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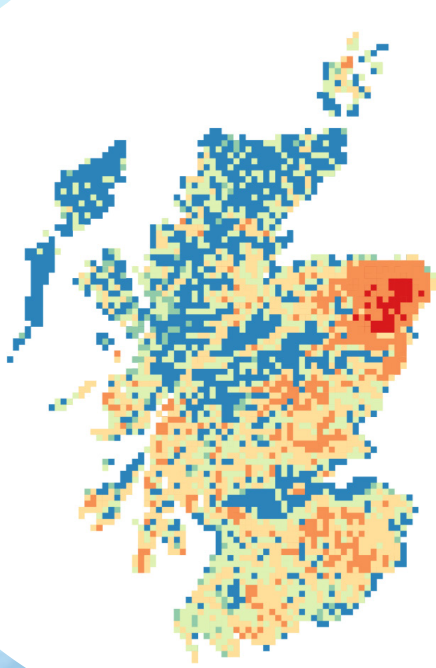

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Private Water Supplies and Climate Change

The likely impacts of climate change (amount, frequency and distribution of precipitation), and the resilience of private water supplies

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Acronyms

BGS	British Geological Survey
BFI	Baseflow Index
DEWS	Drought Early Warning System
DRI	Drought Risk Indicator
DWD	Drinking Water Directive
DWQR	Drinking Water Quality Regulator
HadRM3	Hadley Centre Regional Climate Model
LA	Local Authorities
NAO	North Atlantic Oscillation
PWS	Private Water Supply
SSI	Standardised Streamflow Index
SEPA	Scottish Environment Protection Agency
SG	Scottish Government
RBMP	River Basin Management Plan
RCP8.5	Representative Concentration Pathway (see Box App I.1)
UKCP18	UK Climate Projections 2018

Executive Summary

The aim of this study was to better understand the likely impacts of climate change (amount frequency and distribution of precipitation) on Private Water Supplies (PWS) in Scotland. In particular, it looked at the consequences on their resilience to water shortages in order to assess changes in vulnerability of PWS due to reduced quantity of water as a result of climate change. The objective of this report is to provide evidence to help inform decision-makers on the complexity of the factors influencing PWS and how risks may increase in the future. The research consisted of two phases: a literature review on meteorological-climatic and catchment processes leading to water shortages and their impacts on small rural water supplies (Phase 1); and the identification of potential PWS risk areas by mapping climate change projections (Phase 2).

Background:

Climate change is affecting Scotland's weather patterns, which in turn impacts the quantity, distribution and frequency of precipitation The policy drivers are that: (i) PWS must meet the requirements for Drinking Water Quality in the Drinking Water Regulations (The Water Intended for Human Consumption (Private Supplies) (Scotland) Regulations 2017); and (ii) sufficient water quantity is a basic condition for adequate living standards in line with the Sustainable Development Goal 6 (SDG: Access to water and sanitation for all). Supplies are classified into regulated (Type A) and exempt (Type B) supplies: this report is a general assessment covering PWS types (and their respective sizes) and collection technologies from different sources. Regulated are typically supplies serving more than 50 people, more than 10m^3 or those that supply commercial or public premises. There are some 2500 regulated and 20,000 exempt supplies in Scotland.

Key Findings – Literature review:

1. A meteorological drought (below-normal precipitation) can propagate through the hydrological system (the precipitation input side to the hydrological cycle) and, if prolonged, lead to a hydrological drought, i.e. below-normal water availability in rivers, streams, reservoirs, lakes, or the groundwater table. Hydrological droughts are directly associated with socio-economic impacts including drinking water shortages. In Scotland, very low river and spring flows and low reservoir and loch levels have occurred during the past century in both West and East Scotland in connection with periods of prolonged dry weather. Generally, the impact of meteorological drought on water sources serving small rural water supplies is controlled by catchment water storage levels prior to onset of dry weather, and depends on the type of water source.
2. In addition to meteorological-climatic drivers, catchment properties (e.g. land cover, topography, soil type bedrock geology) and human activities (e.g. abstraction, land and water management and water use) influence the impacts of a hydrological drought event on small supplies.
3. The key drivers of a hydrological drought are:
   i. Climate-atmospheric drivers such as precipitation deficit and temperature anomalies. which are key to shaping the distribution of drought duration in natural and human-influenced catchments.
   ii. Hydrological drivers in natural catchments such as evapotranspiration, soil moisture and water storage (e.g. in the soil and aquifers), and runoff, which are influenced by catchment properties determining aquifer recharge and response to rainfall ("flashiness").
   iii. Human drivers include surface water and groundwater abstraction, urbanisation, damming and deforestation. In short timescales, the onset and duration of a hydrological drought depends on water demand and water management. In longer timescales the threshold below which a hydrological drought occurs is mainly influenced by groundwater depletion and anthropogenic land use change. A human-induced drought has a lower threshold below which a hydrological drought occurs than a climate-induced drought.
4. Hydrological drought events are described by their frequency, severity, duration and deficit (i.e. deviation from normal flows and levels for a given area and season). Generally:
   i. In cold climates, hydrological drought deficit is governed by annual precipitation and winter precipitation, which is controlled by temperature.
   ii. River drought duration is primarily controlled by seasonal water storage (e.g. snow pack and glaciers). River drought deficit is mainly controlled by water storage in soil and aquifer.
   iii. Increased annual precipitation increases soil moisture and subsequently evapotranspiration (when temperatures are sufficiently high), which may or may not influence groundwater recharge. Increased annual temperature increases evapotranspiration rates and reduces recharge in winter. Increased winter temperature reduces the extent of ground frost and shifts the snow melt

from spring toward winter, allowing more water to infiltrate into the ground, resulting in increased groundwater recharge.

5. Generation and propagation of different hydrological drought typologies is controlled by meteorological drivers and catchment processes, such as groundwater storage. Hydrological typology distinguishes drought generating mechanisms as (their key driver in parentheses): Classical rainfall deficit drought (precipitation deficit in any season); Rain-to-snow season drought (precipitation deficit continuing into snow season); Cold snow season drought (low temperature in snow season leading to no recharge); Warm snow season drought (high temperature in snow season leading to no recharge); Snowmelt drought and Glacier-melt drought (in winter, in very high latitudes, leading to no recharge); and composite droughts (multiyear droughts in catchments slowly responding to rain). The classical rainfall deficit drought is the most commonly occurring, but types such as rain-to-snow-season droughts and warm snow season droughts can have more severe impacts.

6. A wide range of indicators, standardised indices and thresholds exist to define a hydrological drought and support early warning systems. Indices are typically computed numerical representations of drought severity, assessed using indicator data such as precipitation, snowpack, streamflow, groundwater or well level, reservoir storage, and modelled data. Ideally, they have both monitoring and forecasting components to prompt action (via "below-normal" threshold triggers) within a drought risk management plan, as a means of reducing potential impacts. Examples of standardised hydrological indices are the Standardized Streamflow Index (SSI), which is used and reported by SEPA, and Standardised Water-Level Index, which is used for assessing risk from groundwater drought. The baseflow (i.e. groundwater contribution to river flow) index (BFI) can be a good proxy for the combination of multiple catchment characteristics indicative of catchment storage.

7. Few studies detail vulnerability to meteorological and hydrological drought of small rural supplies in developed countries by source and water treatment technology. Sources sustained by precipitation (e.g. household rainwater harvesting and some springs) and immediate aquifer recharge from rainwater (e.g. protected springs and protected shallow wells) are more vulnerable to precipitation deficit and variability than boreholes. However, boreholes and deep wells from unconfined and relatively shallow aquifers are sensitive to precipitation variability unless in cases where an aquifer receives recharge from an extensive catchment area. Rivers are vulnerable to a prolonged precipitation deficit. Reservoirs are vulnerable to the variability of rainfall, which outweighs the positive effect of an increase in total annual precipitation.

8. Major knowledge gaps are related to research questions on the following issues: drivers of drought; human influences on the prevention, exacerbation or management of hydrological drought; collecting data on the impacts of hydrological drought; modelling drought propagation, severity and recovery; and identifying "normal" in a constantly changing world.

9. The practical implications of this evidence can be summarised as:

   i. Risk assessment of PWS for water quality issues can be extended to include climate change related issues; the World Health Organisation (WHO) has already provided an extended conceptual flow of activities in water safety plan risk assessment.

   ii. Few studies account for changes in water demand in view of climate change in Scotland; therefore, data on catchment storage will be key towards management of water resources for PWS resilience.

   iii. Policy prescription on fit-for-purpose technologies for collection from source and treatment of water is widely recognised as a feasible way to help build resilience in decentralised, small rural supplies. This approach can be tailored to local conditions and tied into other risk management approaches (e.g. water quality risks), such as the specified technologies' approach to health-based targets described in the WHO's Guidelines for Drinking Water Quality. For example, a change of source (e.g. from spring to borehole) can be a sensible course of action in areas where bedrock aquifers have the potential to sustain borehole water supply, and when vulnerability to drought and contamination co-occur for a given PWS or supply zone.

   iv. Centralised management is key in developing water supply resilience to climate change. This is because the technical, human, and financial resources are usually sufficient to permit the integration of climate issues within management plans and the expertise and ability to identify alternative sources to produce lower-risk source water services.

Key Findings - Future projections:

1. Climate change will result in alterations to the precipitation input to Scotland's hydrological system, with different spatial distributions and seasonality shifts giving reduced rainfall in the east

and increase in the west. There is an increasing probability of experiencing drier years in the future. Warmer temperatures also imply increased rates of evaporation loss.

2. There will likely be an increased risk of meteorological drought which may lead to hydrological drought and impact on PWS with an increase in the number of drier years (low total annual precipitation) occurring more frequently with water shortages due to large water precipitation deficits.

3. Using risk mapping, approximately half of the PWS are estimated to be within areas of High or Very High- (risk categories between 2020 and 2050 (see Figure 1 and explanation of classification).

   i. The geographical distribution of PWS in Scotlands' rural landscape places those supplies at an increasing risk of experienceing more years in the future, when the total annual precipitation is less than the 20th percentile of the observed period.

   ii. The risk mapping does not differentiate between PWS types; however springs and shallow wells will be relatively more vulnerable than boreholes.

4. The level of meteorological drought risk is spatially variable:

   i. The north-east of Scotland may have the greatest exposure to risk of precipitation deficit due to projected changes in precipitation and high concentration of PWS.

   ii. PWS in large areas of upland Scotland including the southern west coast and upland central and south Scotland may also experience increased water deficit.

   iii. Although some areas are estimated to be at lower risk of experiencing more dry years, the risk of experiencing severe drought in some years remains.

5. Analysis of 2018 data indicates that there was a climatic contributor to the large number of requests for support for PWS. For north-east Scotland there were areas that were consistently drier than average. The chance of exceeding 2018 temperatures (joint hottest summer on record) are estimated to become 50% more likely to occur by 2050 than in the past. This implies a larger evapotranspiration amount risking reduced groundwater recharge. The policy implications are for the need for adaptation to reduced water availability.

6. Rainfall seasonality may have changed in the past, with projections indicating further seasonal shifts that may alter the timing at which groundwater recharge occurs.

7. Total annual precipitation volume for the whole land area of Scotland using the UKCP18 data, is estimated to decrease (but is spatially highly variable, see 4 above). This, combined with projected higher temperatures and associated increased evapotranspiration and evaporation and reduced winter snow cover indicate risks of a reduction in the amount of water entering groundwater storage in many parts of the country in some years.

   i. For the whole UK there is an overall increased drying trend in the future, but increased intensity of heavy summer rainfall events.

2. There will likely be increased variation in the climate leading to more frequent extreme weather events such as droughts and floods.

Recommendations:

1. Risk assessment of PWS for water quality issues can be extended to include climate-change related issues.

2. Policy prescription on fit-for-purpose technologies for collection and treatment of water is a feasible way to help build resilience in decentralised, small rural supplies.

3. Improve meteorological drought risk indicators and monitoring of water availability and shortage early warning mechanisms by developing catchment scale meteorological linked to hydrological drought risk indicators and apply to localised contexts to improve early warning systems.

4. Assess potential of bedrock aquifers across Scotland to sustain various levels of borehole water supply and improve PWS resilience to drought (e.g. using Bedrock Productivity map by British Geological Survey as a guide).

5. Provide risk awareness and water conservation advice to PWS users.

6. Develop household water storage capabilities as back-up support to non-drinking water uses during drought. This may be more suitable for non-drinking water use.

7. Identify the potential for cost effective connection to mains water supply by using spatial risk indicator mapping.

8. Integrate policies and associated research for improving catchment storage potential with those focussed on nature-based solutions for improved ecosystem resilience (e.g. water retention in soils, Natural Flood Management). These measures to improve soil and groundwater water retention for agricultural and ecosystem management purposes may also help PWS resilience.

9. Account for changes in water demand in view of climate change.
10. Assess impacts of meteorological and hydrological drought on reservoirs.
11. Review and assess the benefits of centralised management on water supply resilience to climate change in rural areas to inform and enable the use of lower-risk source water services.

1 Aims and Objectives

The aim of this report is to provide an assessment of the risks posed by climate change to private water supplies (PWS) in Scotland. The focus is on the risk of water shortages as there are increasing concerns about changes to the availability of water due to different future precipitation amounts and its spatial and temporal distribution and occurrences of droughts. The findings will help to understand PWS vulnerability to climate change and inform discussions and decision-making on how to improve PWS resilience.

1.1 Introduction

Scotland has abundant water resources as a result of its wet climate, but with a highly variable spatial and temporal distribution of precipitation. The west is wet whilst the east is dry, giving a distinct west to east gradient due to the 'rain shadow' influence of the western uplands. Annual and decadal variability in precipitation can be large: the most recent decade (2009-2018) was on average 7.25% wetter than 1961-1990 (Kendon *et al.* 2019). Seasonal deviations from this trend also occur. For example, during the drought of 2018 spring and summer rainfall registered 74 and 83% of the 1981-2010 average (Kendon *et al.* 2019) and river flows in the Tweed, Dee, Spey, Deveron and other areas were below 40% of the long-term average (Hannaford 2018).

Drought can be an issue with a widespread and big impact for Scotland (About Drought Handbook 2019; Barker *et al.* 2019). Very low river and spring flows and low reservoir and loch levels are known to occur in both west and east Scotland in connection with periods of prolonged (i.e. lasting for one season or longer) dry weather (Gosling *et al.* 2012). The 2015-2021 River Basin Management Plan (RBMP) report compiled by the Scottish Environment Protection Agency (SEPA) points to a greater risk of water flows being worse than the good status required by the Water Framework Directive ("*Directive* 2000/60/EC) in rivers used for irrigating cropland but only during dry weather (SEPA 2015a; b). Given the latest climate projections for the UK (UKCP18) indicating increasingly variable weather, including : altered spatial and temporal precipitation patterns and variable amounts across Scotland (West becoming increasingly wetter, East becoming drier); higher probability of drier and warmer summers; and increased rates of loss of surface water through greater evapotranspiration (from plants and ground surfaces) and evaporation from water bodies. (Adaptation Scotland 2018; Lowe *et al.* 2018, UKCP18 2018)

The drought event of 2018 affected whisky distilleries, which halved or stopped production, as well as irrigation crop yields, livestock and fish stocks (About Drought Handbook 2019; McGrane *et al.* 2018). The 2018 drought was marked by its severe impacts on decentralised rural water supplies, with unprecedented numbers of requests for support. These PWS are the responsibility of their owners and users rather than Scottish Water. The Drinking Water Quality Regulator (DWQR) reported that in summer to autumn 2018 many PWS across the country ran dry and at least 500 of them requested emergency assistance from their respective Local Authorities (LA) (DWQR 2019). The Scottish Government (SG) provided additional funding (£475,432) to LA and to Scottish Water to enable emergency assistance to be provided free of charge in the form of water bottles and water in tankers (DWQR 2019; SG 2018).

The extent of emergency assistance requested by PWS users during 2018[1] raised awareness about their vulnerability in the face of future climate projections and highlighted the need to improve their resilience to drought. PWS numbers vary from year to year but generally serve approximately 4% of the resident population in Scotland and potentially many thousands of tourists (DWQR 2019), primarily in rural areas. Within years, some individual PWS may supply tourism based businesses that have a large daily turnover, particularly at peak summer periods, hence placing additional demands on the PWS at a time of increased water deficit.

In 2018, there were 21,980 PWS and the largest population relying on PWS reaching approximately 30,000 and 40,000 people in Aberdeenshire and Highland, respectively (DWQR 2019). PWS use a variety of sources such as boreholes, wells, springs, river-intakes, lochs or rainfall and may serve a single house, rural communities up to 5000 people, schools, hospitals and other public, holiday and business premises.

The Private Water Supply (Scotland) Regulations 2017 (the PWS Regulations), which transpose the requirements of the Drinking Water Directive (DWD) (Directive 98/83/EC) as amended to national law, put a duty on LA to monitor and carry out risk assessment in PWS serving more than 50 people, or public or commercial premises. However, the PWS Regulations address PWS vulnerability to pollution and public health risks and not to drought.

1 There may have been a larger number of PWS that experienced shortages in 2018, but were not reported. Data was only available for Aberdeenshire Council areas.

1.2 Project Aims, Objectives and Research Questions

The aim of the research was to provide an assessment of the risks posed by climate change to private water supplies (PWS) in Scotland. This focused on the risk of water shortages as there are increasing concerns about changes to the availability of water due to different future precipitation amounts and its spatial and temporal distribution and occurrences of droughts.

The objectives of the project were to explore the likely impacts of climate change (amount, frequency and distribution of precipitation) and the resilience of PWS with a view to understanding their vulnerability to drought.

The main research questions are summarised as:

- What are the main influencing factors on PWS vulnerability?
- What are the likely impacts of future changes in the amount, frequency and distribution of precipitation and the resilience of private water supplies (PWS)?
    - o What can be deducted from climate change projections (modelling data) regarding changes in precipitation?
    - o How will different regions in Scotland be affected? How will it affect regions where PWS predominate?
- What recommendations can be provided to policy-makers to enhance the resilience of PWS?

To address these questions, the project was carried out in two phases consisting off:

Phase 1:

- Review existing studies and experiences from Scotland to understand how processes such as snow accumulation, rainfall frequency and intensity, recharge of the aquifer, etc. influence each type of water source (i.e. river, well, boreholes, springs) and how/whether catchment characteristics (e.g. geology, soil type and land use) make some water supplies more vulnerable to potential future decline in water quantity.
- Briefly review and evaluate hydrological drought indicators and early warning systems.
- Identify knowledge/research gaps that need to be filled.

Phase 2

- Assess through characterising observed and climate model projections rainfall spatial and temporal patterns using:
    - o A set of estimates of rainfall characteristics using daily observed weather data at a 5km spatial resolution for 1960-2018.
    - o The same characteristics estimated using the UKCP18 probabilistic climate projection data ('high' emissions scenario, RCP8.5, ×12 simulations) for 2020 – 2050.

The findings will help to understand PWS vulnerability to climate change and inform discussions and decision-making on how to improve PWS resilience.

Here, we use the concepts of PWS resilience and vulnerability as follows:

- We define resilience as the ability of a drinking water supply system to undergo change in the quantity of water resources and maintain a reliable service to meet their users' needs, i.e. supply sufficient amount of safe and affordable tap water, in line with definitions by Amarasinghe *et al.* (2016) and Howard *et al.* (2010).
- For vulnerability, we adopt the definition proposed by Blaikie (1994) and Kromker *et al.* (2008), whereby vulnerability refers to 'the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard". In this context a lower water supply vulnerability is associated with higher protection capacity against the risk of a decline in water quantity.

1.3 Structure of the report

The report is divided into two phases in line with the methodological approach taken.

Phase 1 sets out the results of a detailed literature. This includes climate change and water quantity, details on drought definitions and how different types may propagate though the hydrological system, hydrological drought typologies, and drought indices. It has a Scotland focus but draws on information from international sources and global perspectives. Additional material of the literature review is also provided in appendices.

