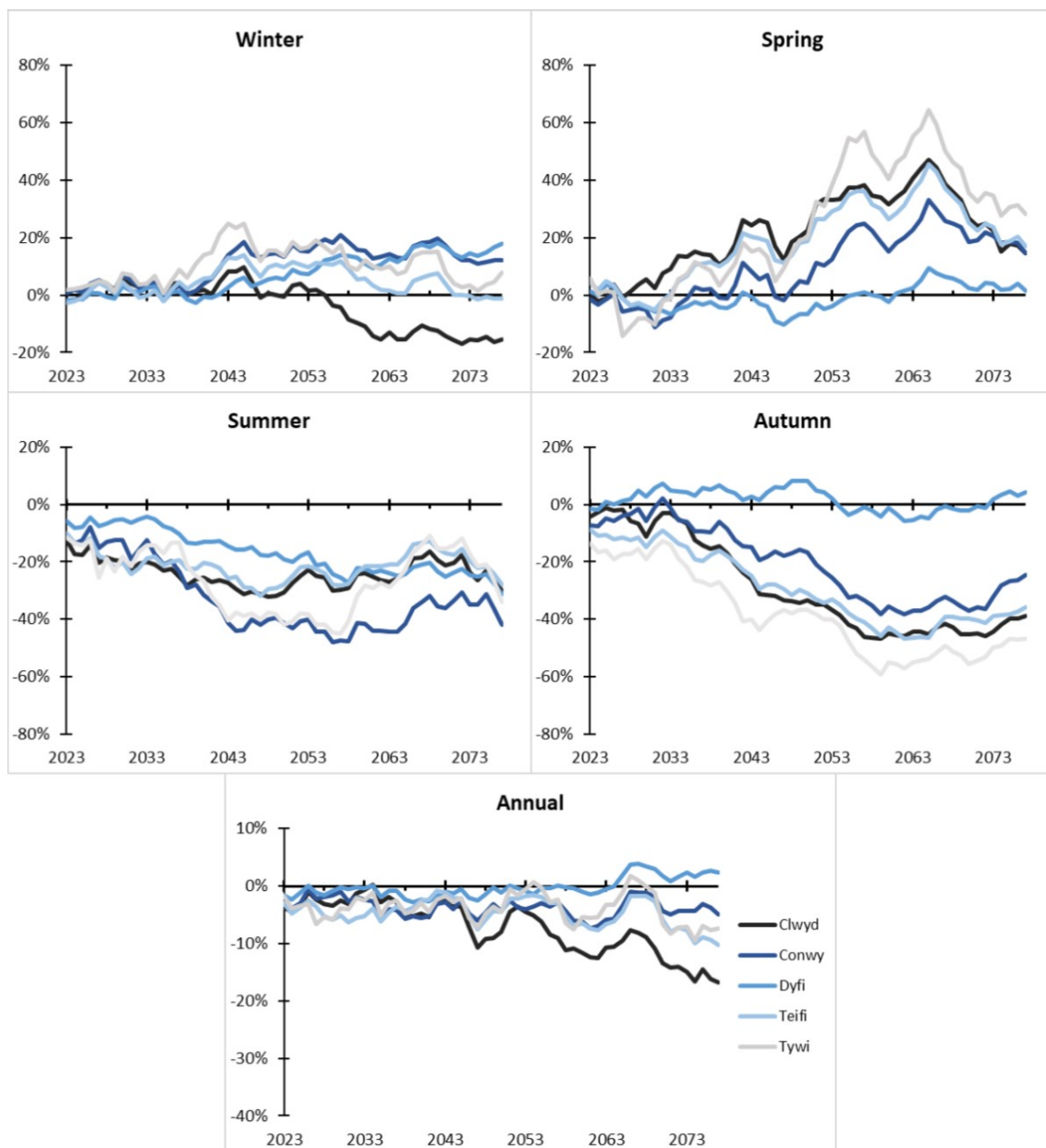
Legend

- Study rivers
- Study catchments
- Wales outline
- ⊗ Pseudo-meteorological stations



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	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 $p < 0.05$

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

No of high flow events					
	Win	Spr	Sum	Aut	Ann
Clwyd	▼	▲	△	▼	▼
Conwy	▲	▲	▽	▼	△
Dyfi	▲	△	▼	△	▲
Teifi	△	▲	▽	▼	▽
Tywi	△	▲	△	▼	△

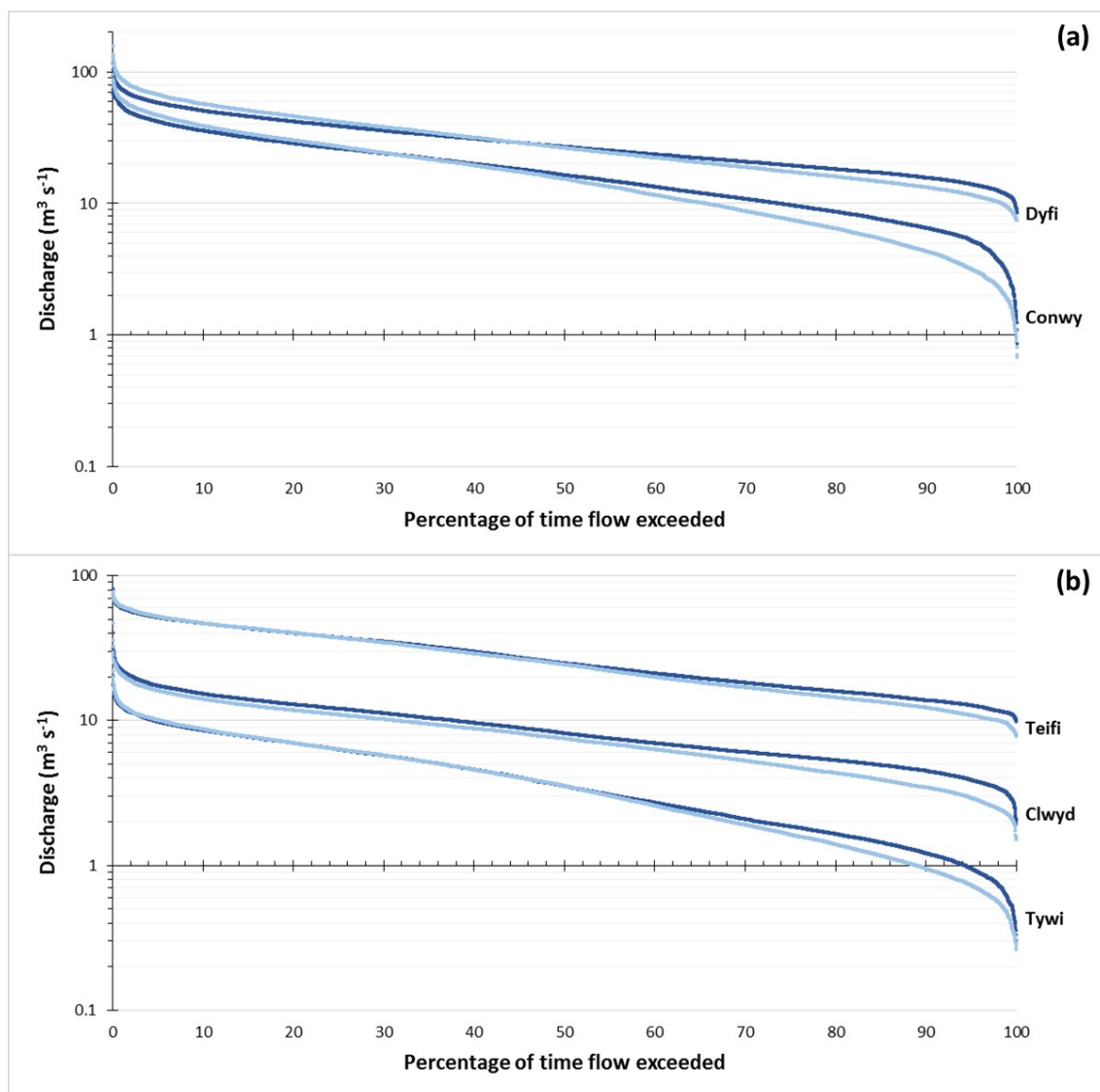
Mean high flow event duration					
	Win	Spr	Sum	Aut	Ann
Clwyd	▽	△	▽	▽	△
Conwy	△	△	▽	▽	▽
Dyfi	▼	▼	▽	▽	▼
Teifi	△	△	▽	▼	▽
Tywi	▽	▲	▽	▼	▼