Phase 2 presents results from spatial analyses of climate change projections and changes in the number of future dry years and seasonality of precipitation. A Meteorological Drought Risk Indicator is mapped to illustrate how risk may vary spatially. Additional supporting material from other future projection studies relevant to risks to PWS are presented in appendices.

We conclude with some suggested next steps, practical implication and summary conclusions.

1.4 Methods, assumptions and limitations

Phase 1. Literature review approach

Computerised searches were performed using web-based search engines. Overall, approximately 80 peer-reviewed articles and reports were used for compiling the key evidence on the processes rendering the sources of small water supplies vulnerable to below-normal river and groundwater levels (hereafter reported as hydrological drought in line with the findings of the literature review) and identifying indicators and early warning systems to improve PWS resilience to hydrological drought.

The review revealed a number of catchments affected by below-normal water availability in the past in Scotland due to natural causes and during the first river basin management planning (RBMP) cycle due to human activity. These catchments were projected on the map of Scotland using ArcMap to help understand catchment vulnerability in relation to the locations of the types of PWS affected by the drought in Summer 2018.

Phase 2: Future risk assessment

The analyses of future risks are based on assessments of meteorological drought by considering precipitation quantity as the primary input to the hydrological system determining water availability for PWS. As such this study has not considered ground water, river flows and other aspects of hydrology that influence PWS. The underpinning assumption is that changes to the spatial and temporal distribution and amount of precipitation due to climate change is an appropriate indicator of changes in the levels of water available to PWS (and the hydrological in general) and thus the level of risk. This is on the basis that future levels of risk arising from climate change can be assessed through assessment of historical risks, as indicated by observed weather and requests for assistance due to water shortages. The methods used are detailed in Appendix I.

Scope and limitations of the research: Phase 1 focused on impacts of drought on small rural water supplies in terms of water quantity and not water quality. Phase 2 considered precipitation as the primary input to indicate changes in risk to PWS. Thus, only one key aspect of the hydrological system (the input side of the hydrological cycle) is considered in Phase 2, as evapotranspiration and evaporation surface water loss and variations in ground water are not assessed, as this would require a considerably greater research effort. Hence, we consider below-normal precipitation levels (i.e. precipitation deficit) only and not river or groundwater levels. This study has not assessed *per se* the potential influence of projected change in the context of land use, land use change (e.g. afforestation) or water abstraction for agricultural, energy production or industrial purposes that may reduce the amount of water available as input to PWS. However, a reasonable assumption is that under future warmer conditions water use for agriculture and industry, as well as increased use for renewable power generation, may also contribute to restrictions of water available for some PWS.

Modelling future conditions: The modelling of future climate consequences on PWS is based on the projections generated by the UK Met Office for the UKCP 18[2] for a high emissions scenario (RCP8.5) (UKCP18 2018). This Representative Concentration Pathway (RCP) gives projected warming of 8.5 W m^{-2}, equivalent to a global temperature increase of 2.6 (2.0 to 3.2)°C by 2046-2065 and 4.3 (3.2 to 5.4)°C by 2081-2100 relative to 1850-1900 temperatures). This is the emissions rate we are currently on. The UKCP18 data is based on a single global climate model (HadGEM3) and single Regional Climate Model (RCM, HadRM3), thus a representation of the range of climate models available. The HadRM3 was run as a 12-member ensemble (×12 parameterisations of the RCM reflecting different climate sensitivities) to give 12 future projection data sets. This gives a probability distribution of potential changes in the UK climate, with the ensemble mean representing the mid-range level of probability (see section 3.3 and Figure 7).

2 Phase 1: Drought and its implications for PWS

Here, we give a brief background on climatic and non-climatic pressures on the quantity of water resources and review evidence on how climatic, hydrological and other catchment-based processes influence river and groundwater levels. We also list and briefly assess key hydrological drought monitoring indices and early warning systems. Finally, we review climate-related impacts on water services, with emphasis on small rural decentralised water supplies[3] to better understand PWS vulnerability to drought.

2 See: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/about

3 PWS are by definition small rural decentralised water supplies (Hendry and Akoumianaki 2016); see also Section 2.5

2.1 Climate change and quantity of water resources in Scotland and internationally

Climatic drivers of change in the global water cycle. The global water cycle involves evapotranspiration[4], condensation, precipitation and collection Water evaporates from the land, sea and vegetation, condenses into clouds, falls to Earth as precipitation (rain or snow), drains to soils, rivers, lakes, the aquifer and the ocean, and then the water cycle starts again. Regional water balance is the net result of gains (rainfall, snowfall, ice and snow melt, river inflow, and groundwater recharge) and losses[5] (evapotranspiration, river outflow, groundwater discharge, ecological and human water use). Impacts of climate change on the global and regional water cycle are due to multiple environmental drivers besides rising temperatures, such as: rising atmospheric CO_2; changing rainfall patterns (e.g. wet regions becoming wetter and dry regions becoming drier); rising sea levels; increasing ocean acidification; and extreme events, such as floods, droughts, and heat-waves (IPCC 2018). Appendix II.1 summarises key climate change terms. Appendix II.2 outlines climate change-driven changes in the water cycle.

Climate change and water in the UK. The natural variability of the UK climate makes change hard to detect; only historical increases in air temperature can be attributed to anthropogenic climate forcing, but over the last 50 years more winter rainfall has been falling in intense events (Watts *et al.,* 2015). Future changes in rainfall and evapotranspiration could: alter flow regimes; impact water quality, aquatic ecosystems and water availability; and increase the magnitude and frequency of floods, despite a predicted decrease in summer flows (Watts *et al.,* 2015; Garner *et al.,* 2017). However, research has focused on rainfall and river flows in relation to flooding and not to drought. Very few studies examined the links between low or lack of rainfall, river flows, evapotranspiration, aquifer recharge, groundwater levels. This knowledge gap remains a significant barrier to informed climate change adaptation to the impacts of low or lack of rainfall on catchment hydrology (Garner *et al*. 2017). See also Appendix II.3 for trends of climatic and hydrological variables in the UK.

Non-climatic drivers of change in water resources. Widely recognised non-climatic factors influencing the availability of water resources refer to: demography and socioeconomic vulnerabilities (e.g. population living in water stressed areas); land use (e.g. extent of forest and urban land and cropland); food production and consumption; economy (e.g. water pricing); technology (e.g. efficient irrigation, increased water storage and artificial aquifer recharge); and societal views regarding the use and value of water. It is also important to account for socioeconomic vulnerabilities such as population without access to safe water within premises when needed. To determine the impacts of change on water resources we need to account for both, climatic factors under different climate scenarios and non-climatic factors (e.g. demography and socioeconomic vulnerabilities). However, non-climatic factors change both exposure to climate hazards (e.g. drought and flooding) and socioeconomic demand for water resources (Cramer et a 2014). Therefore, it is difficult to understand what factors, climatic or non-climatic, are the key determinants of change in the availability of water resources.

Non-climatic pressures on flows and levels in Scotland. The main pressures on river flows and the water levels in lakes, lochs and groundwaters are from water abstractions used for public water supply, hydroelectricity generation, the irrigation of crops and water uses for the food and drink industries (SEPA 2015a; b). The scale of pressures and their impacts varies between wet and dry years and between catchments (SEPA 2015a; b). It is expected that climate change will alter the pattern of demand for water and the availability of water to meet it, therefore efficient water use would be key to avoiding unnecessary demands being placed on water resources (SEPA 2015a; b). Appendix IV.2 shows a map of groundwater bodies affected by anthropogenic pressures.

2.2 Drought: definition and types

Definition of drought. No universal definition of drought exists because drought is a complex phenomenon and can therefore be defined in many ways. Here, we adopt the definition of drought proposed by Tallaksen and Van Lanen (2004): Drought is a sustained period of below normal water availability and a recurring and worldwide phenomenon, with spatial and temporal characteristics that vary significantly from one region to another.

4 i.e. evaporation to the atmosphere from soil and water surfaces, and vegetation is a function of solar radiation, surface temperature, vegetation cover, soil moisture, and wind (Kay *et al.* 2013).

5 aka demand.

Box 1. Definitions related to lack of water in the hydrological system

- Drought: Temporary deficit of water compared to normal conditions.
- Meteorological drought: Temporary period of less than average rainfall in a given region.
- Hydrological drought: Below-normal water availability in rivers, streams, reservoirs, lakes, or the groundwater table.
- Low flows: Flow rates corresponding to the 95th percentile (Q95), of the flow duration curve (FDC), meaning those normal flow rates that are equalled or exceeded for 95% of the time.
- Aridity: Permanent deficit of water in a region
- Water stress: Condition whereby water available in a country drops below 1,700 m^3/year or 4 600 litres/day per person
- Water scarcity: Condition referring to low availability resulting from long-term imbalance between water demand and water supply mainly due to the failure of institutions to ensure a regular supply or due to a lack of adequate infrastructure. It is experienced when the 1 000 m^3/year or about 2 700 litres/day per person threshold in a country is crossed.
- Absolute water scarcity: it is experienced in countries where less 500 m^3/year or roughly 1 400 litres/day are available per person.
- Water shortages: exceptional lack of water compared to normal conditions.
- Desertification: Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities.
- Heat-wave or warm spells: A period of abnormally hot weather.

Source: van Loon 2015; Rijsberman, 2006, UN Water 2019; European Commission 2018;

UN 2014; Maliva and Missimer 2012; Tsakiris et al. 2013.

Drought is as an episodic phenomenon of exceptional lack of water compared to normal conditions caused and modified by natural as well as human processes (van Loon, 2015). In this context, drought is a relative, rather than absolute, condition of the hydrological system, both spatially and temporally (Wilhite 2014) encompassing both atmospheric and terrestrial components of the water cycle (i.e. precipitation, evapotranspiration, snow accumulation, soil moisture, surface waters, and groundwater) (Sheffield and Wood 2011). The terms low flow, aridity, water scarcity, water stress, desertification, and heat-waves are distinct from the term hydrological drought (see definitions in Box 1). Van Loon (2015) warns that probably the worst situation with regard to water management is a hydrological drought in the low-flow season in an area that suffers from water scarcity.

Types of drought. Droughts are generally classified into four categories: meteorological, soil moisture, hydrological and socio-economic (Tallaksen and Van Lanen 2004; Sheffield and Wood 2011; Wilhite 2014). Impacts on society are mostly related to hydrological rather than meteorological drought (Van Loon 2015). Table 1 gives an overview of drought impacts.

Meteorological drought: A prolonged precipitation deficit compared to long-term average precipitation, possibly combined with increased potential evapotranspiration, extending over a large area and spanning an extensive period of time (e.g. one season or longer). This type of drought precedes all other types (Hisdal *et al.* 2000) and its impacts affect mainly rainfed-crops and terrestrial ecosystems (Table 1).

Soil moisture drought: A deficit of soil moisture (mostly in the root zone), reducing the supply of moisture to vegetation. This drought is also called agricultural drought because it is strongly linked to crop failure. Soil moisture deficits have additional impacts on terrestrial ecosystems (e.g. forests), carbon cycling and infrastructure, e.g. roads, pipelines and rail (Seneviratne *et al.* 2012; Van Loon 2015) (Table 1). Land cover is key: during dry spells a soil moisture deficit depends not only on precipitation deficit but also on vegetation's water requirements, with trees and forests using significantly greater amount of soil water than grassland or cropland[6]. This type of drought precedes hydrological drought.

Hydrological drought. This is a broad term related to deficit in surface water (e.g. lochs and reservoirs) levels, river (or stream) flows and groundwater levels compared to normal flows and levels based on long-term averages. Several examples in the literature point to a distinction between the terms river (flow)

6 Where the water table is relatively close to the surface, groundwater from below the water table may move upward by capillary action to higher levels in the soil profile in order to reduce the soil-moisture deficit. Ultimately, such groundwater may be lost by a combination of plant removal and evaporation leading to a lowering of the level of the water table. Water use by trees can decrease the proportion of the soil water in the unsaturated zone draining down to the water table, potentially reducing groundwater recharge as a proportion of total precipitation, despite high rainwater infiltration rates in forest soils. Interested readers can find details in Allen and Chapman (2001) and Yawson *et al.* 2019.

drought, groundwater drought, navigational drought and ecological drought[7] (van Loon 2015; Canal and River Trust 2015; National Drought Mitigation Centre-NDMC 2019). Hydrological droughts are usually out of phase with the occurrence of meteorological and soil moisture droughts, as it takes longer for precipitation deficiencies to show up in components of the hydrological system such as streamflow, and groundwater and reservoir levels. A hydrological drought can be framed as a natural hazard, because of its severe socioeconomic impacts (Wilhite 2014; Tsakiris *et al.* 2013) (Table 1). It is also a water resource issue, whereby emphasis is on the imbalance between water gains and losses in the water cycle (See Section 2.1) (van Loon 2015).

Socioeconomic drought. This is the least understood and studied type of drought (Mehran *et al.*, 2015; Huang *et al.*, 2016; Guo *et al.* 2019). It is associated with the impacts of the three above-mentioned types. It occurs when water demand for domestic purposes, economic demands (e.g. crop irrigation, hydropower generation, and other industries) and ecological or health-related impacts of drought (e.g. wetlands and their ecosystem services and benefits) exceed water supply as a result of meteorological, soil moisture or hydrological drought (Table 1).

Vulnerability to hydrological drought. If water demand increases more rapidly than water supply due to drought, then vulnerability to drought depends on the feasibility of alternative pathways to drinking water (e.g. through increasing water storage capacity) and delivery of economic goods such as energy or food. It is difficult to disentangle the socio-economic impacts of drought from the impacts of policy changes (e.g. on water use), water pollution, political instability, or commodity prices (van Loon and van Lanen 2013). Further, socio-economic impacts and ecological impacts are connected. For example, increasing water use to mitigate the socio-economic impacts of drought on agriculture, forestry and recreation in a given area, can reduce the proportion of ecological flows available for other ecosystems in that area and thus aggravate ecological impacts (Christian-Smith *et al.* 2015). Socioeconomic droughts are likely to occur more frequently around the world in the future (Smirnov *et al.*2016).

2.3 Hydrological drought generation and drought propagation

A prolonged lack of precipitation (meteorological drought) can propagate through the hydrological system by affecting soil moisture, groundwater levels and river discharge, resulting first in soil moisture drought and then in hydrological drought (Tallaksen and Van Lanen, 2004; Mishra and Singh, 2011). Natural and human-influenced catchments respond to similar drought generation and propagation mechanisms.

- **Natural catchments.** Without heavy modification of the water cycle by human activities, both normal water availability and the threshold[8] below which a hydrological drought occurs are governed by natural processes in response to weather and climate-atmospheric drivers as well as to hydrological drivers (van Loon *et al.* 2016b). Climate-atmospheric drivers of hydrological drought, such as precipitation deficit and temperature anomalies, are a result of climatic variability due to natural or anthropogenic climate change (Sheffield and Wood 2011). Hydrological drivers in natural catchments refer to evapotranspiration, soil moisture, water storage and runoff and are influenced by catchment properties such as land cover, topography, soil type and geology (Mishra and Singh 2011). Climate and hydrological/catchment-based drivers are further discussed in the Scottish context in Appendix III.1 and III.2, respectively.

7 When hydrological drought is associated with ecological stress.

8 See Section 2.4

Table 1. Major impacts of drought in relation to different drought categories. Source: van Loon 2015.

		Drought Category		
Impact Category		**Meteorological Drought**	**Soil Moisture Drought**	**Hydrological Droight**
Agriculture	Rainfed	x	x	
	Irrigated		x	x
Ecosystems	Terrestrial	x	x	
	Aquatic			x
Energy and industry	Hydropower			x
	Cooling water			x
Navigation				x
Drinking water				x
Recreation				x

- **Human-influenced catchments.** In catchments influenced by human activities both the generation mechanisms and the propagation cascade from meteorological drought via soil moisture drought to hydrological drought can be seen as the propagation of both a natural hazard and a water resource issue (van Loon *et al.,* 2016a). For example, human drivers such as surface water and groundwater abstraction can be modified by climate change and catchment properties reshaped by human activities such as urbanisation, damming and deforestation (van Loon 2015). In short timescales, streamflow and water levels (lakes, reservoirs and groundwater) can be influenced by water use and water management, whereby the drought threshold depends on water demand (van Loon *et al.,* 2016b). In longer timescales, the threshold below which a hydrological drought occurs is mainly influenced by groundwater depletion and anthropogenic land use change (van Loon *et al.* 2016b). It is also important to acknowledge drought impacts depend on season; for example water abstraction for crop irrigation has different effects on the propagation of summer and winter drought. Policy response to drought impacts can also influence drought generation and propagation (van Loon *et al.* 2016a). In this context, a distinction can be made between climate-induced drought, human-induced drought and human-modified drought (van Loon *et al.* 2016a; b).
- **Human-induced hydrological drought versus water scarcity and climate-induced drought.** In a human-influenced catchment, water demand hinges on a variety of factors such as population, standard of living, water efficiency and climate. In many areas, water demand is higher than average water availability, because of, for example, rapid population growth and changes in diet and crops. A long-term imbalance can lead to water scarcity (see review by Rijsberman, 2006) and when this coincides with a hydrological drought it leads to acute water shortage. If society satisfies its demand by abstracting more water from the same catchment, human-induced drought can occur in the short-term and overexploitation of water resources can occur in the long-term. Human-induced drought occurs sooner than a climate-induced drought (van Loon *et al.* 2016a).
- **Precipitation and groundwater recharge.** A review by Jalota *et al.* (2018) showed that:
    - o Effect of precipitation on groundwater is positive as it increases recharge.
    - o With increased precipitation, the contribution of base-flow to river runoff is increased.
    - o Increased annual precipitation increases soil moisture and subsequently evapotranspiration, which may or may not change the recharge.
    - o The higher intensity and frequency of precipitation contribute significantly to surface runoff.
    - o Increased annual temperature increases evapotranspiration rates and reduces recharge in winter.
    - o Increased winter temperature reduces the extent of ground frost and shifts the snow melt from spring toward winter, allowing more water to infiltrate into the ground, resulting in increased groundwater recharge.
    - o Seasonal changes in precipitation would influence groundwater recharge. For example, (in Germany) increased precipitation in winter increases recharge in winter but this effect is counteracted by the reduced recharge during summer caused by longer-lasting soil-moisture deficits.
    - o A thick saturated zone (i.e. the area below the water table in which the soil is completely *saturated* with groundwater) can effectively smooth the impact of seasonal variation.
    - o Spatial distribution in recharge of groundwater levels can be much greater than that of temporal/ seasonal variation.
- **Drought propagation characteristics and features.** Drought research identifies the threshold below normal for the onset of a hydrological drought (see Section 2.4) to describe drought initiation, propagation and end. A range of characteristics are used such as catchment precipitation, soil moisture, groundwater storage and river discharge (simulated and/or observed). Box 2 summarises findings of drought propagation research (van Loon and van Lanen 2012; Van Loon *et al.* 2011; Di Domenico *et al.* 2010). Figure 1 describes the key features characterising drought events (i.e. frequency, severity, duration and deficit) and propagation from a meteorological to a hydrological drought (i.e. pooling, attenuation, time-lag, and lengthening) (Eltahir and Yeh, 1999; Peters *et al.* 2003; Van Lanen *et al.* 2004; Van Loon *et al.* 2011). Lag and attenuation are controlled by catchment processes while pooling and lengthening are determined by both catchment and climatic factors (Van Lanen *et al.* 2004). Hydrological drought duration and deficit are related: a deficit accumulates over the duration of the drought event (Hisdal *et al.* 2003) but their relationship is not linear (Van Lanen *et al.* 2013).