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

No 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 $p < 0.05$



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

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

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

Dissolved oxygen					
	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 $p < 0.05$

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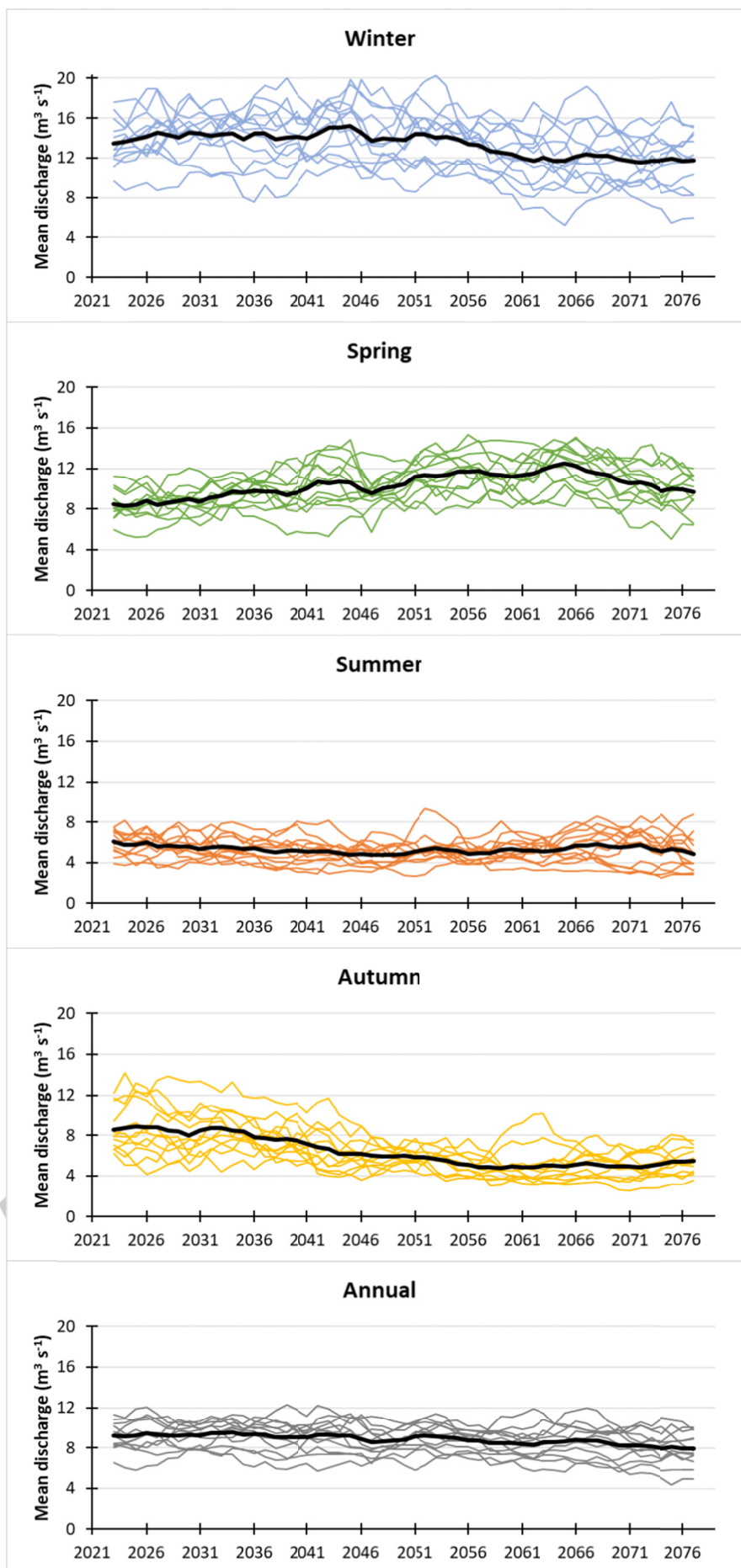