Box 2. What we know about drought propagation

- Drought events become fewer and longer when moving from precipitation via soil moisture to groundwater storage, so the number of hydrological droughts decreases and their duration increases.
- Events whereby river discharge levels that are lower than normal (river hydrological drought) have characteristics comparable to those of soil moisture drought, because they reflect both fast (rainfall-surface runoff) and slow (subsurface runoff) pathways in a catchment.
- In fast responding catchments, where rivers are "flashy" and flows rise and fall fast in response to rain and snow-melt), river hydrological drought is more comparable to meteorological drought, hence more events of shorter duration are expected. This usually refers to small, headwater catchments where there is less potential for buffering of flows by groundwater storage.
- In slowly responding catchments, where rivers are "sluggish" and flows rise and fall slowly in response to rain and snow-melt, river hydrological drought is more comparable to groundwater storage levels below normal (groundwater hydrological drought), hence fewer events of longer duration are expected. This usually refers to large catchments with more potential for groundwater storage.
- Deficit volumes are higher for meteorological droughts than for river hydrological droughts, because precipitation is more variable, resulting in higher threshold (see footnote 6) values and a larger deviation from the threshold.
- Mean maximum deviation from "normal" is higher for soil moisture droughts than for groundwater droughts, because soil moisture values are much more variable, while in groundwater the signal is smoothed. Exceptions from this general observation may be found in catchments with shallow, coarse soils.

Source: van Loon and van Lanen 2012; Van Loon et al. 2011; Di Domenico et al. 2010

- **<u>Most important factors in drought propagation.</u>** On a global scale, hydrological drought duration might be more related to climate than to catchment control (Van Loon and Laaha, 2015; Tallasken and Hisdal 1997). On the national or regional scale (i.e. the scale water resource management takes place) and at temperate (and continental) wet climates, as in Scotland, the effect of climate on hydrological drought duration hinges on geology, soil, land use, and other catchment characteristics (Van Loon and Laaha, 2015; van Lanen *et al.,* 2013). Growing evidence shows that river drought duration is primarily controlled by seasonal water storage (e.g. snow pack and glaciers) (van Loon and van Lanen 2012; van Loon and Laaha, 2015; see also Appendix III.1). Drought deficit is mainly controlled by catchment water storage in soil and aquifer (van Loon and Van Lanen, 2012; Van Loon and Laaha, 2015; Van Lanen *et al.,* 2013; see also Appendix III.2). In cold climates, hydrological drought deficit is also governed by annual precipitation and winter precipitation (Van Loon and Laaha, 2015; van Loon *et al.,* 2015). Drought propagation features are further discussed in conjunction with hydrological drought typology in Appendix III.3.
- **<u>Hydrological drought typology.</u>** Van Loon and van Lanen (2012) proposed a hydrological drought typology that uses the diversity of climate-driven drought-generating mechanisms as the basic principle. This typology distinguishes drought generating mechanisms depending on precipitation or temperature control (or their combination) on hydrological drought generation and propagation, as follows: Classical rainfall deficit drought; Rain-to-snow season drought; Cold snow season drought; Warm snow season drought; Snowmelt drought; Glacier-melt drought; Wet to dry season drought (Table 2). The processes underlying these drought types are the result of the interplay of temperature, precipitation and water storage at catchment scale in different seasons and <u>show that antecedent storage in the catchment is key to preventing a hydrological drought from developing</u> (van Loon and van Lanen, 2012). These typologies are discussed in Appendix III.3.
- **<u>Typology of most severe drought events.</u>** Van Loon and van Lanen (2012) studied about 125 groundwater droughts and 210 river droughts in five contrasting headwater catchments in Europe. Although their findings showed that the most common drought type in all catchments was the classical rainfall deficit drought (almost 50 % of all events), the five most severe drought events of each catchment in terms of duration shifted towards rain-to-snow-season droughts, warm snow season droughts, and composite droughts. The occurrence of these types was found to be determined by climate and catchment characteristics (Table 2).

Figure 1. Hydrological drought event characteristics and key features of drought propagation.
Source: Van Loon and van Lanen, 2012; Van Loon and Laaha, 2014; van Lanen et al., 2013; van Loon, 2015).

Table 2. Drought propagation processes per hydrological drought type and severity of occurrence in terms of duration in Koppen-Geiger major climate types. ***A: Tropical. B: Dry. C: Temperate. D: Continental. E: Polar. P: Precipitation deficit. T: Temperature anomaly. Modified from: van Loon and van Lanen, 2012. See also Appendix III.3.***

Hydrological drought type	Governing process(es)	P-/T-control	Climate type	Type of catchment where drought gets more severe
Classical rainfall deficit drought	Rainfall deficit (in any season)	P -control	A, B, C, D, E	Quickly responding
Rain-to-snow-season drought	Rainfall deficit in rain season, drought continues into snow season	P and T -control	C, D, E	Snow-influenced
Wet-to-dry-season drought	Rainfall deficit in wet season, drought continues into dry season	P and T -control	A, B, C	Semi-arid
Cold snow season drought	Low temperature in snow season, leading to:			
Subtype A	Early beginning of snow season	T -control	D, E	
Subtype B	Delayed snow melt	T -control	D, E	
Subtype C	No recharge	T -control	C, D	
Warm snow season drought	High temperature in snow season, leading to:			Snow-influenced
Subtype A	Early snow melt	T -control	D, E	
Subtype B	In combination with rainfall deficit, no recharge	P and T -control	C, D	
Composite drought	Combination of a number of drought events over various seasons	P and/or T -	A, B, C, D, E	Slowly responding

- **Historical droughts in Scotland.** Studying historic droughts is key to informing water management practices and improving efficiencies towards water sustainability. Anecdotal and research evidence shows that severe multi-season droughts are a recurrent feature of the UK hydroclimate including in parts of Scotland (see Appendix IV.1 for anecdotal timeline of meteorological and hydrological droughts in Scotland). Reconstructing historical droughts for Scotland and the UK showed that:
    - o The longest observed run of below average rainfall (meteorological drought) since the 1870s persisted for four years (1892–1896) in northern England and parts of Scotland and that the catchments Nith, Dee, Findhorn, Ewe and Cree were found to show 100-year return period of low flows spells lasting six to eight seasons (Wilby *et al.*, 2015).[9]
    - o Scotland is "normally" (i.e. regardless of anthropogenic influences on the water cycle) subject to frequent moderate hydrological droughts but to a lower incidence of major droughts than England and Wales (Rudd *et al.*, 2017)[10].
    - o Simulated results showing a high drought severity in north-west Scotland in the absence of severe droughts elsewhere in the UK (e.g. 1916, 1920, 1936, 1940, 1969, 1977 and 2002) could be due to (i) poor quality of rainfall observations; (ii) limited knowledge of historic Scottish droughts; and (iii) need to apply an improved snow module for simulations in high altitude Scottish catchments (Rudd *et al.*, 2017; Smith *et al.*, 2019).
    - o Drought characteristics are spatially and temporally variable, but no trends can be discerned (Hannaford, 2015; Rudd *et al.*, 2017).
    - o Ranking of reconstructed historical droughts according to duration, deficit and maximum intensity showed that events of flow deficit from January to December in the early to the mid-1970s were the longest in Scotland in the period 1891-2015 (Barker *et al.* 2019)[11].
    - o Extreme and severe flow deficits did not occur simultaneously across all UK regions, e.g. 1895 saw extreme flow deficits across Scotland and Northern Ireland, mild drought in northern England, and higher-than-average flows in the rest of England (Barker *et al.*, 2019); see also Phase 2: Section 3.5.

Catchments with historical droughts and current water quantity issues in Scotland. According to the observations presented in SEPA's scarcity reports (SEPA, 2018)[12]., by August 2018 river beds in Aberdeenshire had become extensively exposed and where there was water it was very shallow and slow flowing. Very low levels of storage were recorded in the north east compared to the long-term record. In addition, groundwater levels were the lowest on record in the east. Further, loch levels were low in the west. To gain an understanding of how historical droughts and current pressures and PWS water shortages may relate, we mapped: (i) surface waterbody catchments where historical river droughts with a 100-year return period of low flows lasting up to six to eight seasons had been evidenced (Wilby *et al.*, 2015); (ii) anthropogenic pressures on groundwater water bodies at below-good state under the Water Framework Directive - WFD (2000/60/EC); and (iii) the location of PWS that required assistance during Summer 2018. The map is shown in Figure IV.2.1 (Appendix IV.2). The reason for mapping areas vulnerable to natural river droughts and groundwater waterbodies with low levels together is because we need to understand the role of human influences on drought occurrence. Groundwater contribution to river flow (i.e. baseflow), when sufficient, is key to buffering precipitation deficits and low river flows (Appendix III.2).

The map in Figure IV.2.1 suggests:

(i) A predominance of PWS served by springs or wells amongst the PWS requiring assistance in 2018 in Aberdeenshire[13]. Of the total 162 cases reported serving 325 properties, 33 were for springs, 92 were wells [of unknown depth] whilst only 4 were for boreholes, and 33 were of unknown PWS source type. This is an indirect indication that the problem of water shortages in Aberdeenshire in Summer 2018 was directly related to a precipitation deficit, to which spring sources are most vulnerable (see Section 2.5). However, it is also useful to note that wells and PWS

9 The researchers used monthly rainfall and discharge from 1961–1990 as the reference period and performing Markov model simulations to generate multiple realisations of 100-year sequences of each rainfall and river flow station.

10 The researchers used a national-scale gridded model to characterise drought across Great Britain over the last century, first fitting the model at low flows and then applying the threshold level method to time series of monthly mean river and soil moisture to identify historic droughts (1891-2015).

11 The researchers used the Standardised Streamflow Index (SSI) to reconstruct a flow series for 1891-2015 according to severity reviewed in the context of the past 50 years.

12 see footnote 15 in this report for PWS support requested per type.

13 This should not be confused with the PWS locations in Appendix IV.3.

served by river intakes located in the Dee catchment also required assistance, in line with SEPA's Scarcity report on low river levels in the wider region (SEPA 2018).

(ii) Occurrences of historical river droughts in both the east and the west but a predominance of anthropogenic pressures on groundwater waterbodies in the east. This is an important finding in the context of the distribution of PWS (see map of PWS locations by source type in Appendix IV.3), i.e. a slight predominance of surface water (river) PWS in the northwest over the east and south and a clear predominance of springs and boreholes in the east over the west. This points to different technological challenges for each PWS source type specific to each geographic region of Scotland. Therefore, it highlights the need for fit-for-purpose approaches to management and control of drought propagation in the interests of PWS users (see Section 2.7).

(iii) A small overlap between areas where historical river droughts have occurred with a 100-year return period for low spells lasting six to eight seasons and areas where groundwater levels are low due to anthropogenic pressures. It remains to be explored whether and how a precipitation deficit will affect both areas and what management measures can prevent the propagation of a precipitation deficit into a river or groundwater drought.

Future risk of hydrological drought in Scotland. Gosling *et al.* (2014) demonstrated a method of combining indices of drought (see Section 2.4) with projections of future climate and hydrology to produce an indication of the potential change in drought vulnerability in Scotland. Combining indices of hydrological drought (i.e. Standardised Streamflow Index) with projections of future climate (UKCP09), showed: (i) more frequent hydrological droughts in the summer; and (ii) more frequent summer hydrological droughts lasting 1-month and 3-months in areas where the current 1 in 40-year drought event translates to approximately a 1 in 20-year event by the 2050s. This evidence suggests that those PWS served by river intakes located within the high risk areas according to the Meteorological Drought Risk Indicator developed in Phase 2 (Section 3.5) may be vulnerable to water shortages in the future.

2.4 Hydrological drought monitoring indices and early warning systems

Understanding the hydrological drought generation and the drought propagation cascade, i.e. how a precipitation deficit is transformed into soil moisture drought and hydrological drought and how human activities are affecting this transformation positively and negatively, is key to drought management through drought monitoring and attribution. Monitoring data will enable modelling and assessments of past and future groundwater levels or river discharge in the context of natural and human influences to inform management (Tidjeman *et al.*, 2018; Visser-Quinn *et al.*, 2019). Attribution of the causes of a hydrological drought in an area will inform whether drought management should focus on adaptation to climate-induced drought or to mitigating the actions that lead to human-induced drought (van Loon *et al.* 2016b).

A wide range of indicators and indices exist to define a drought and to support early warning systems (see Appendix V.1 for hydrological drought indices). The definition of these terms has been reviewed by the World Meteorological Organisation (WMO) and Global Water Partnership (GWP) (Svoboda and Fuchs 2016). The term drought indicator refers to variables or parameters used to describe drought conditions, e.g. precipitation, temperature, river discharge, groundwater and reservoir levels, soil moisture and snowpack. Indices[14] are typically computed numerical representations of drought severity, assessed using climatic or hydro-meteorological inputs aiming to measure the qualitative state of droughts on the landscape for a given time period. Drought early warning systems (DEWS), on the other hand, typically aim to track, assess and deliver relevant information concerning climatic, hydrologic and water supply conditions and trends having (ideally) both a monitoring and a forecasting component. The objective of DEWS is to provide timely information in advance of, or during, the onset of drought to prompt action (via threshold triggers) within a drought risk management plan as a means of reducing potential impacts.

Broad types of drought indices include standardised indices and thresholds (Zargar *et al.*, 2011; Van Loon, 2015). These are outlined below.

14 Indices are technically indicators as well (Svoboda and Fuchs 2016).

1. Standardised meteorological and hydrological drought indices (Appendix V.1)

- Commonly used standardised meteorological drought indices are the Standardised Precipitation Index (SPI; Mckee *et al.,* 1993), the Standardised Precipitation and Evaporation Index (SPEI; Vicente-Serrano *et al.,* 2010) and the Standardised Palmer Drought Index (SPDI; Ma *et al.,* 2014).
- Examples of standardised hydrological indices are the:
  - Standardized Streamflow Index (SSI: Vicente-Serrano *et al.,* 2012), which uses streamflow data and is used and reported by SEPA as Normalised Flow Index (e.g. Gosling 2014; SEPA n.d.).
  - Standardized Water-Level Index (SWI: Bhuiyan, 2004), which uses data from wells to investigate the impact of drought on groundwater recharge.).
  - Baseflow index[15] (BFI), which can be a good proxy for the combination of a number of catchment characteristics indicative of catchment storage (Van Loon and Laaha 2014).

2. Thresholds. The threshold level method can be used to derive drought characteristics from time series of observed or simulated hydro-meteorological variables. A drought occurs when the variable of interest (i.e. precipitation, soil moisture, groundwater storage, or river discharge) is <u>below</u> a predefined threshold and continues until the threshold is exceeded again. Characteristics such as drought severity, intensity and duration can then be calculated (Hisdal *et al.,* 2004). Drought experts usually use a variable threshold (e.g. monthly, seasonal or daily) to explore rainfall and flow deficits in the high-flow season that can lead to a drought in the low-flow season (Hisdal and Tallaksen, 2000). The monthly flow threshold can be derived from the upper percentile of the monthly flow duration curves. The range of 70th–95th percentile is commonly used in drought studies in temperate climates (e.g. Hisdal *et al.,* 2004; Fleig *et al.,* 2006; Tallaksen *et al.,* 2009; Wong *et al.,* 2011). For example, choosing the 80%-ile implies that for each month a value of a precipitation, soil moisture, groundwater storage, or river discharge is chosen that is exceeded 80 % of the time in a specific month. The choice of a different percentile in the calculation of the threshold level does not affect drought generation typology but changes drought characteristics, e.g. there would be lower deficit volumes of fewer events with shorter duration with a 95%-ile than with a 70%-ile threshold.

15 A measure of the ratio of long-term baseflow to total stream flow and it represents the slow continuous contribution of groundwater to river flow.

<u>**Evaluation of the role of standardised indices.**</u> An advantage of standardised indices is that regional comparisons can be made because they represent anomalies from a normal situation in a standard way (Rudd *et al.,* 2017). A disadvantage is that they generally require an appropriate statistical distribution to be identified (unless no extrapolation is required, Vidal *et al.* 2010). In addition, hydrological droughts have very different causes that cannot be captured by a single index (Wanders *et al.,* 2010). There are similar indices based on spatially continuous remotely sensed data, but these are used for identifying stress related to droughts affecting agriculture or droughts with multiple impacts on the landscape, e.g. vegetation indices (see review by Svoboda and Fuchs 2016).

<u>**Evaluation of the threshold method.**</u> Advantages of the threshold level method are that there is no need to fit a distribution to the data and that it is easy to calculate the drought characteristics (Rudd *et al.,* 2017). A disadvantage is that there is no standard definition for the threshold level(s) (van Loon and van Lanen 2012). As suggested by Svoboda and Fuchs (2016), the preferred approach is to use different thresholds with different combinations of inputs to select thresholds best suited to the timing, area and type of climate and drought.

<u>**Applications of drought indices.**</u> The main applications of drought indices are (Rudd *et al.* 2017; Svoboda and Fuchs 2016):

(i) Drought monitoring and early warning. Drought indices – in combination with additional information on exposed assets and their vulnerability characteristics – are essential for tracking and anticipating drought-related impacts and outcomes.

(ii) Analysis of past, historical droughts. Indices may also play another critical role, depending on the index, in that they can provide a historical reference for planners or decision-makers. This provides users with a probability of occurrence, or recurrence, of droughts of varying severities.

(ii) Understand the likely impacts of climate change. Climate change will begin to alter historical patterns. Information derived from indicators and indices is useful in planning and designing applications (such as risk assessment, DEWSs and decision-support tools for managing risks in drought-affected sectors), provided that the climate regime and drought climatology is known for the location. In addition, various indictors and indices can be used to validate modelled, assimilated or remotely sensed indicators of drought.

Box 3. Key technical terms used in relation to the management and governance of small rural water supplies.

Key technical distinctions, which are used when assessing the vulnerability of small supplies, refer to centralised versus decentralised small supplies; and improved versus unimproved small supplies, as follows:

- Centralised water supply systems (i.e. on the mains) usually refer to large scale supplies owned and controlled by the public sector or private companies under a top-down governance system and where water is transported to households from distant sources and is of high quality. In some EU countries small supplies serving less than 5000 people may be under public ownership and therefore under centralised operational management (Domenech 2011; Hendry and Akoumianaki 2016).
- Decentralised water supply systems usually refer to small-scale systems owned and controlled by private individuals under multilevel local governance (e.g. including local authorities, local communities, citizens, and farmers and other local stakeholders) and where water is sourced from local, short-distance sources and water quality varies with land use and weather (Domènech 2011). In this context, PWS in Scotland are decentralised systems.
- Improved sources include sources that, by nature of their construction technology or through active intervention, are protected from outside contamination, particularly faecal matter including piped water in a dwelling, plot or yard, and other improved sources such as public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs and rainwater collection (World Health Organisation -WHO n.d.). In Scotland, boreholes, and protected springs and wells serving PWS are improved drinking water sources.
- Unimproved drinking water sources are unprotected from outside contamination and include dug well, unprotected spring, cart with small tank/drum, tanker truck, and surface water (river, dam, lake, pond, stream, canal, irrigation channels), bottled water (WHO n.d.). In Scotland, lochs, rivers, and unprotected springs and wells serving PWS are unimproved drinking water sources.

2.5 Climate change and small rural water supplies

Here, we use the term small supply because we found limited evidence on PWS in Scotland. PWS are small, rural, decentralised (not on the mains) supplies (Hendry and Akoumianaki 2016). In the European Union, small supplies are defined as supplies serving less than 5000 people and very small supplies refer to supplies serving less than 50 people (European Commission 2015). The term small may be relevant to (see technical terms in Box 3): (i) reliance on decentralised, small-scale systems for treatment/purification and water distribution; (ii) limited capacity for protection or pollution control from source to tap; (iii) low availability of resources required to address operational cost, maintenance, treatment, source protection, risk assessment and monitoring; and (iv) less stringent regulations than those applied for public water supplies (Hendry and Akoumianaki, 2016). For example, the European DWD requires a less frequent monitoring in small supplies and places no obligation for the monitoring of very small supplies. This is also reflected in the PWS Regulations (See Section 1.1).