Figure A1.

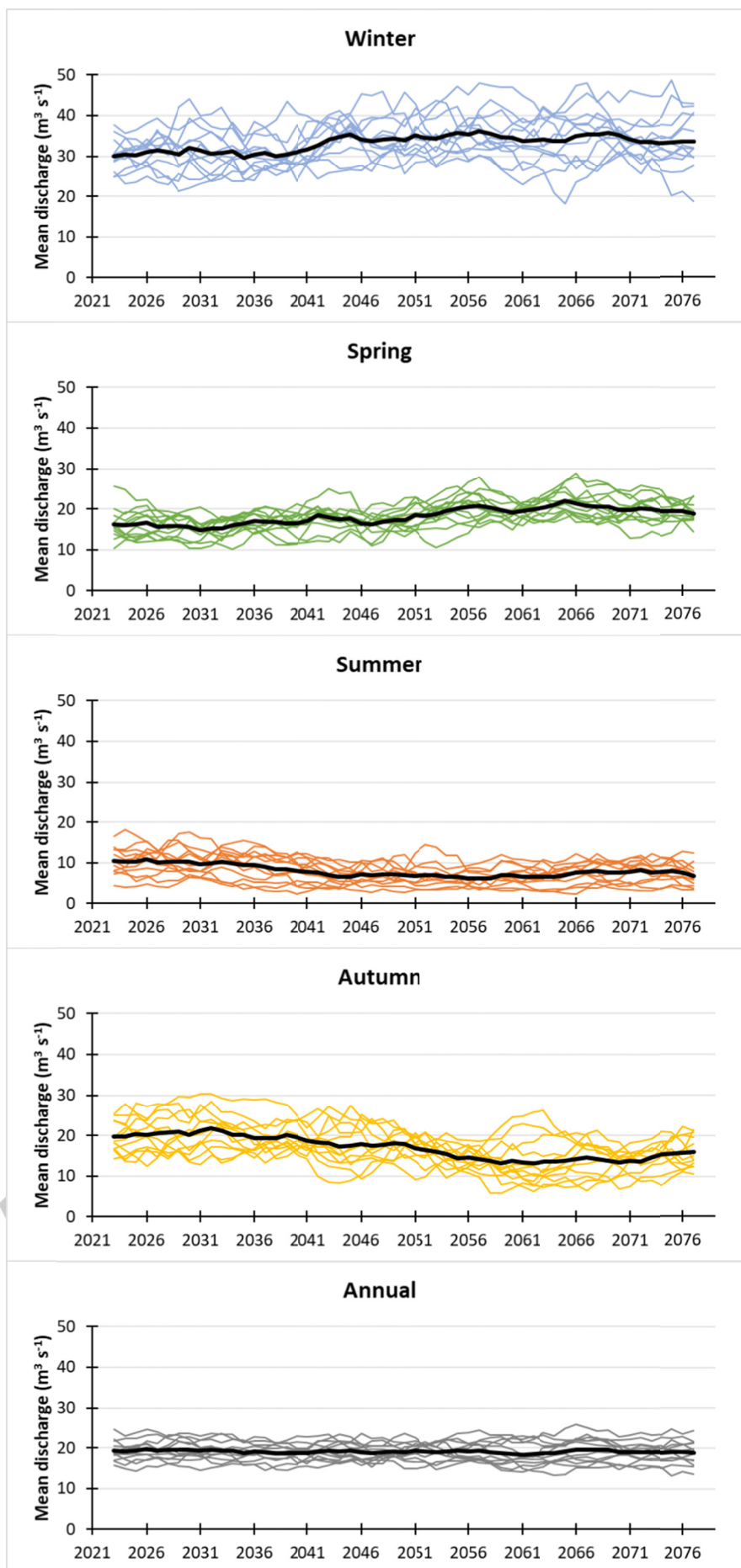


Figure A2.