There is a growing evidence-base for water quality issues regarding small supplies. Small water supply systems are often associated with non-compliances with microbiological and chemical quality standards; and unclear legal responsibilities for both operators and regulators in the case of a disease outbreak or non-compliances (Sinisi and Aertgeerts 2011; Rickert and Schmoll 2011; WHO 2012; Hendry and Akoumianaki 2016; McFarlane and Harris 2018). This shows that water supplies are faced with operational as well as with a wider set of institutional, financial, and environmental issues (McConville and Mihelcic 2007). Climate change can add extra stress on small supplies (Charles *et al.*, 2010; Howard *et al.*, 2010; Howard *et al.* 2016).

Challenges facing small water supplies. In the context of operational functionality of water supplies, the cause of the problem can often be unclear. For example, for rural groundwater supplies served by boreholes, wells or springs there are a number of reasons for operational failures related to both water shortages and water quality (Bonsor *et al.*, 2015; Charles *et al.*, 2010; Clapham 2010) [16]:

16 Examples emphasise challenges related to drought. Challenges related to flooding are outwith the scope of this report.

- Primary causes:
  - Resource depletion due to meteorological or hydrological drought, particularly for systems relying on surface water and springs.
  - Water quality issues, which may be exacerbated by low water table levels e.g. from resuspension of sediments with falling water levels [17], and decreased dilution of sewage discharged to rivers.
  - Mechanical failures, e.g. mechanical failure of the pipework and the pumping system by corrosion and when supply becomes intermittent, and leaking water storage tank.
- Secondary causes:
  - Poor siting, e.g. springs located in areas vulnerable to both contamination and summer meteorological drought.
  - Poor management, e.g. lack of storage tank maintenance.
  - Lack of governance, e.g. inadequate measures for preventing or responding to events such as supply contamination and water shortages.

- Underlying conditions: Institutional, financial, and social factors moderated by cultural norms shaping environments when failure is more likely.
- Long-term trends: Climate change, changes in water demand, evolution of governance, reduction in resource availability, and changes in water quality.

Small supply construction technology and resilience. Despite the role of resource depletion and climate change play in the operational functionality of rural supplies, very few studies deal with the specific climate change impacts on them in the developed world. Only one study was found to deal with climate change and PWS in Scotland (Holdsworth 2019); however, that study focused on the impacts of the drought event in Summer 2018 and not on the threat and impacts of hydrological drought on PWS. Howard *et al.* (2010) and Howard and Bartram (2009) provided a global assessment of the resilience of small water supply technologies (e.g. construction for source protection in improved supplies) and management systems. They provided assessments of the robustness of technologies including those for construction and treatment under dry conditions (Figure 2).

17 There is evidence that warming increases the risk of cyanobacteria blooms. For example, intense summer storms or resuspension of river or lake sediments during periods of droughts may fuel receiving waters with a pulse of nutrients during the growing season leading to cyanobacteria growth (Elliott, 2012a,b).

Highly resilient technologies are expected to function during a drought event. Low resilient technologies are expected to have limited functionality.

Household-level rainwater harvesting and protected shallow springs. These are the sources least resilient to drought (Howard *et al.,* 2010); see also Figure 2. Both are inflexible as their location is determined by the roof catchment or the outlet of spring. Both have limited adaptability in design and are rapidly susceptible to rainfall changes, although the less commonly found artesian springs are less vulnerable. Household rainwater harvesting rarely delivers a year-round supply and the yield of many springs declines during dry periods, particularly where the springs emerge from shallow renewable groundwater resources. Without good operational management, both these sources of water are vulnerable to microbial contamination, especially during periods of low water supply. Adaptations exist to improve the performance of both these technologies, for instance through improving treatment (e.g. changes in filtration media) for protected springs or increased size of storage tanks. However, improvements are generally limited.

Protected wells (boreholes). These were found to be relatively more resilient to most impacts of reduced precipitation but were less resilient to issues of saline intrusion resulting from sea-level rise in areas with areas with low groundwater levels (Howard *et al.,* 2010); see also Figure 2. A detailed account of the influence of geology on the groundwater source of boreholes is given in Section 2.5: **Groundwater as an improved and climate-resilient source for small supplies.**

Piped (public or community supplies) water supplies (regardless of type of source). As a technology, these supplies were found to be inherently highly vulnerable because of their size and complexity (Howard *et al.,* 2010); see also Figure 2. They were found vulnerable to multiple threats from the source, through treatment systems (if deployed) and subsequent distribution. The quality and protection of water sources and available treatment processes exert a significant influence on vulnerability.

Planning to improve small supply resilience to water shortages. On a global level, the threats to small supplies from drought relate to changes in temperature, precipitation and water demand, leading to changes in hydrology (Howard and Bartram 2009; Howard *et al.,* 2010; Charles *et al.,* 2010); see also Appendix III. The nature of the threats relates to increasing unpredictability in surface water and spring flows and a change in groundwater availability. However, whereas threats related to floods and storm surges may be experienced as short-term and unpredictable events with very limited

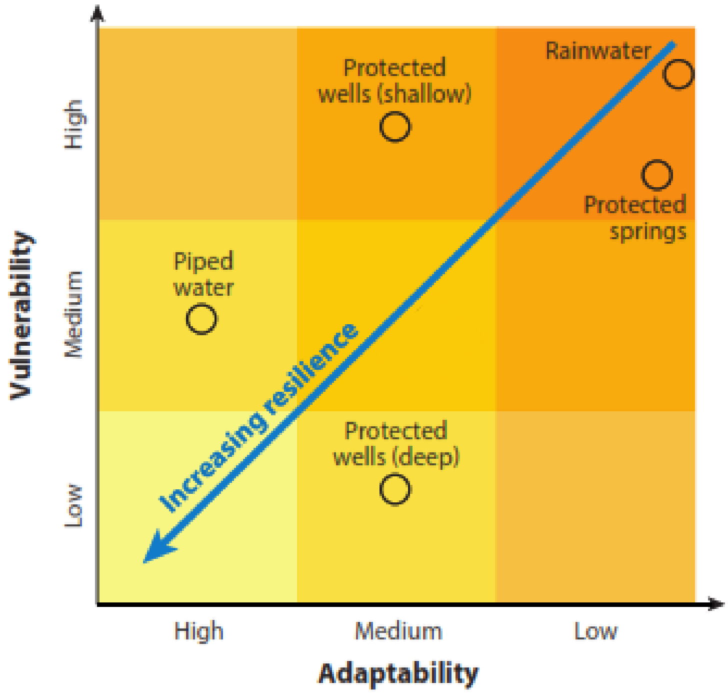


Figure 2. Water supply resilience in terms of technology of collection and distribution of water under reduced rainfall. Source: Charles *et al.*, 2010; Howard *et al.*, 2016.

time for action to be taken thus requiring prior planning and investment, **threats related to water shortages and drought are slow-onset threats** (Howard *et al.*, 2016). Although the impact on water services of these events can be similar to those of short-term events, planning responses may be different and operate over different timescales. Preventive action should be possible, and for individual drought events there may be time to tailor responses to the specific nature of the event. Droughts may lead to loss of sources for small supplies served by springs and river intakes and the need for support; this is discussed in relation to the drought of 2018 in Scotland (Phase 2 Section 3.1 A). Groundwater sources, although more resilient to drought, may also require more rigorous treatment as drought can increase concentrations of chemicals and pathogens, with contamination occurring because water treatment systems or source protection measures fail, e.g. due to reduced dilution of contaminants (Charles *et al.*, 2010; Howard *et al.*, 2016).

Drought and public supplies in Scotland. Where climate change results in declining water availability, utilities serving populations with water piped into homes from reservoirs may find securing sufficient water challenging. Localised and short-term dry periods have put stress on public water supplies in the recent past as seen in the mid-1970s, 1984, 2003 and 2008 (SEPA n.d.). In addition:

- In 2010, when Dumfries and Galloway experienced some of the most prolonged periods of no or low rainfall, starting in May, Scottish Water considered its first Scottish Drought Order [18] in five years (BBC 2010).
- In Summer 2018, Scottish Water issued advice to customers to use water wisely in two localised areas, parts of Moray and the Stornoway area of Lewis in summer 2018 (BBC 2018a). 'The advice was issued because of prolonged dry weather in these areas, despite some recent rainfall, and (in the case of Moray) increased demand. When Stornoway reached its 22nd consecutive day of a long dry spell, Scottish Water advised people to reduce water usage' (BBC 2018a). Most of Scotland is being supplied by upland reservoirs, which experience normal water levels. Moray, however, is served by the River Spey, which in Summer 2018 had the lowest river levels since 1954 (BBC 2018b). Further, when levels in two reservoirs serving Fife, i.e. Glendevon and Glenfarg located in Perth and Kinross, dropped below normal levels, Scottish Water used water from the River Earn to top up supplies and asked customers to be water-wise (BBC 2018c).
- In 2019, Scottish Water was reported as asking parts of the Western Isles and Argyll customers served by the Tolsta Water Treatment Works (WTW) in north Lewis and by the Tarbert WTW in Argyll to make conservation efforts by taking shorter showers and only washing car windscreens and lights instead of the whole vehicle (Herald Scotland 2019).

Drought and PWS in Scotland. Appendix IV.3 shows PWS distribution by type of source. The drought event of summer 2018 (Section 1 and Phase 2) suggested that the sources and simple technologies used for PWS are more vulnerable than the complex Scottish Water systems used to deliver higher levels of service. An article on the BBC reported on the problem faced by PWS served by springs and wells in upland areas Aberdeenshire (BBC 2018b); see also Section 1 and Phase 2: Section 3.1 for a summary on the events of summer 2018 in relation to PWS.

Groundwater and small supplies in Scotland. In Scotland, groundwater is estimated to sustain more than a third of the annual flow in all river bodies, even in small upland streams, rising to over 60 per cent in some rivers in drier eastern Scotland (Gustard *et al.*, 1987 cited in O'Dochartaigh *et al.*, 2015).

18 Water orders may be made by Scottish Water where needed to protect public water supplies when "it believes that there is (a) a serious deficiency of water supplies in an area, or (b) a threat of a serious deficiency of water supplies in an area (The Water Resources (Scotland) Act 2013). A Water Shortage Order may permit Scottish Water to carry out various actions such as to gain access to land to abstract from an alternative source or to impose water saving measures on organisations or individuals if deemed necessary, including the imposition of hosepipe bans.

A dataset [19] describing the potential of bedrock aquifers across Scotland to sustain various levels of borehole water supply [20], and the dominant groundwater flow type in each aquifer was published under license by BGS on 1st April 2020 (BGS, 2020). Five aquifer productivity classes were identified: very high, high, moderate, low and very low, and three groundwater flow categories (i.e. significant intergranular flow; mixed fracture/intergranular flow; and fracture flow) (Appendix III.2. Groundwater in Scotland). However, the complexity and heterogeneity of geological formations in Scotland means that the dataset can only be used as a guide (BGS, 2020). It has also been estimated that in 2005 there were in excess of 4000 boreholes across Scotland used for public and private supply, industry and agriculture, and many more (>20 000) small springs and wells used for private water supply (MacDonald *et al.,* 2005). As of 2018, there were 17,891 PWS served by springs, wells and boreholes [21] (based on data provided to us by DWQR). These numbers show that groundwater storage is key to the resilience of both groundwater and surface water PWS in Scotland.

Groundwater as an improved and climate-resilient source for small supplies. Groundwater storage is key in increasing the resilience of small water supplies to climate change. This is the case not only for small supplies served by boreholes, springs and wells but also for supplies served by lochs and river intakes. For example, during a meteorological drought the main contribution to discharge is via baseflow. For groundwater sources, it can generally be expected that (Kundzewicz and Doell, 2009; Jalota *et al.,* 2018: Chapter 4.2.3;) (see also Appendix III):

- The groundwater source will be more sensitive to climate if its quantity depends on seasonal recharge, as in shallow wells in unconfined aquifers (i.e. where water seeps from the ground surface directly above the aquifer).
- Shallow unconfined aquifers and shallow groundwater systems such as unconsolidated sediment or fractured bedrock aquifers are more responsive to smaller-scale climate variability than confined aquifers, therefore groundwater sources (e.g. springs and shallow wells) from these aquifers would be vulnerable to a precipitation deficit.
- Unconfined aquifers are likely to face substantial problems due to the indirect effects of increased abstraction by humans to meet future water demand under a changing climate.
- Confined aquifers with upper impermeable layers where recharge only occurs from precipitation where the water-bearing formations outcrop at land surface (e.g. springs) are vulnerable to precipitation variability and deficit.
- Deeper aquifers display a slow response to large-scale climate change and not to short-term climate variability, therefore boreholes in these areas will be relatively resilient to summer drought events.
- An aquifer receiving recharge from extensive catchment areas is insensitive to short-term climatic variability, therefore in these cases groundwater sources (e.g. wells, boreholes and river intakes) are more resilient to a precipitation deficit.
- Coastal aquifers are vulnerable to rising sea levels due to climate change and salt-water intrusion.

Key Findings from Section 3.5

- Few studies refer to vulnerability of small supplies by source type and technology to drought.
    - o Household rainwater harvesting and protected springs are highly vulnerable to drought and precipitation variability.
    - o Boreholes from unconfined and relatively shallow aquifers are sensitive to precipitation variability unless in cases where an aquifer receives recharge from an extensive catchment area. In this context, boreholes are comparatively more resilient to drought and precipitation variability than other types. However, .
- Of all the type of small supplies, springs and shallow wells appear to be most vulnerable to a precipitation deficit due to their immediate reliance on recharge from rainwater.
- It is difficult to draw conclusions on PWS vulnerability to drought in Scotland based on international evidence on small rural supplies, incidents of PWS running dry and public supply (Scottish Water) sources needing topping up from alternative sources. Private and public supplies in Scotland are different in terms of technology, planning and siting of sources. These differences are potentially more important in determining vulnerability to drought than precipitation, temperature and catchment-based factors.

19 The dataset is designed to be used at a scale of 1:100,000, and not to assess aquifer conditions at a single point. However, it may have several uses in policy analysis and development, such as: prioritising aquifer and site investigations; informing planning decisions; and improving awareness of groundwater in general.

20 Note: Anecdotal evidence from Aberdeenshire Council indicates that supply users who have invested in sinking boreholes to improve their supply often cannot find a good enough water source, either due to high mineral content or just a lack of water.

21 Of the 21,980 PWS reported in 2018 (DWQR 2019), we found that there were: 1401 PWS served by wells (194 Regulated and 1,207 unregulated); 14, 905 PWS served by springs (976 Regulated and 13,929 Unregulated); and 1,585 PWS served by boreholes (319 Regulated and 1,266 Unregulated).

2.6 Knowledge gaps

Compared to other natural or anthropogenic disasters, knowledge of processes leading to hydrological drought still has large gaps (Mishra and Singh, 2011). Human activities influence these processes and therefore modify the propagation of drought and can even be the cause of drought in the absence of natural drivers of drought. Van Loon *et al.* (2016) analysing the reasons for failing to prevent the propagation of hydrological drought suggested that it stems from a failure to address the multi-directional relationship between climatic and human drivers.

Drought research is gradually shifting away from taking only a meteorological perspective into taking a hydrological perspective on drought generation and propagation. A hydrological perspective on drought research addresses a range of processes that are the result of (van Loon *et al.* 2016a; b):

- Low inputs to the hydrological system (e.g. lack of rain, low snow cover, and low irrigation sewage return flows).
- High outputs (e.g. evapotranspiration and abstractions for human water use).
- Limited storage in soil, groundwater, lakes, or reservoirs.

For characterization of this complete multi-directional system, unfortunately, our understanding and observation of drought processes have important gaps and the modelling and prediction tools at our disposal are therefore inadequate. Major knowledge gaps are related to research questions on the following issues:

- Drivers of drought, e.g. what is the most common and most severe type of hydrological drought -river or groundwater drought- in each region of Scotland?
- Human influences on the prevention, exacerbation or management of hydrological drought, e.g. how does catchment management of drought enhance or alleviate river or groundwater drought severity?
- Collecting data on the impacts of hydrological drought, e.g. how could drought impacts on small supplies be monitored and quantified?
- Modelling drought propagation, severity and recovery, e.g. are there "tipping points" in rural water use (i.e. a threshold that, when exceeded, can lead to large changes in the state of rural water supply) in relation to the build-up of large numbers of boreholes, abstraction for irrigation etc.?
- Raising awareness about hydrological drought, e.g. what is the best approach to raising awareness about drought risk among PWS users?
- Identifying "normal" in a constantly changing world, e.g. if rural communities adapt to a higher frequency of droughts (e.g. through water conservation attitudes) would that lead to less impact of drought in the future?

Appendix V.2 provides a list of research questions that emerged from the review of the literature in relation to the impact of drought on small rural water supplies.

2.7 Evidence-based practical implications

Here, we discuss the practical implications of the findings of the literature review to help policy makers develop a framework for action towards improving the resilience of PWS.

Include climate change consideration in water safety planning (aka risk assessment). Most of the guidance offered with regard to climate change and water services emphasises the need for a good understanding of the resources that supply water through monitoring of water quantity and pressures on flows and groundwater levels. Despite focusing on water quality issues, risk assessment as prescribed by the PWS Regulations and implemented in Scotland can provide the starting point for building a risk assessment procedure addressing climate change-related risks. To this end, collaboration between users, local authorities, DWQR and SEPA will be key to aligning management of PWS sources and information (e.g. early warning). That said, the World Health Organisation (WHO 2017) has already provided an extended conceptual flow of activities in water safety plan risk assessment including risk assessment of the frequency of climate hazards. Here, we provide an example illustrating how risk of drought can be factored into PWS risk assessments (Figure 3).

Improve evidence-base to fill knowledge gaps and enable adaptation to future challenges. Catchment storage (i.e. groundwater, wetlands, lakes, bogs, reservoirs) is key to buffering the effects of a prolonged precipitation deficit. Scotland's Bedrock Aquifer Productivity Map (BGS 2020) can provide useful guidance but little information is available on water storage in different geologies and catchments in Scotland. This lack of knowledge is a key barrier in understanding where and whether boreholes are the most sustainable approach to water provision through PWS (see Footnote 20). It is widely recognised that increased investment in water resources assessment and accounting, particularly for groundwater protection and artificial recharge, is an urgent priority on a global scale. Given the few studies on changes in water demand in view of climate change it is useful to recognise that decisions on the management of surface and groundwater

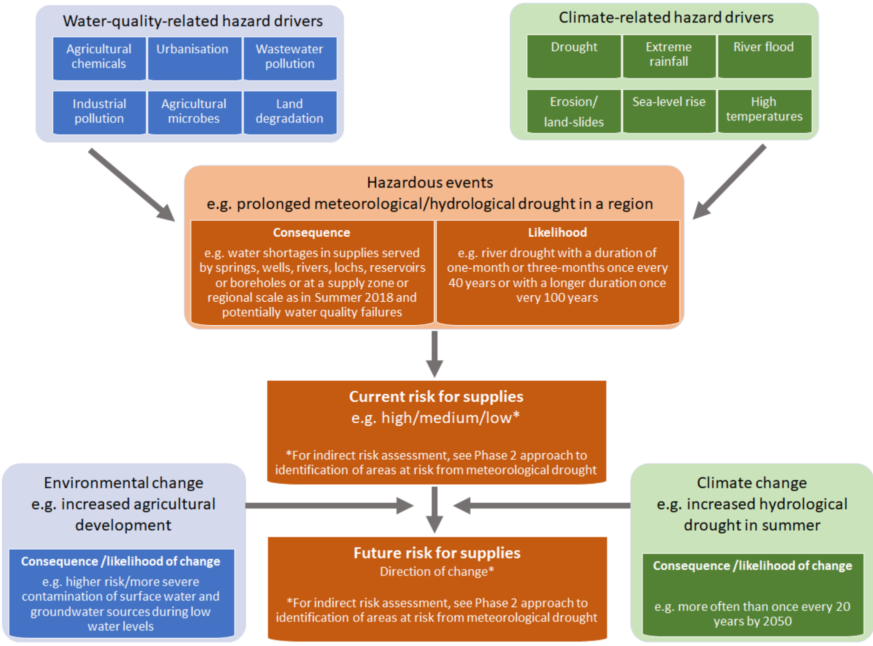


Figure 3. Conceptual flow of activities in water safety plan risk assessment, extended to consider changes in climate and environment. (Adapted from WHO 2017 to fit the context of this study using the evidence reviewed under Phase 1 and the results of Phase 2).

resources to ensure PWS resilience should take account of catchment-wide hydrological processes.

Identify acceptable technologies for water provision tailored to local conditions. In rural areas, where small supplies continue to be the norm or a necessity in the developed world, key policy decisions revolve around which technologies are acceptable and fit-for-purpose, i.e. technologies that are in line with the definitions of improved and climate-resilient supplies; see Section 2.5). Such decisions should be made on a case-by-case basis. Policy prescription on acceptable technologies is a feasible way to help build resilience (Howard *et al.* 2016). In order to apply a specified technology approach, the current and likely future trends in key climatic and other variables should be assessed to establish how the technology performs against current threats and what future threats may challenge the technology. The technology approach can be tied into other risk management approaches, such as the specified technologies approach to health-based targets described in the WHO's Guidelines for Drinking Water Quality (WHO 2017). This must be based on local conditions and trends rather than simply transferring practice from elsewhere. For example, if in a specific PWS served by a spring, a river-intake or a shallow well -all of which are vulnerable to meteorological and hydrological drought and also vulnerable to contamination – there are water quality issues, then the approach could be to advise for a change in source technology (.e.g. from spring to borehole – however, see Section 2.5: Groundwater as an improved and climate-resilient source for small supplies and Footnote 20.

This would address both occasional water shortages and water quality issues, as suggested by Howard *et al.* (2016).

Address governance and management issues. Small water supply governance approaches and in particular the level of decentralization of management will have an important impact on resilience (Hendry and Akoumianaki, 2016; Howard *et al.*, 2016). It is beyond the scope of this report to analyse how climate change risks are being addressed under different water supply management and governance approaches. However, it is useful to recognise that the available literature points to the benefits of more organized, centralised management in developing water supply resilience to climate change (see review by Howard *et al.*, 2016). This is because the technical, human, and financial resources are usually sufficient to permit the integration of climate issues within management plans and the expertise and ability to identify alternative sources to produce lower-risk source water services (Howard *et al.*, 2016; Charles *et al.*, 2010). However, it has also been suggested that centralised supplies have limited adaptation capacity compared to decentralised supplies (Domenech 2011). Decentralised supplies can adapt to different situations potentially being able to develop localised strategies for water collection, storage and distribution faster than centralised supplies. It is also expected that in rural areas the users of decentralised water supplies are more in contact with the means of water production, and therefore water conservation attitudes would become more entrenched in the everyday life of householders (Herman and Schmida, 1999; Domenech 2011). It remains to be explored whether this is the case among PWS users in Scotland (see also Section 2.6: Knowledge gaps).

3. Phase 2: Climate and climate change analysis and risk mapping

This chapter analyses changes between observed and future projection precipitation amount and its spatial and temporal distribution. To explore the future climate, we use the UKCP18 climate projections provide by the UK Met Office. These projections are compared to observed daily data (a gridded set produced through interpolation between met stations to produce a 5km grid, Perry *et al.* 2009). The aim of this chapter is to explore how distributions of rainfall? may change in the future and what consequences this may have on PWS vulnerability.

We initially assess the background weather that lead to the conditions experienced in 2018 when a large number of PWS experienced water shortages. This is to put future projected conditions into perspective. The key UKCP18 projections results are detailed to set the overall scene for possible future conditions. An explanation is provided as to the probabilistic climate projections used in this study. Results of analyses of future dry years and a bespoke Drought Risk Indicator are then presented. The aim of the Drought Risk Indicator is to help identify locations of high PWS density and high probability of experiencing dry years in the future.

3.1 How unusual was the weather in 2018?

Concern for the vulnerability of PWS in Scotland was prompted after 2018 saw a large number of requests for support, e.g. for Aberdeenshire on the 27th September (Figure 5)[22]. This raises the question as to how unusual 2018 was in respect of past levels of vulnerability and how this relates to probable future conditions. The summer of 2018 was the joint hottest on record[23] (together with 2006, 2003 and 1976). The next section considers how different the weather was from previous years (anomaly), and how that may have contributed to low water supplies in 2018.

The mean temperature for the winter and spring of 2018 were close to the 1981-2010 average however the summer was warmer (Figure 6). For precipitation, large parts of central and eastern Scotland were drier than average in the winter (up to c. 50% anomaly), with the west continuing to be drier in spring whilst the east was near normal or slightly wetter. In the summer much of east and north of Scotland was drier than the average. This indicates that there was a climatic contributor to the large number of requests for support for PWS. For north-east Scotland there were areas that were consistently drier than average.

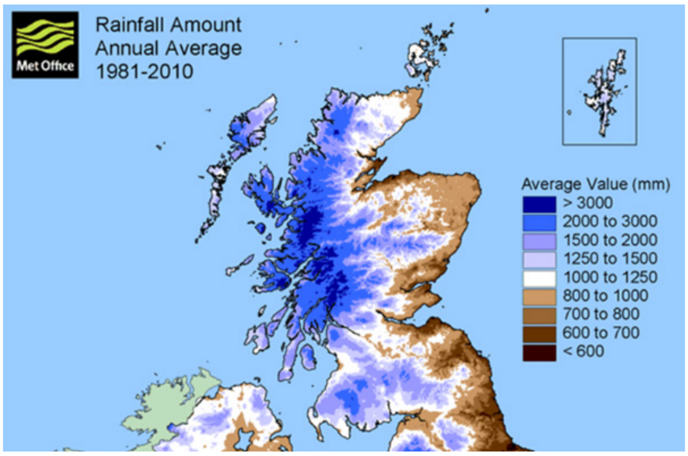


Figure 4. Rainfall amount annual average distribution in Scotland 1981-2010.

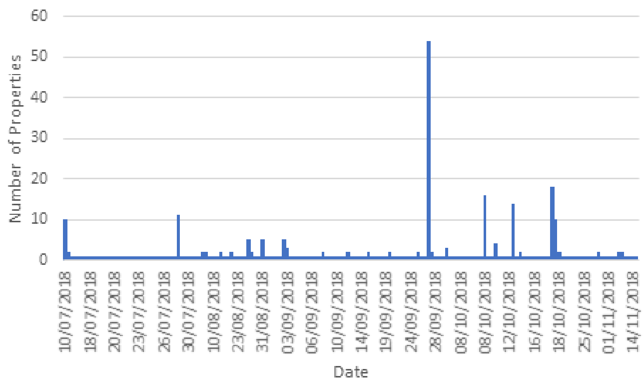


Figure 5. Aberdeenshire PWS requesting support in 2018 (source: Aberdeenshire Council)

22 Note: data on requests for PWS support in other locations in Scotland were not available for analysis in this study. Of the total 162 cases reported (serving 325 properties) 33 were for springs, 92 were wells whilst only 4 were for boreholes. 33 were for unknown PWS type.

23 See: https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2018/end-of-summer-stats and https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2018/summer-2018---met-office.pdf

The pattern is slightly different when considering individual months[3]. The winter was slightly cooler than average, but with regional variations in rainfall distribution: February was generally drier, but March had a distinct wetter east and drier west, reverting to near normal conditions for April. May to June was c. 1.5 to 2.5 °C warmer but August was the same as the average. Rainfall was lower in May across most of Scotland and drier in the east in June, with some drier areas in July and August.

Sunshine duration between May and July in many parts of Scotland was approximately 10-20 % above the 1981-2010 average (associated with higher temperatures), with areas of the north and north-east reaching c. 30% longer duration. Sunnier and warmer conditions imply a probability of higher rates of evapotranspiration (higher water loss of water through evaporation from soil surfaces and plants).

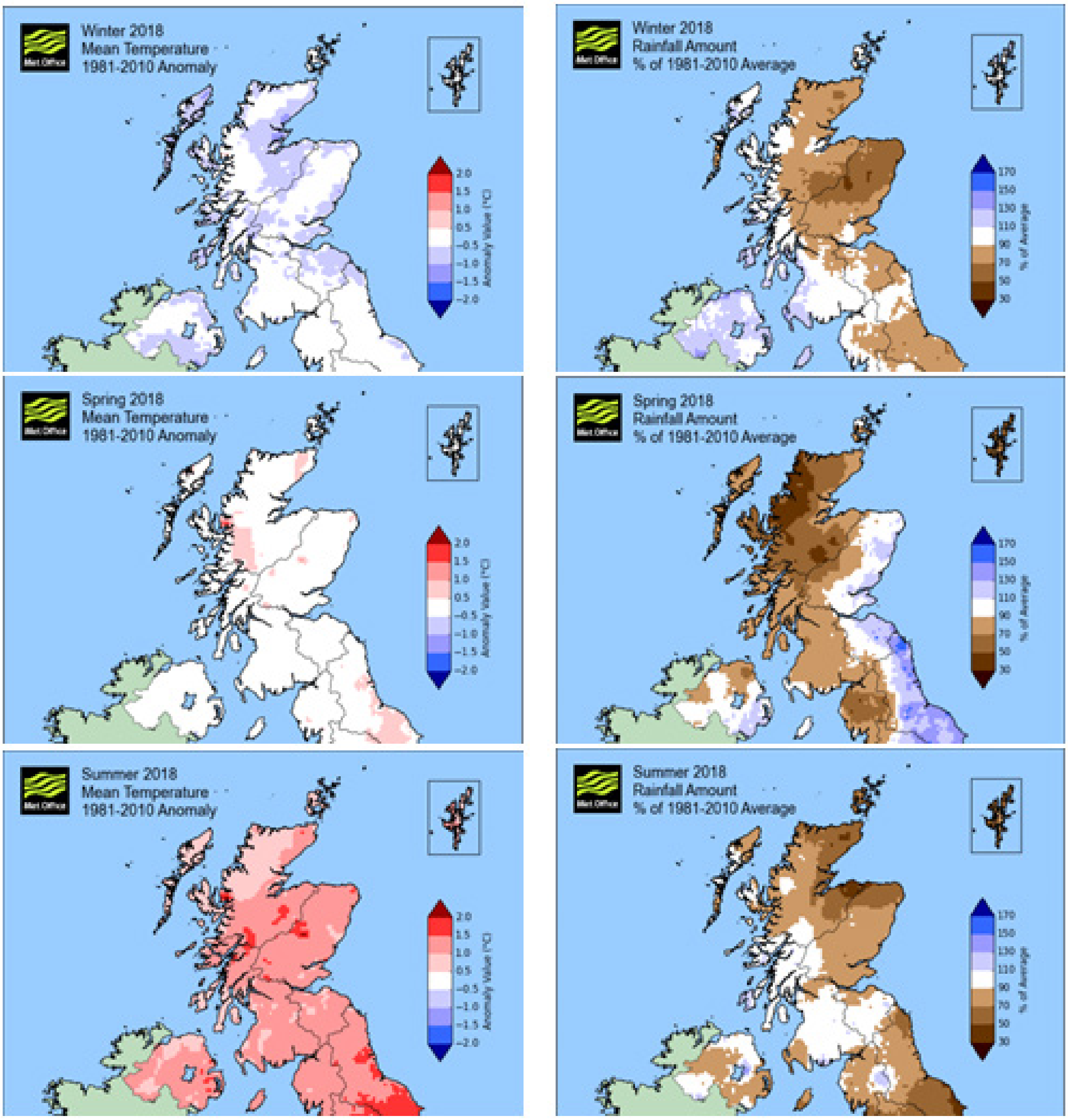


Figure 6. Mean temperature and rainfall anomaly maps for the winter, spring and summer of 2018 compared against the 1981-2010 average.

24 See Figures VI.1a-c in Appendix VI showing the mean temperature and % rainfall anomalies per month and season for January to September 2018

This part of the analysis indicates that for any individual PWS in 2018, the weather was not the only determining factor, and that other influencing factors also affected the amount of water available (as covered in section 2.3). Hence there is likely to be a combination of contributing weather factors, that lead to shortages in 2018. This implies that this drought has similarities to a composite drought (section 2.3 and Appendix III.3), which started in the cold period and ended in the warm period. The accumulative affect was a water shortage. Years such as 2018 are estimated to occur more frequently in the future (UKCP18 and Figure 9 and 10), with extreme heatwaves becoming more likely, with projections indicating that by 2100 every summer may be as warm as 2018 (Undorf *et al.* 2020).

3.2 Climate Projection Summary

The UKCP18 climate projections published key messages (UKMO 2019), as relevant to PWS and their resilience are:

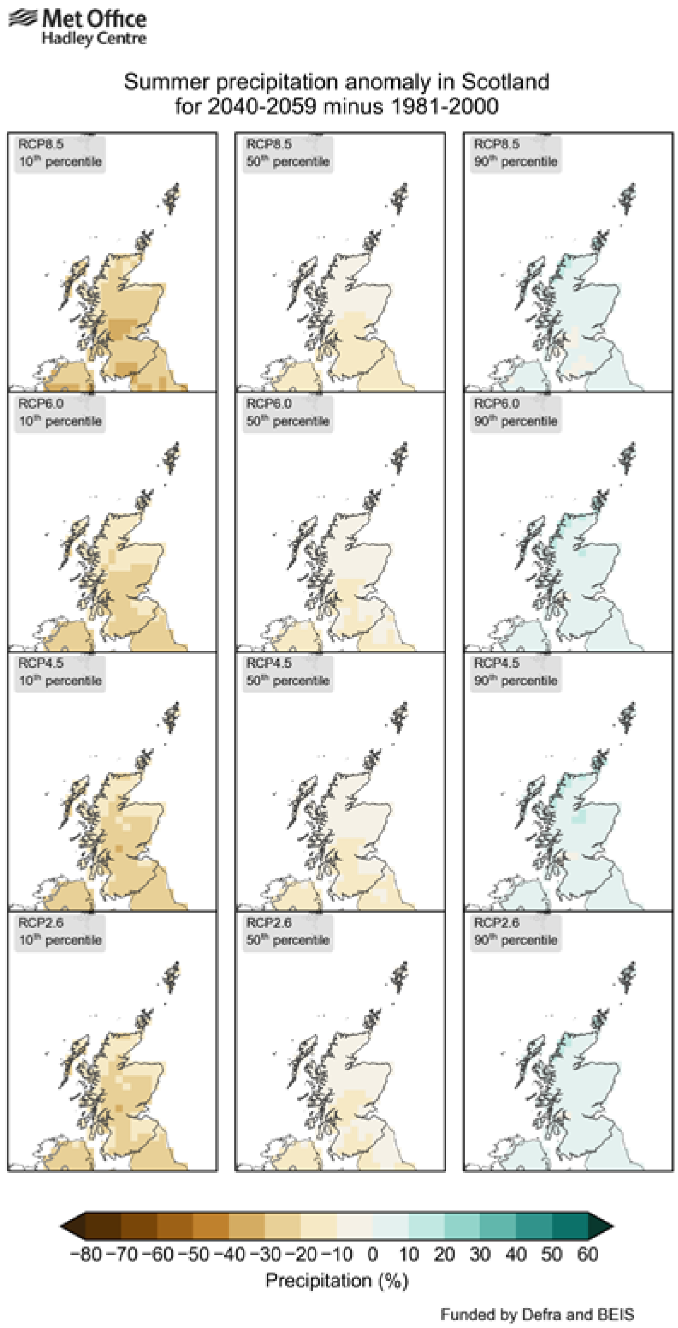
- Hot summers are expected to become more common. The summer of 2018 was the equal-warmest summer for the UK along with 2006, 2003 and 1976. Climate change has already increased the chance of seeing a summer as hot as 2018 to between 12-25%. With future warming, hot summers by mid-century could become even more common, near to 50%.
- The temperature of hot summer days, by the 2070s, show increases of 3.7 °C to 6.8 °C, under a high emissions scenario, along with an increase in the frequency of hot spells.
- UKCP18 Global (60km), Regional (12km) and Local (2.2km) scale climate model simulations all project a decrease in soil moisture during summers in the future, consistent with the reduction in summer rainfall. Locally this could lead to an exacerbation of the severity of hot spells, although large-scale warming and circulation changes are expected to be the primary driver of increases in the occurrence of hot spells.
- The probabilistic projections (see Section 3.4 below) provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of seasonal average precipitation changes between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to -47% to +2% in summer, and -1% to +35% in winter (where a negative change indicates less precipitation and a positive change indicates more precipitation).
- Overall increased drying trends in the future, but increased intensity of heavy summer rainfall events, indicating greater variability and increased frequency of extreme events.
- Change in the seasonality of extremes with an extension of the convective season from summer into autumn, with significant increases in heavy hourly rainfall intensity in the autumn.
- By the end of the 21st century, lying snow decreases by almost 100% over much of the UK, although smaller decreases are seen over mountainous regions in the north and west.

These projected changes will impact PWS by altering the amount, spatial distribution and timing of rainfall and increase surface water loss from evaporation. The estimated probability increases of years similar (or worse) to 2018 imply that PWS relying directly on precipitation and seasonal groundwater recharge, such as springs, shallow wells and river intakes may experience in the future a considerable increased risk of variable water availability.

3.3 Probabilistic Climate Projections

The UKCP18 projections are provided as probability distribution, aiming to represent a range of possibilities rather than a distinct prediction (see Figure 6). For the RCP8.5 emissions scenario used, the Regional Climate Model (HadRM3) was run 12 times under different initialisation value and parameter settings. For the RCP8.5 high emissions scenario, the estimated probabilistic temperature increase for the UK by 2070 ranges between 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter.

The UKCP18 uses probability projections rather than absolute predictions. Figure 7 illustrates the range of possible summer precipitation for three points on a probability distribution (see inset figure). These three points are the low levels of probability (10th percentile, blue part of the inset figure representing likelihood of precipitation lower than the observed period, and the 90th percentile, red, representing the likelihood of increased precipitation), and the mid-range (50th percentile, white part). The way to interpret this information is that the greater probability is the 50th percentile mid-range amount, whilst the other two are possible but less likely.



These Met Office maps are based on the original 12km resolution Regional Climate Model estimates. They represent a probability distribution:

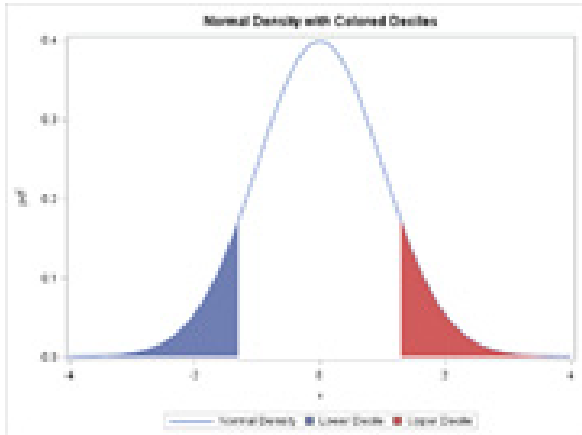


Figure 7. Scottish summer precipitation anomaly (%) for 2040-2059 minus 1981-2000 for RCP8.5, 6.0, 4.5 and 2.6 for the 10th, 50th and 90th percentiles (probability levels).

Here the 10th percentile (blue) and 90th percentile (red) represent the tails of the distribution and hence lower probability of occurring than the mid-range 50th percentile (white) area. This means that each condition shown in the maps are possible, but that the mid-range 50th percentile is the most likely.

The summer precipitation probabilistic projections for Scotland in the 2040-2059 period indicate that under the 50th percentile (mid-range) medium probability (compared to the 1981-2000 observations) that the southern half of the country will have 10-20% less rainfall under the high emissions scenario, but this reduces slightly under the lower emissions rates. The northern half may see a 10% reduction in precipitation. However, at the 10th percentile probability range, there is a risk of 30-40% decreases for central Scotland, with the rest having 20-30%. Conversely at the 90th percentile probability the whole of Scotland may see a slight increase (up to 10%) increase in precipitation. Overall, it is likely to see a reduction in summer rainfall.