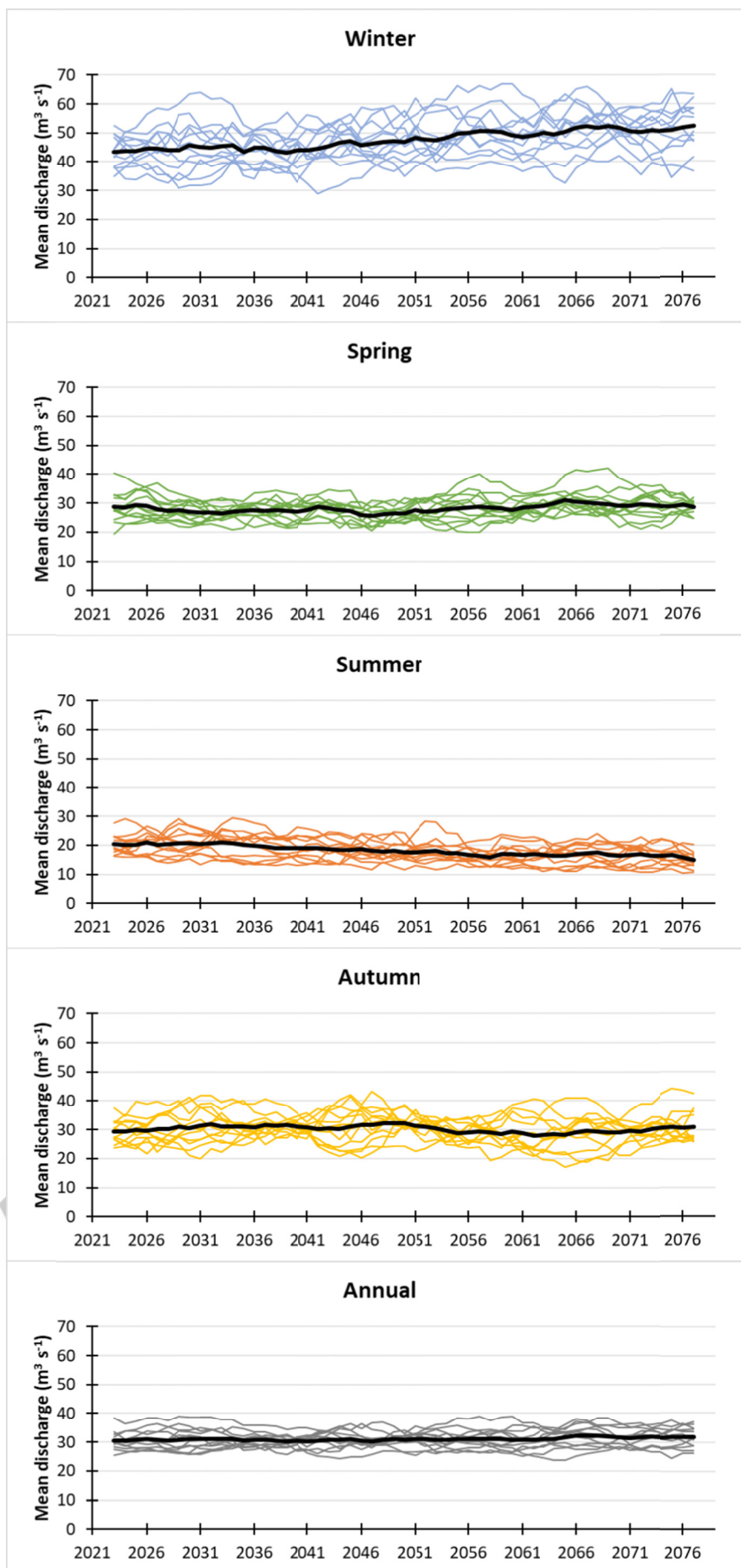


Figure A3.

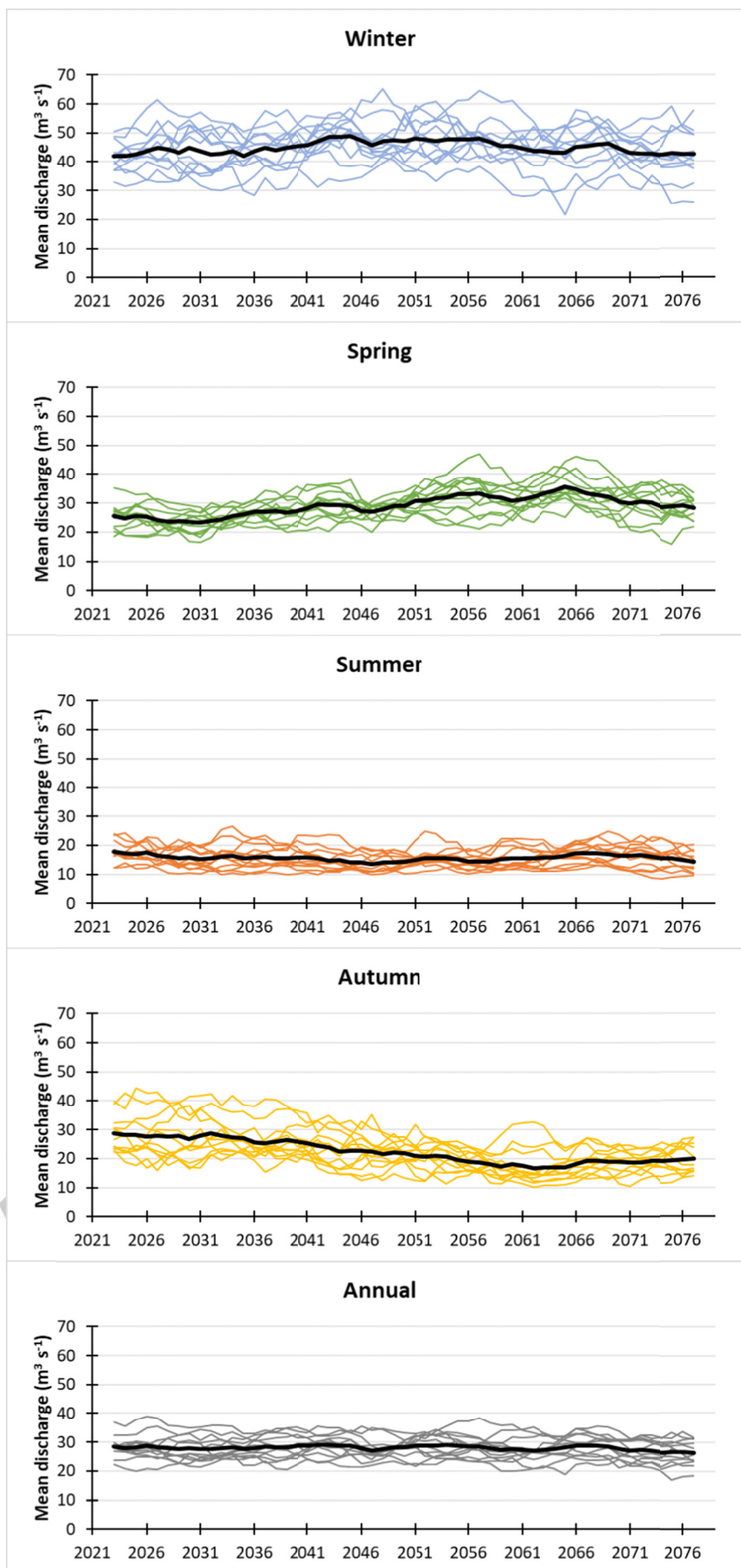


Figure A4.