Observed changes in precipitation: There has been an observed change in annual total rainfall spatial distribution and amount (Figure 8). The west has become wetter and the east drier. However, the total volume of precipitation water has increased (see Figure 17). However, this may not be a continuing trend, as the change in total may be attributable to increased winter rainfall (Watts *et al.* 2015). The projections indicating a probability of reduced precipitation.

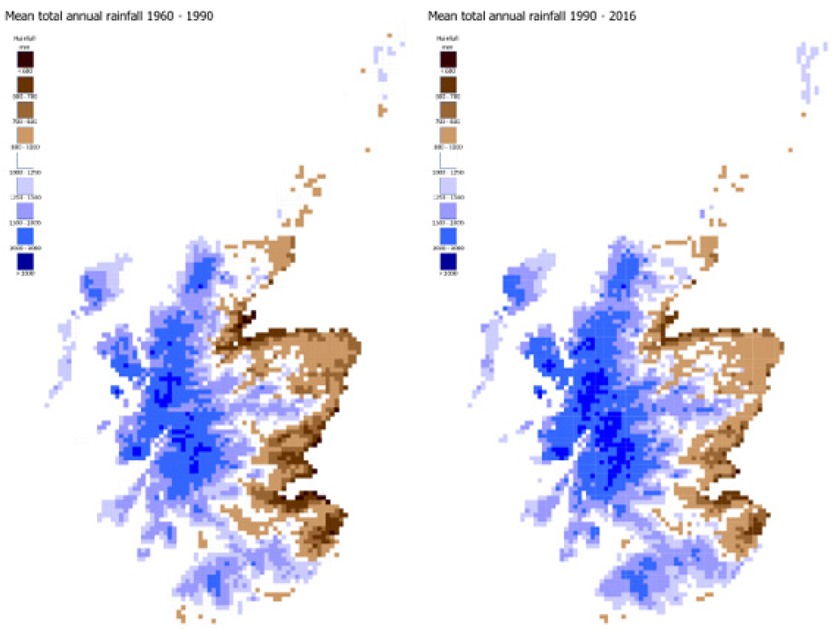


Figure 8. Observed changes in mean total annual precipitation between 1960-1990 and 1990-2010.

3.4 Projected changes in dry year frequency

To assess the risks of increasing dry year conditions, we compared the 5km observed precipitation data with the UKCP18 for each ensemble member (climate model run). Figures 9 and 10 show the number of times in the period 2020-2050 that the UKCP18 projected annual precipitation (per ensemble member 1-12) falls below the 20th percentile of the actual observed precipitation between 1960-1990. In other words, if the future projection annual precipitation for any year and 5km cell is lower than the 20th percentile of the observed period (1960-1990, e.g. a historical dry year), then this is counted and summed for the 31 year future period.

Key Finding: Across all 12 climate model ensemble members and two time periods of baseline comparison a pattern emerges that the eastern half of Scotland shows a substantial increase in the likelihood of more dry years occurring (Figures 9 and 10). However, there are also likely to be years with precipitation totals similar to the current climate. In the context of the hydrological drought typology (Section 2.3, Appendix III.3), a decline in annual precipitation (meteorological drought as snow or rain deficit) implies an increase in probability of occurrence of severe hydrological droughts in terms of duration and deficit.

This particular analysis is for annual total precipitation hence does not consider the seasonal distribution within a year (this is covered in Figures 10 and 11). However, as an indicator of precipitation input to the hydrological system it does provide useful information on the spatial distribution of the regional differences in risk to PWS.

How to read and interpret the maps: The maps in Figures 9 and 10 show how many years per 5km cell that the future total precipitation will be lower than the lowest 20% of the observed years observed. The assumption is that the driest years in the past may have resulted in some risk to PWS, and that by considering how many of the future years are similar provides an indication of increased frequency risk. Figure 9 shows the projected change compared against the 1960-1990 period for the 12 climate model ensemble members used, whilst Figure 10 shows the change from comparison of the 1990-2016 period. These 12 ensemble members represent some of the range of probabilities and uncertainties.

Blue indicates that for a 5km cell that the future will have no years that are drier the lowest 20th percentile of the observed period and thus similar to historical levels of risk, whilst for dark green between 1 and 5 years will be dry. However, there is still a possibility that for any one location there remains the risk that a severe drought may occur, but it is not possible to state how severe these may be.

Red cells indicate that the majority if not all of the years' annual precipitation will be lower than the dry historical years by 2050. There is variation between the ensemble members due to their parameterisation and resultant spatial distribution and amount of estimated precipitation.

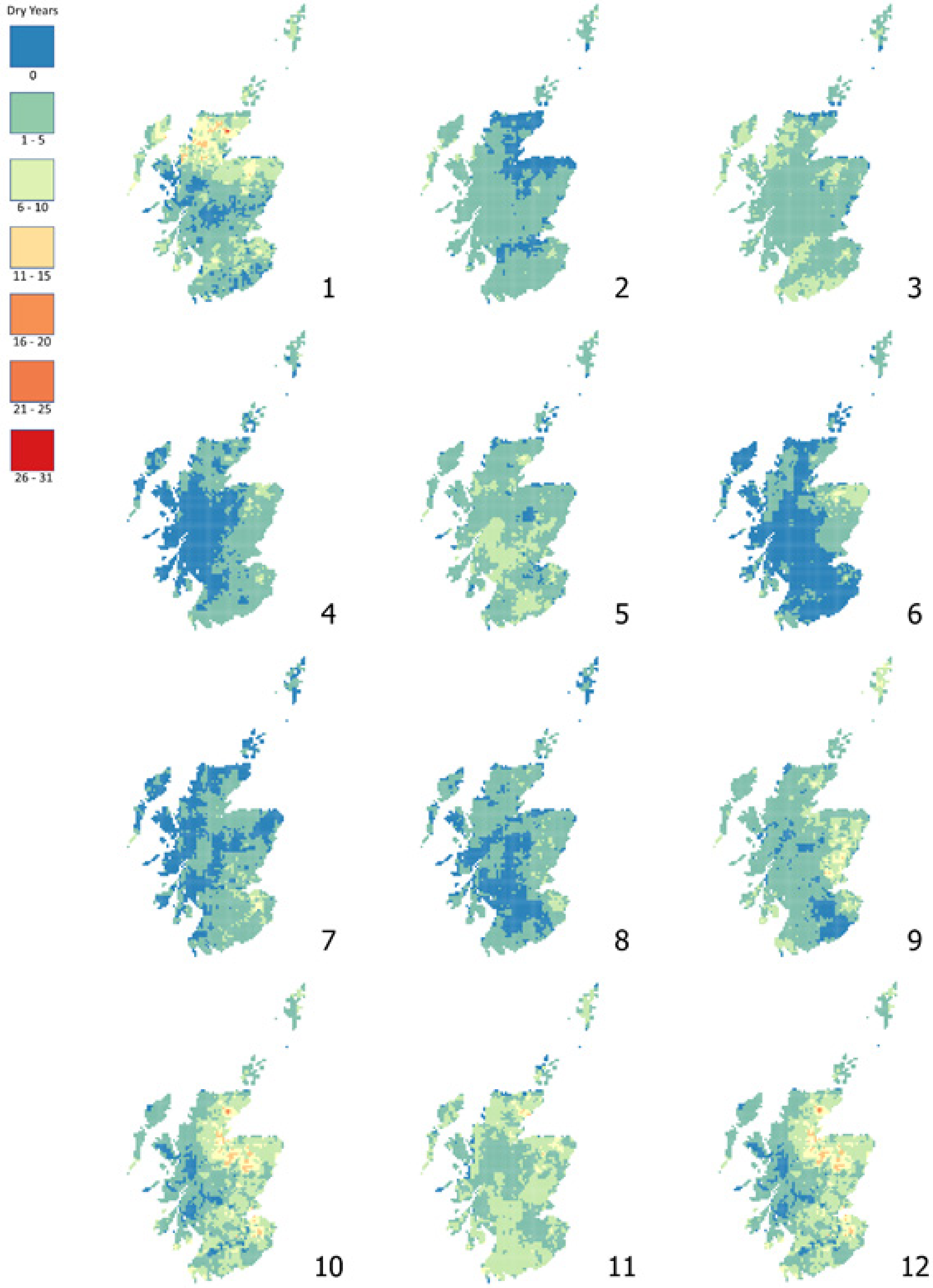


Figure 9. Dry years comparison: the number of times in the period 2020-2050 that the UKCP18 projected annual precipitation (per ensemble member 1-12) falls below the 20th percentile of the actual observed precipitation between 1960-1990.

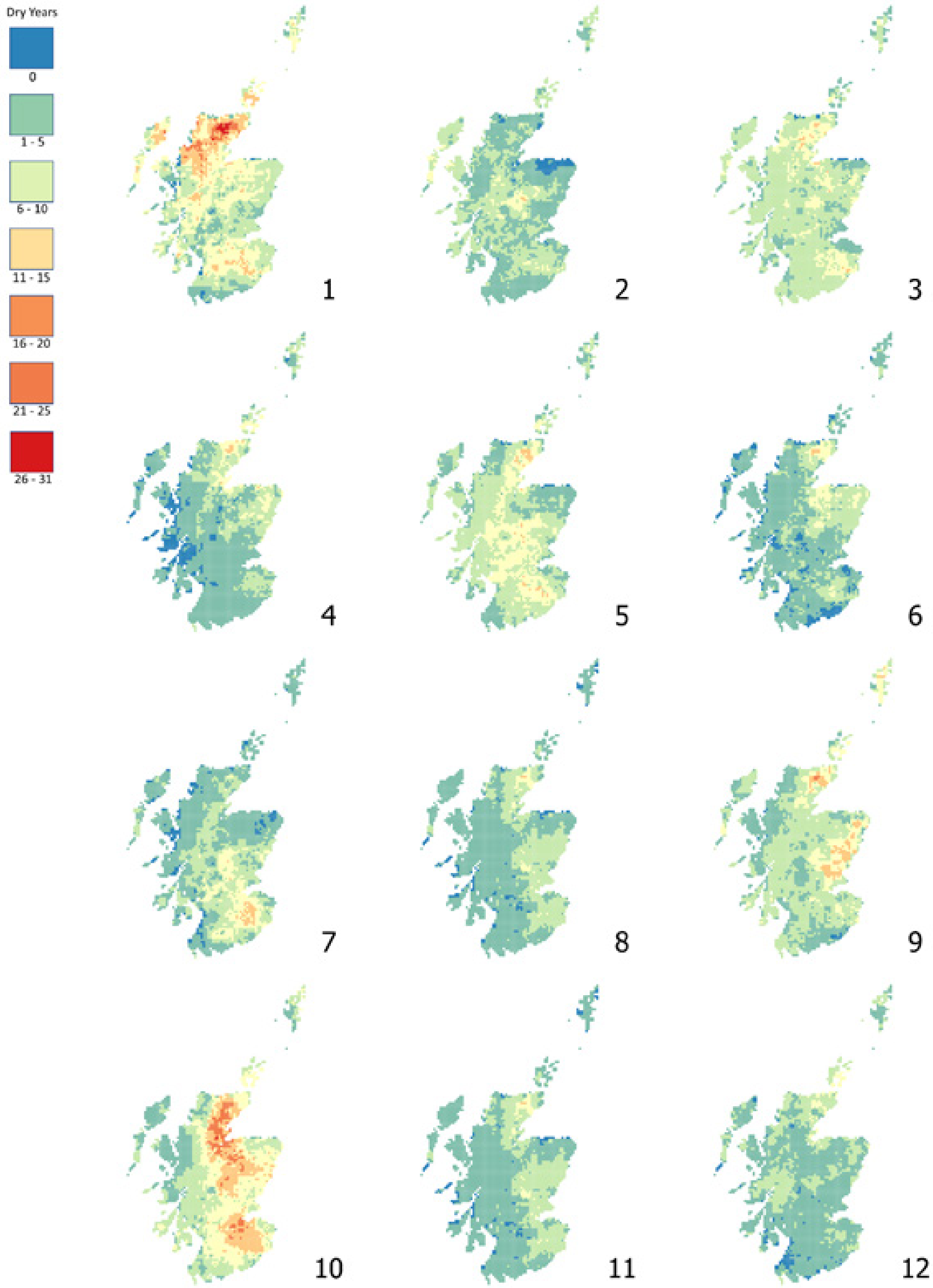
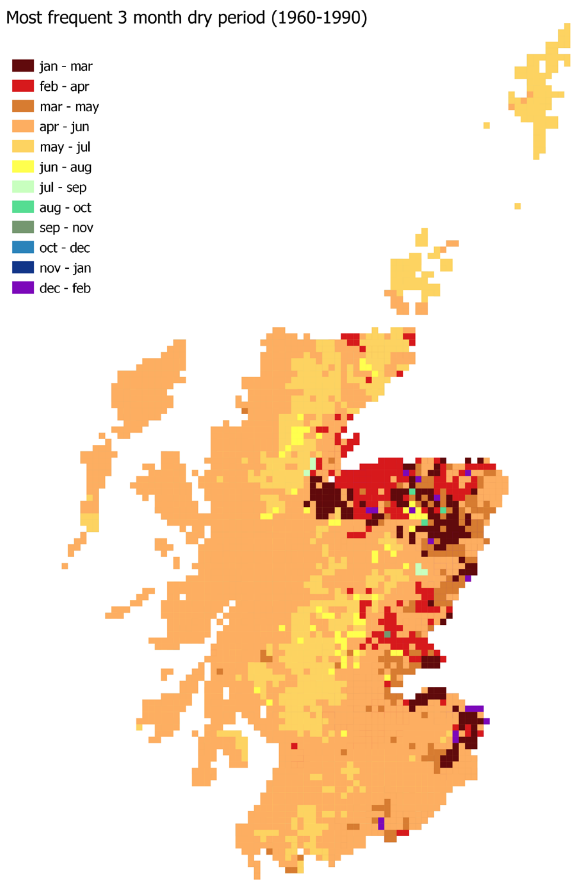


Figure 10. Dry years comparison: the number of times in the period 2020-2050 that the UKCP18 projected annual precipitation (per ensemble member 1-12) falls below the 20th percentile of the actual observed precipitation between 1990-2016.

3.4 Assessing changes in precipitation seasonality

To assess shifts in the seasonality, the driest three month periods were identified for the two baseline periods (1960-1990 and 1990-2016) (Figure 11). Over time there has been a shift towards locations experiencing their driest periods at different times in the year. For example, the upland areas of south-west Scotland's driest 3 months were previously in the April-June or May-July periods, but his has shifted to June-August and July-September. For much of the Highlands there has been a shift April-June to May-July or June-August. Conversely parts of eastern Scotland show a shift towards the driest 3 months being earlier, e.g. from January-March to December-February.

For the future (2020-2050) period projections (Figure 12), the 12 ensemble member projections show varied estimates, with the east of Scotland shifting towards the driest period in the summer rather than spring. The west continues to be driest in the April to July periods, but the boundary between this and the June-September period shifts further to the west. This implies a probability of increased drying in the central and eastern parts of Scotland as the reduced rainfall coincides with the warmer months.



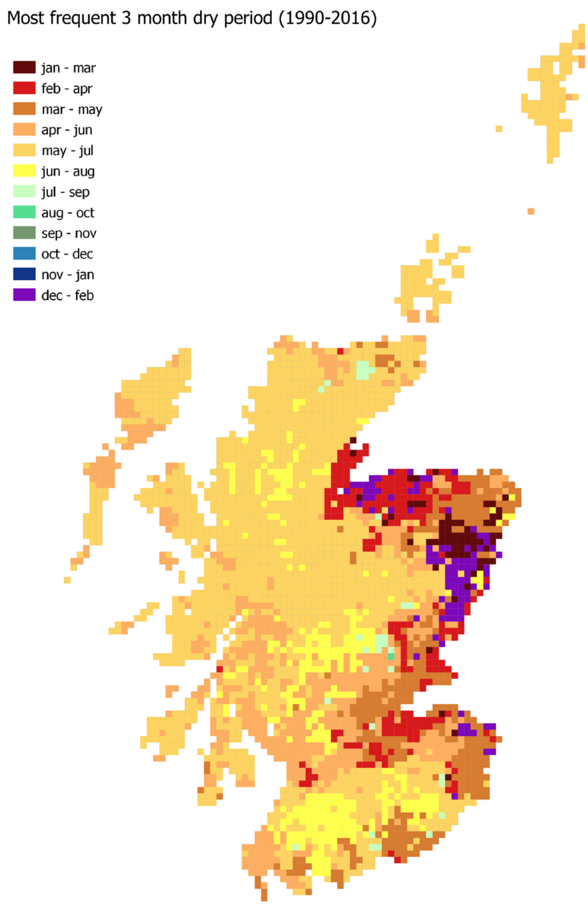


Figure 11. 5km cells that most frequently have the driest three months for the two observed baseline periods (1960-1990 and 1990-2016).

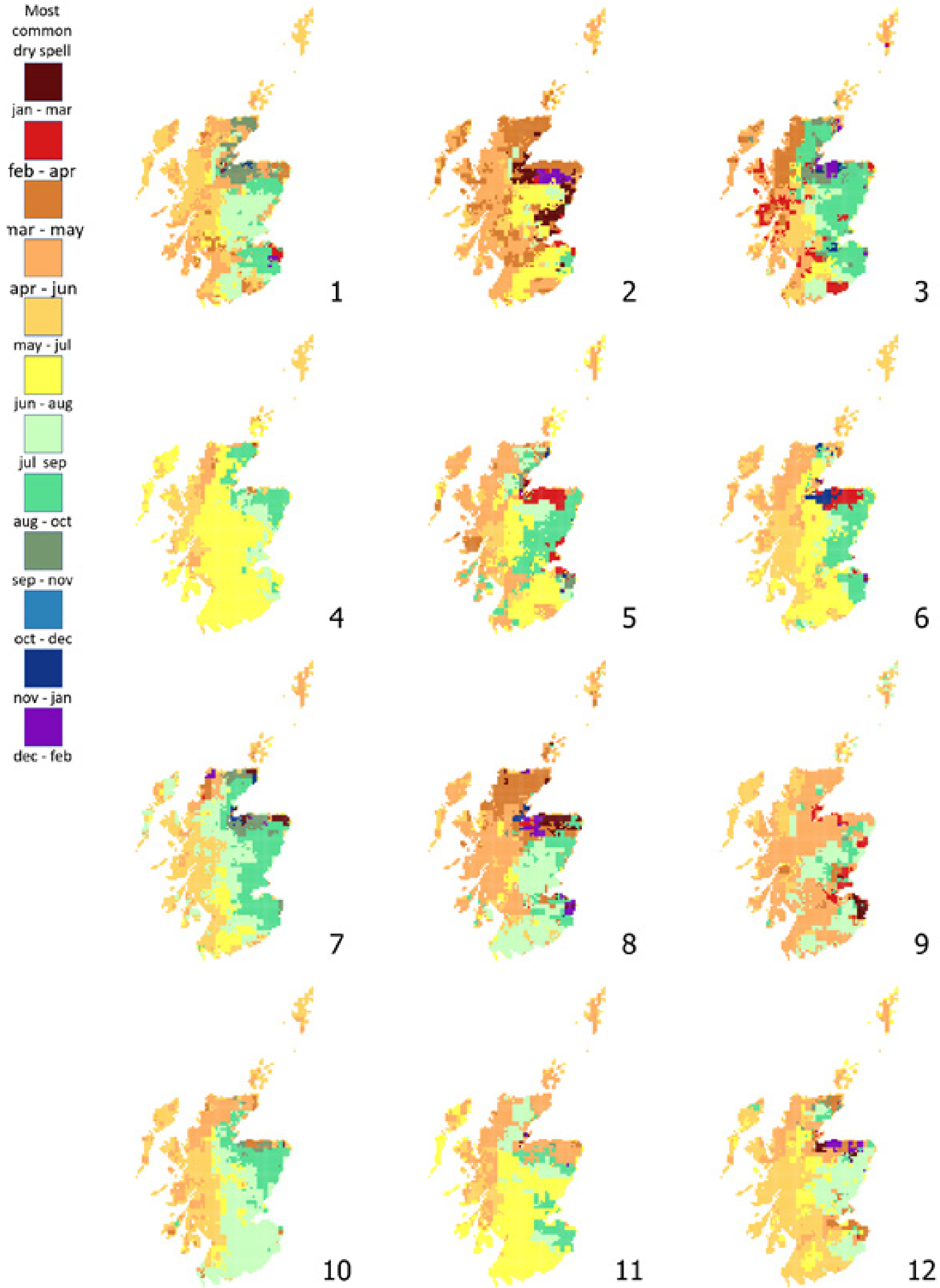


Figure 12. Areas with the highest frequency of driest three months for the projected period of 2020-2050 (5km2 grid cells).