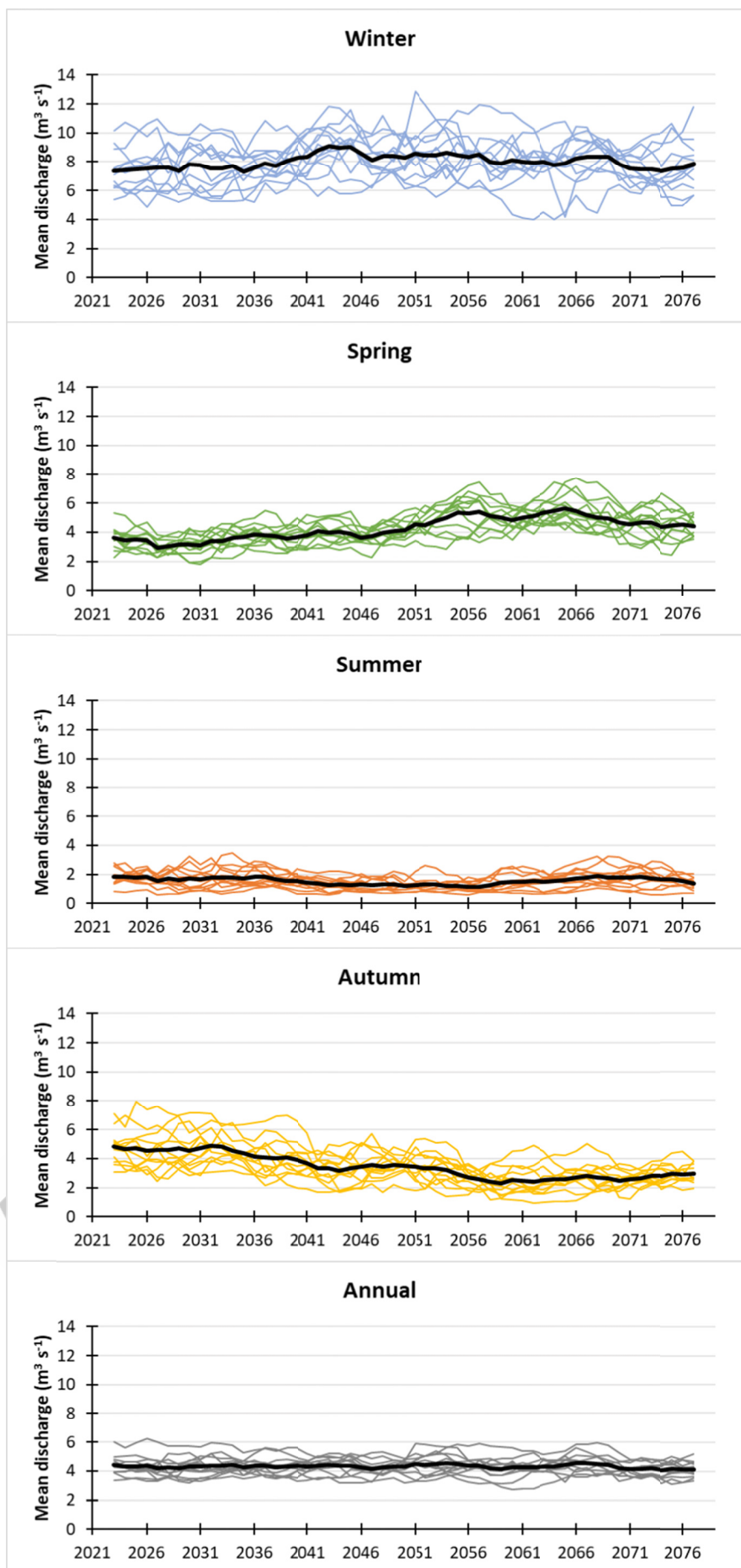


Figure A5.

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