These projected shifts in seasonality imply changes in ground water recharge and hydrological drought propagation (Appendix III.3) which may lead to increased risks to PWS, or potential improved resilience, depending on nature of the shift and quantity change.

3.5 Meteorological Drought Risk Indicator

The Drought Risk Indicator (DRI) presented here is a bespoke meteorological drought one for the purposes of assessing risks of PWS. It is a combination of data from the future driest years (Figure 8) and the actual locations of PWS.

In the example below (Figure 13) the left-hand map shows the locations (dots) of PWS and the number of times in the period 2020-2050 that the UKCP18 projected annual precipitation falls below the 20^{th} percentile of the actual observed precipitation between 1960-1990. From this a drought risk category is allocated: if there are no PWS then there is no risk (dark blue in right-hand map), even if the future climate projection indicates an increased frequency of dry years. Where there are few PWS and moderate numbers of drier futures years the risk indicator is low to moderate (green), but where there is a high density of PWS and a large increase in the number of future dry years, the risk is high (brown) or very high (red). This means the category is a combination of the density of PWS and probability of dry years increasing. However, cells with a single PWS but low category may still have high risks of severe drought years.

A key caveat to this indicator is that it **does not** (in this analysis) differentiate between PWS types and technologies. Thus cells with just boreholes (relatively better resilience to higher precipitation deficit or hydrological drought) for example, will have the same indicator category as a cell with just springs (more vulnerable to rainfall deficit) if the number of future dry years is the same for both cells. More detailed spatial analyses will be able to differentiate between PWS types. The assumption to the use of DRI is that more frequent dry years in the future means an increase in probability of meteorological drought and thus more severe consequences on PWS relying on rain.

The purpose of this indicator is to illustrate **where** in Scotland the highest probability of increased precipitation deficit is. This method has not been developed to assess individual PWS *per se*, but is a useful starting point to assess locations where there may be need for exploration of alternative solutions. Figure 14 shows the DRI for each ensemble member for the 2020-2050 period, showing the variation due to differences in the precipitation projections determining the number of future dry years. Figure 15 is the ensemble mean (from all 12 members) and shows that the north-east of Scotland has either a high or very high future drought risk in relation to the density of PWS.

Key Finding: These maps show that the north-east of Scotland, central and southern uplands and parts of the southern west coast are likely to experience increased risk to PWS due to the higher probability of drier years (below the 20^{th} percentile of the observed period annual total). This is seen for all ensemble members, which represent a range of likely precipitation totals. This range of probabilities is compiled as the ensemble mean (Figure 14), thus representing the mid-range probability for the emissions scenario used.

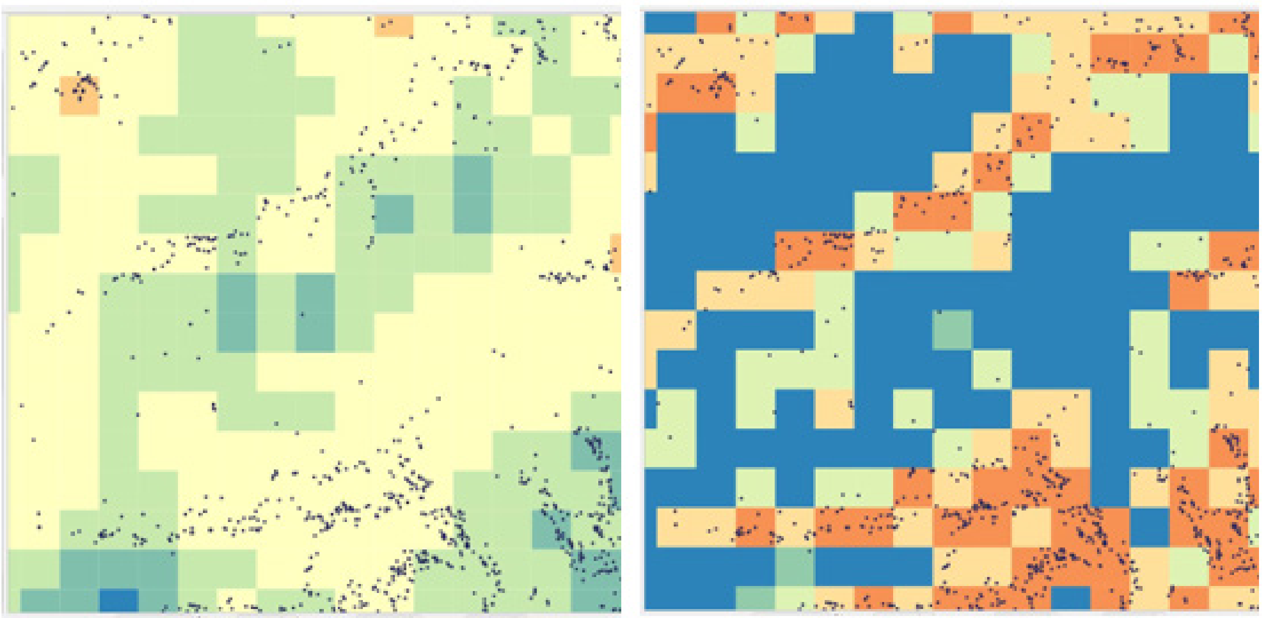


Figure 13. Example of how the Meteorological Drought Risk Indicator for PWS is estimated.

How to interpret the Meteorological Drought Risk Indicator (DRI):

The risk classes shown on the maps in Figures 14 and 15 are the sum of the number of years (0 - 31) in the future projections where the annual total rainfall falls below the 20th percentile threshold of the observed years (in Figure 9) and was multiplied by the number of private water supplies in the same 5km cell. The values were then classified into 6 drought risk classes:

- None: dry year count x PWS number = 0
- Very Low: dry year count x PWS number = 1-5
- Low: dry year count x PWS number = 6-25
- Moderate: dry year count x PWS number = 26-100
- High: dry year count x PWS number = 101-500
- Very High: dry year count x PWS number = >500

Where there are no PWS, the classification is None, but that is most likely to be because there are no PWS, as our analysis indicates that for al cells in the future there will be at least one drier year.

Examples:

A cell is estimated to have 4 years in the future when the precipitation is less than the 20th percentile of the annual total in the observed record, and has only one PWS in the cell. Therefore: 4 x 1 = 4, so a DRI classification of Very Low.

A cell has 15 years in the future that are projected to be below the 20th percentile of the observed annual total (therefore many more dry years than the past) and has 10 PWS in it. Therefore: 15 x 10 = 150, so a DRI classification of High.

This method is designed to give an indication of risk based on probability of future dry years and PWS density. It would be possible however to have situations where a future year is very dry and has only one PWS. Hence a Low classification does not imply no risk, but less likely than a High classification. It is also possible that a 5km cell with one PWS is estimated to have many years in the future that are drier than the past, but has a lower total number, for example: 1 PWS x 20 dry years = 20, so a Low classification, when clearly there is a large increase in risk of experiencing dry conditions.

Hence this DRI needs careful interpretation, which is best done in conjunction with Figure 9 and or 10.

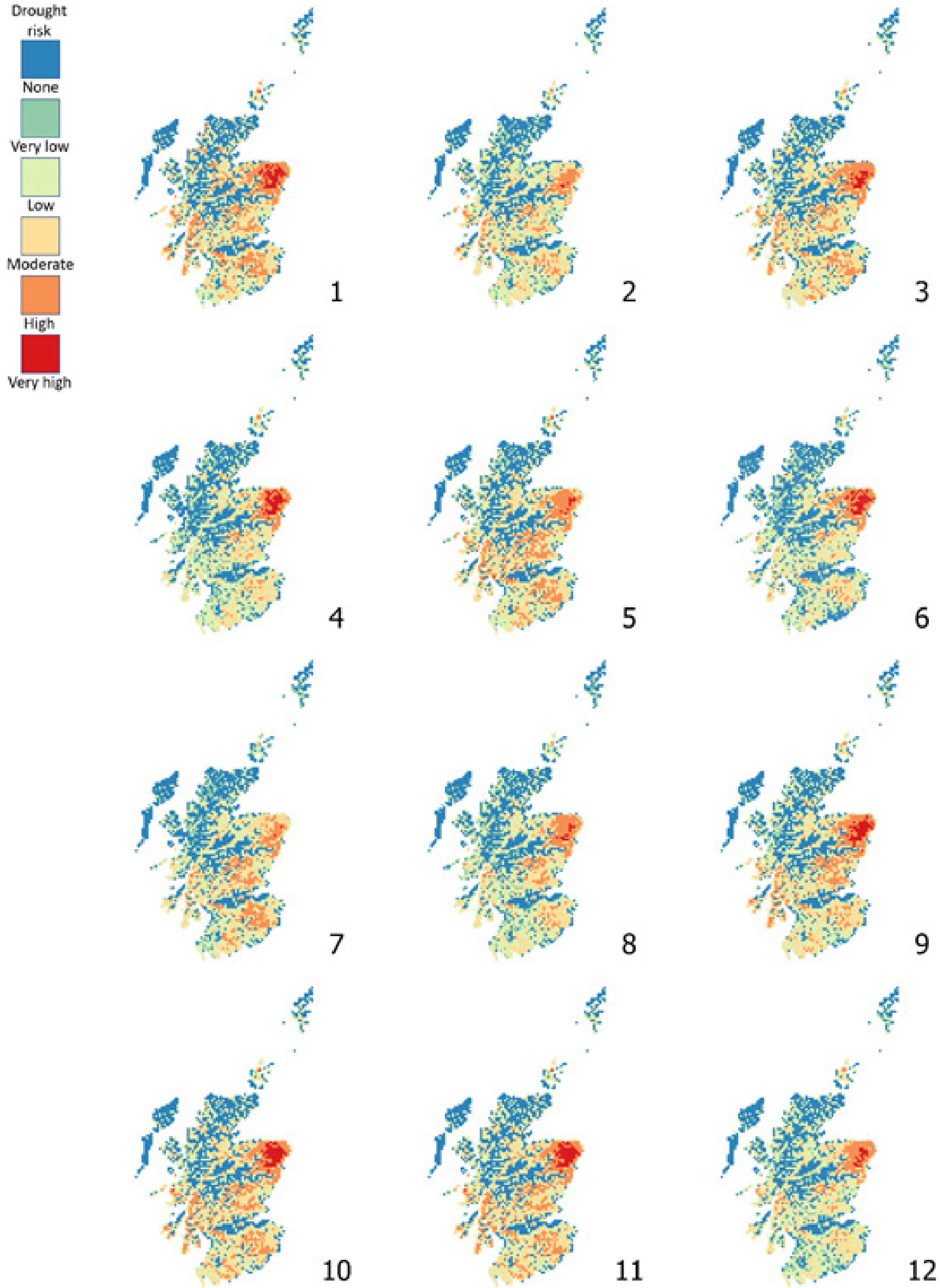


Figure 14. Meteorological Drought Risk Indicator: combination of the number of years in the period 2020-2050 that the UKCP18 projected annual precipitation (per ensemble member 1-12) falls below the 20th percentile of the actual observed precipitation between 1990-2016 in relation to the density of Private Water Supplies.

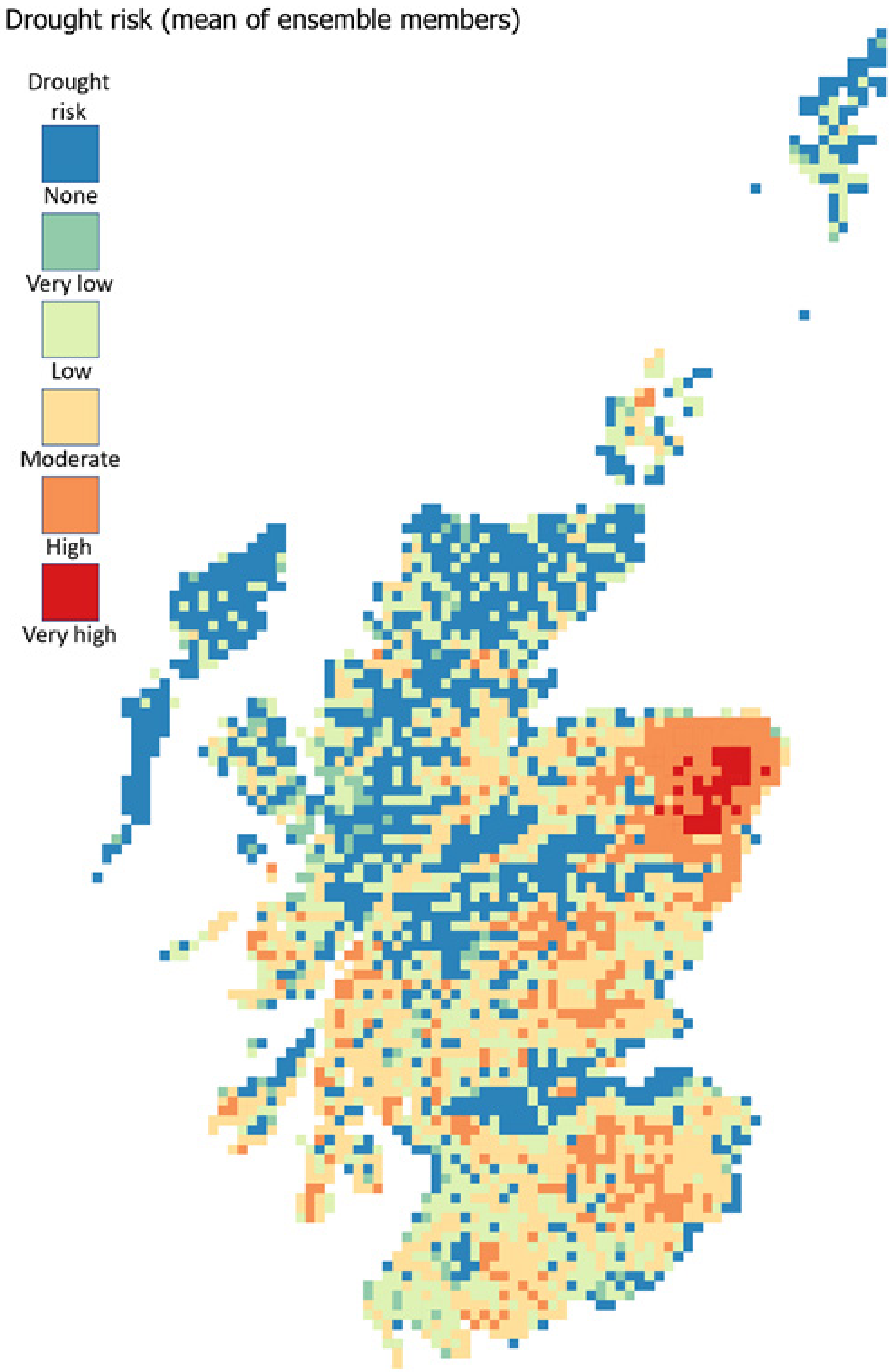


Figure 15. Ensemble mean Meteorological Drought Risk Indicator: combination of the number of years in the period 2020-2050 that the UKCP18 projected annual precipitation (mean of 12 ensemble members) falls below the 20th percentile of the actual observed precipitation between 1990-2016 in relation to the density of Private Water Supplies.

The DRI indicates risk for PWS only, but clearly the increase in dry years also implies a risk to public water supplies, (see Box 2 and Section 2.7) which may occur in the blue cells in the above figures. Thus this analysis indicates that both centralised and decentralised water supplies may experience an increase in shortage risk due to increased water deficit, e.g. low reservoir levels.

Key Finding: From the DRI, there are approximately half of the PWS that are found within the High- or Very High-risk categories between 2020 and 2050 (Figure 16). This does not take account of the type of PWS or that the current number or location may change over time. The purpose of Figure 15 is to illustrate the proportions of PWS that may experience increased risks of meteorological drought. Within each risk category there are many different types of PWS and individual catchment characteristics influencing drought propagation.

3.6 Precipitation volume

The total precipitation volume for the land area of Scotland, and the UK as a whole, has increased since 1960 (Figure 17). There has been substantial annual variability in the past, varying by c. 50 billion m³ between drier and wetter years. The future projections indicate that the total volume may decrease, but with continued annual variability. Climate models generally do not capture annual precipitation variability well, as they are developed to estimate long-term changes. The ensemble mean value (red lines) in Figure 17 is the mean total precipitation from the 12 individual runs of the HadRM3 regional Climate Model for the RCP8.5 scenario.

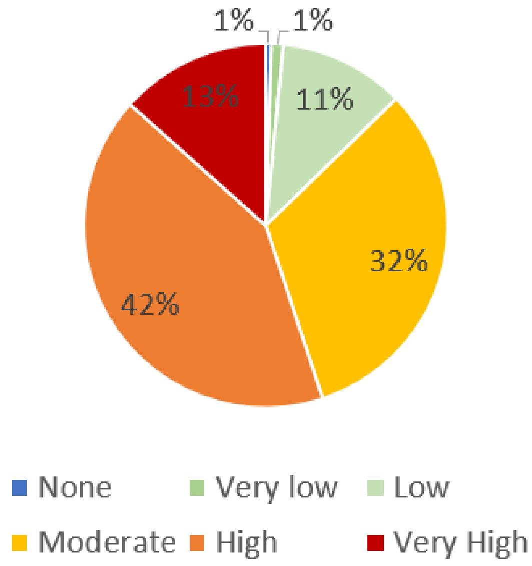


Figure 16. Proportions of PWS per Meteorological Drought Risk Indicator category for the 2020-2050 ensemble mean.

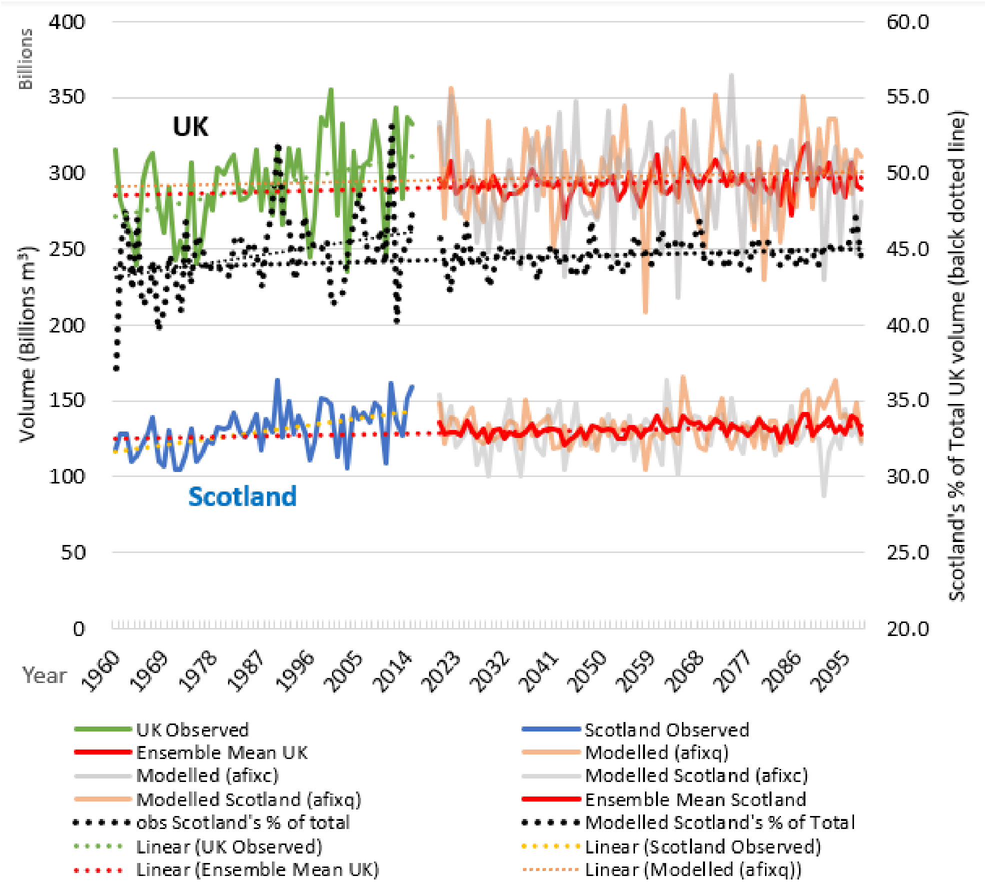


Figure 17. Observed total precipitation volume (billions m3) for the UK and Scotland land area and UKCP18 climate projections to 2100 (ensemble mean and two members), and Scotland's percentage share of the UK total.

3.7 Additional Indicators of change

Through a separate Scottish Government funded research project, a series of Agrometeorological Indicators have been produced and estimated using observed and future climate projections (UKCP09, also downscaled and bias corrected to 5km resolution). These are detailed in Appendix VII. The key finding from these is that there is likely to be a complex set of changing climate driven dynamics that affect land and land use, thus influencing hydrological processes and water availability for PWS. In summary;

- There is some increase in the count of the number of days above 25°C per year (Plant Heat Stress Indicator) from 2-3 to 6-9 days. This indicates the probability of increasing evapotranspiration as plants growing in the spring and summer, potentially using more water thus reducing infiltration into ground water and thus reducing water available for PWS.
- Heatwave indicator: There has been an observed trend towards an increase in the number of heatwave days since 1960. This is projected to continue in the future, particularly in the west coast areas. More frequent and prolonged heatwaves will increase water deficit hence supply to PWS.
- Erosivity of rainfall (Precipitation Heterogeneity Indicator): There has been some increase since the 1960-1990 period, with the north-west coastal areas of Scotland projected to have the largest increases but south-eastern Highlands may see a rain shadow effect giving a slight decrease in indicator values. The projected future increase in the Indicator implies more intense rainfall events and associated higher risks of soil erosion that may result in blocking of PWS.
- The timing of when a soil becomes driest is estimated to occur at similar times to the present or later in the year (c. 30 days in some cases), varying with soil types. This is likely to be due to continued soil moisture loss from evapotranspiration and reduced summer period rainfall. This aligns to the findings in Figures 8 and 9 in respect of shifts in the driest 3 month periods.
- Analysis of how dry the soil becomes (Maximum soil moisture deficit) shows that generally soils show a range of higher deficit (more become drier), or thee is little or no change. A few soils showed lower deficit responses (they become wetter). This varies with soil type.
- The amount of excess winter rainfall (total amount of rainfall between 1st October and 31st March and when soils are at field capacity) may reduce in the future. This may in part be due to soils being drier in the summer, requiring more autumn and winter rain to recharge to field capacity or saturation point.

Snow cover: The amount of snow cover over winter in the Scottish mountains plays in import role in the amount of water and timing of it contributed to groundwater, rivers and water bodies. Climate change will likely alter the amount of snow cover and rates of melting. For example, there has been a decline in winter snow cover in the Cairngorm National Park (CNP) since 1969, but with large annual variation (Rivington *et al.* 2019). Whilst a clear warming trend has been observed in the CNP during the winter (October and November show approximately 1.6°C + maximum temperature and 0.8 °C minimum temperature rises), there was no clear trend in precipitation change. This increase in temperature, particularly in March, April and May indicates a likelihood of earlier onset of snow melting. There has been a clear decrease in the number of days of snow cover at all elevation levels over the 35 winters between 1969/70 and 2004/05, with higher elevations having a larger proportional decrease (south-eastern CNP). Modelled future snow cover (using the same UKCP18 data as this PWS study) indicate the potential for a continuation of snow cover at the current range of variation in the near-term, but with a substantial decline from the 2040s. These findings are in line with results from the UK Meteorological Office and Inter-governmental Panel on Climate Change (IPCC 2019). There may be some years in the future when the weather conditions create snow and enable lying snow that may be comparable to the past, but such occasions will become fewer. This applies to all elevations, but with larger proportional decreases at higher levels. Results indicate a likelihood of some years with very little or no snow by 2080.

3.9. Practical implications

There is likely to be a need for greater flexibility in how vulnerable PWS (springs, shallow wells and rivers) are used and managed to cope with dry periods. Our ability to estimate future conditions is constrained by multiple uncertainties, hence any deliberation or decision making based on these findings (or indeed anywhere when climate model projections are used) needs to include understanding of the limitations and caveats. This study has used one climate model (run 12 times with different parameterisations) and one emissions scenario. Hence it represents one set of possible futures. The methods, data and analytical approach used do however provide a useful guide as to the likely direction of change in meteorological drought risk. Our results fit with wider research findings hence we can have confidence that what has been presented, whilst not definitive, has good utility in informing deliberation.

4. Next steps

The James Hutton Institute holds high spatial resolution daily data for historical weather and bias corrected (5km) UKCP18 climate projections, as well as the National Soils Data. This enables the potential to assess vulnerability for individual or catchment scale groupings of PWS for any given soil-weather unique combination.

There is need to estimate a total water balance as input to the hydrological system by estimating evaporation and transpiration (by plants), which is collectively referred to as evapotranspiration (ET). Research to estimate ET is underway but for accuracy could be improved by using specific parameters of individual land covers (rather than the current uniform grass sward). Evapotranspiration forms an important part of cooling the ground and air, hence when less water is available (e.g. soils become drier) there is less cooling and the ground and air become even warmer (creating a positive feedback loop).

It will be possible with further spatial analyses to differentiate between PWS types and category of Meteorological Drought Risk Indicator. There are also other types of indicator, as detailed in Phase 1, which could be coded and applied to the spatial analysis to give a broader perspective of drought risk than that provided here.

It will be possible, with the appropriate data and permissions, to map existing mains water supplies and proximity to the different types of PWS, e.g. those identified as most vulnerable.

The UK Met office have also recently released high resolution (2.2km) climate projections derived from a new Convection Permitting Model that provides improved localised representation of cloud formation and precipitation. Use of this new data would enable improved localised estimation of precipitation and thus risk assessments, allowing for a more detailed understanding of risk to individual PWS.

5. Conclusions

This project has shown that the issue of vulnerability of Private Water Supplies to drought is complex due to multiple interacting factors. This study has assessed the available literature to review the known understanding of the complexity of the issues, and then applied future climate projection modelling to provide information about how levels of resilience and vulnerability may change.

Research questions and conclusions:

What are the main influencing factors on PWS vulnerability?

The key interacting factors controlling the vulnerability of an individual PWS at a specific location or catchment include:

- Meteorological-climate drivers, such as rainfall or snowpack deficit and temperature anomalies.
- Catchment characteristics such as geology, topography, soil types, land cover.
- Catchment hydrological processes, such as evapotranspiration, soil moisture, groundwater recharge and groundwater-surface water interactions.
- Human activities, such as land and water management and water use (e.g. rates of water abstraction), climate) and the location of the PWS within the catchment;
- The source of PWS, with rainwater harvesting, springs, shallow wells, and flashy rivers (i.e. rivers where flow rises and falls fast in response to intense rainfall or snow-melt, usually draining small headwater catchments). These are more vulnerable to a precipitation deficit than sluggish rivers (i.e. rivers where flow rises and falls slowly in response to rain and snow-melt, usually draining larger catchments) and boreholes from aquifers receiving recharge from extensive catchment areas and sustained from confined deep aquifers.
- Future levels of PWS vulnerability will likely be a combination of changes in the climate that affect water quantity availability and interactions of the specific catchment scale water use. Across Scotland this will be spatially and temporally variable due to precipitation and temperature differences affecting overall water balance.

What are the likely impacts of future changes in the amount, frequency and distribution of precipitation and the resilience of private water supplies (PWS)?

- The analysis indicates there is a high probability that climate change will result in drier and warmer summers that will result in increased water deficits which will result in increased vulnerability of PWS, particularly those more reliant on surface water.
- Summers similar or more dry and warm than 2018 are projected to occur more frequently, indicating an increased probability of requests for support from PWS users.

What can be deducted from climate change projections (modelling data) regarding changes in precipitation?

- The timing of when and rates at which precipitation enters the hydrological system is likely to change.
- There is an increased probability of warm dry summers, but with more intense rainfall events.
- Seasonality shifts have occurred and are projected to continue changing, altering the timing of when ground water is recharged.
- It is not just an issue of precipitation, as we also need to consider increasing temperatures leading to great rates of water loss from evaporation.

How will different regions in Scotland be affected? How will it affect regions where PWS predominate?

- Geographically the distribution of precipitation will likely change, with the west and east becoming drier with the west experiencing high precipitation events (e.g. westerly storms).
- The north-east of Scotland is estimated to experience the largest increase in water shortages, where there is also the highest density of PWS.

These overview conclusions should be interpreted within the context of the key findings from the literature review and future modelling projection estimates and details on caveats and uncertainties about future modelling, as provided below.

What recommendations can be provided to policy-makers to enhance the resilience of PWS?

1. Risk assessment of PWS for water quality issues can be extended to include climate-change related issues.
2. Policy prescription on fit-for-purpose technologies for collection and treatment of water is a feasible way to help build resilience in decentralised, small rural supplies.
3. Improve meteorological drought risk indicators and monitoring of water availability and shortage early warning mechanisms by developing catchment scale meteorological linked to hydrological drought risk indicators and apply to localised contexts to improve early warning systems.
4. Assess potential of bedrock *aquifers* across *Scotland* to sustain various levels of borehole water supply and improve PWS resilience to drought (e.g. using Bedrock Productivity map by British Geological Survey as a guide).
5. Provide risk awareness and water conservation advice to PWS users.
6. Develop household water storage capabilities as back-up support to non-drinking water uses during drought. This may be more suitable for non-drinking water use.
7. Identify the potential for cost effective connection to mains water supply by using spatial risk indicator mapping.
8. Integrate policies and associated research for improving catchment storage potential with those focussed on nature-based solutions for improved ecosystem resilience (e.g. water retention in soils, Natural Flood Management). These measures to improve soil and groundwater water retention for agricultural and ecosystem management purposes may also help PWS resilience.
9. Account for changes in water demand in view of climate change.
10. Assess impacts of meteorological and hydrological drought on reservoirs.
11. Review and assess the benefits of centralised management on water supply resilience to climate change in rural areas to inform and enable the use of lower-risk source water services.

Literature Review Key Findings:

1. A meteorological drought (below-normal precipitation) can propagate through the hydrological system (the precipitation input side to the hydrological cycle) and, if prolonged, lead to a hydrological drought, i.e. below-normal water availability in rivers, streams, reservoirs, lakes, or the groundwater table. Hydrological droughts are directly associated with socio-economic impacts including drinking water shortages. In Scotland, very low river and spring flows and low reservoir and loch levels have occurred during the past century in both West and East Scotland in connection with periods of prolonged dry weather. Generally, the impact of meteorological drought on water sources serving small rural water supplies is controlled by catchment water storage levels prior to onset of dry weather, and depends on the type of water source.
2. In addition to meteorological-climatic drivers, catchment properties (e.g. land cover, topography, soil type bedrock geology) and human activities (e.g. abstraction, land and water management and water use) influence the impacts of a hydrological drought event on small supplies.
3. The key drivers of a hydrological drought are:
    i. Climate-atmospheric drivers such as precipitation deficit and temperature anomalies. which are key to shaping the distribution

of drought duration in natural and human-influenced catchments.

   ii. Hydrological drivers in natural catchments such as evapotranspiration, soil moisture and water storage (e.g. in the soil and aquifers), and runoff, which are influenced by catchment properties determining aquifer recharge and response to rainfall ("flashiness").

   iii. Human drivers include surface water and groundwater abstraction, urbanisation, damming and deforestation. In short timescales, the onset and duration of a hydrological drought depends on water demand and water management. In longer timescales the threshold below which a hydrological drought occurs is mainly influenced by groundwater depletion and anthropogenic land use change. A human-induced drought has a lower threshold below which a hydrological drought occurs than a climate-induced drought.

4. Hydrological drought events are described by their frequency, severity, duration and deficit (i.e. deviation from normal flows and levels for a given area and season). Generally:

   i. In cold climates, hydrological drought deficit is governed by annual precipitation and winter precipitation, which is controlled by temperature.

   ii. River drought duration is primarily controlled by seasonal water storage (e.g. snow pack and glaciers). River drought deficit is mainly controlled by water storage in soil and aquifer.

   iii. Increased annual precipitation increases soil moisture and subsequently evapotranspiration (when temperatures are sufficiently high), which may or may not influence groundwater recharge. Increased annual temperature increases evapotranspiration rates and reduces recharge in winter. Increased winter temperature reduces the extent of ground frost and shifts the snow melt from spring toward winter, allowing more water to infiltrate into the ground, resulting in increased groundwater recharge.

5. Generation and propagation of different hydrological drought typologies is controlled by meteorological drivers and catchment processes, such as groundwater storage. Hydrological typology distinguishes drought generating mechanisms as (their key driver in parentheses): Classical rainfall deficit drought (precipitation deficit in any season); Rain-to-snow season drought (precipitation deficit continuing into snow season); Cold snow season drought (low temperature in snow season leading to no recharge); Warm snow season drought (high temperature in snow season leading to no recharge); Snowmelt drought and Glacier-melt drought (in winter, in very high latitudes, leading to no recharge); and composite droughts (multiyear droughts in catchments slowly responding to rain). The classical rainfall deficit drought is the most commonly occurring, but types such as rain-to-snow-season droughts and warm snow season droughts can have more severe impacts.

6. A wide range of indicators, standardised indices and thresholds exist to define a hydrological drought and support early warning systems. Indices are typically computed numerical representations of drought severity, assessed using indicator data such as precipitation, snowpack, streamflow, groundwater or well level, reservoir storage, and modelled data. Ideally they have both monitoring and forecasting components to prompt action (via "below-normal" threshold triggers) within a drought risk management plan, as a means of reducing potential impacts. Examples of standardised hydrological indices are the Standardized Streamflow Index (SSI), which is used and reported by SEPA, and Standardised Water-Level Index, which is used for assessing risk from groundwater drought. The baseflow (i.e. groundwater contribution to river flow) index (BFI) can be a good proxy for the combination of multiple catchment characteristics indicative of catchment storage.

7. Few studies detail vulnerability to meteorological and hydrological drought of small rural supplies in developed countries by source and water treatment technology. Sources sustained by precipitation (e.g. household rainwater harvesting and some springs) and immediate aquifer recharge from rainwater (e.g. protected springs and protected shallow wells) are more vulnerable to precipitation deficit and variability than boreholes. However, boreholes and deep wells from unconfined and relatively shallow aquifers are sensitive to precipitation variability unless in cases where an aquifer receives recharge from an extensive catchment area. Rivers are vulnerable to a prolonged precipitation deficit. Reservoirs are vulnerable to the variability of rainfall, which outweighs the positive effect of an increase in total annual precipitation.

8. Major knowledge gaps are related to research questions on the following issues: drivers of drought; human influences on the prevention, exacerbation or management of hydrological drought; collecting data on the impacts of hydrological drought; modelling drought propagation, severity and recovery; and identifying "normal" in a constantly changing world.

9. The practical implications of this evidence can be summarised as:

   i. Risk assessment of PWS for water quality issues can be extended to include climate change related issues; the World Health Organisation (WHO) has already provided an extended conceptual flow of activities in water safety plan risk assessment.

   ii. Few studies account for changes in water demand in view of climate change in Scotland; therefore, data on catchment storage will be key towards management of water resources for PWS resilience.

   iii. Policy prescription on fit-for-purpose technologies for collection from source and treatment of water is widely recognised as a feasible way to help build resilience in decentralised, small rural supplies. This approach can be tailored to local conditions and tied into other risk management approaches (e.g. water quality risks), such as the specified technologies' approach to health-based targets described in the WHO's Guidelines for Drinking Water Quality. For example, a change of source (e.g. from spring to borehole) can be a sensible course of action in areas where bedrock aquifers have the potential to sustain borehole water supply, and when vulnerability to drought and contamination co-occur for a given PWS or supply zone.

   iv. Centralised management is key in developing water supply resilience to climate change. This is because the technical, human, and financial resources are usually sufficient to permit the integration of climate issues within management plans and the expertise and ability to identify alternative sources to produce lower-risk source water services.

Key Findings – Future Projections:

1. Climate change will result in alterations to the precipitation input to Scotland's hydrological system, with different spatial distributions and seasonality shifts giving reduced rainfall in the east and increase in the west. There is an increasing probability of experiencing drier years in the future. Warmer temperatures also imply increased rates of evaporation loss.

2. There will likely be an increased risk of meteorological drought which may lead to hydrological drought and impact on PWS with an increase in the number of drier years (low total annual precipitation) occurring more frequently with water shortages due to large water precipitation deficits.

3. Using risk mapping, approximately half of the PWS are estimated to be within areas of High or Very High-(risk categories between 2020 and 2050 (see Figure 1 and explanation of classification).

   i. The geographical distribution of PWS in Scotlands' rural landscape places those supplies at an increasing risk of experienceing more years in the future, when the total annual precipitation is less than the 20th percentile of the observed period.

   ii. The risk mapping does not differentiate between PWS types, however springs and shallow wells will be relatively more vulnerable than boreholes.

4. The level of meteorological drought risk is spatially variable:

   i. The north-east of Scotland may have the greatest exposure to risk of precipitation deficit due to projected changes in precipitation and high concentration of PWS.

   ii. PWS in large areas of upland Scotland including the southern west coast and upland central and south Scotland may also experience increased water deficit.

   iii. Although some areas are estimated to be at lower risk of experiencing more dry years, the risk of experiencing severe drought in some years remains.

5. Analysis of 2018 data indicates that there was a climatic contributor to the large number of requests for support for PWS. For north-east Scotland there were areas that were consistently drier than average. The chance of exceeding 2018 temperatures (joint hottest summer on record) are estimated to become 50% more likely to occur by 2050 than in the past. This implies a larger evapotranspiration amount risking reduced groundwater recharge. The policy implications are for the need for adaptation to reduced water availability.

6. Rainfall seasonality may have changed in the past, with projections indicating further seasonal shifts that may alter the timing at which groundwater recharge occurs.

7. Total annual precipitation volume for the whole land area of Scotland using the UKCP18 data, is estimated to decrease (but is spatially highly variable, see 4 above). This, combined with projected higher temperatures and associated increased evapotranspiration and evaporation and reduced winter snow cover indicate risks of a reduction in the amount of water entering groundwater storage in many parts of the country in some years.

i. For the whole UK there is an overall increased drying trend in the future, but increased intensity of heavy summer rainfall events.

8. There will likely be increased variation in the climate leading to more frequent extreme weather events such as droughts and floods.

Large uncertainties remain in estimating future climate conditions (e.g. emissions rates, atmospheric responses to different gas concentrations, natural emissions balance changes etc.), making accurate projections of precipitation change difficult. This research has used one climate model (run 12 times with different parameterisations) and one emissions scenario, hence representing only one set of possible futures. Under the climate projections used there is likely to be a substantial change to the risks of meteorological droughts occurring in Scotland. This will be due to combinations of changes to the amount, spatial distribution and timing. This will only affect the drivers of a hydrological drought not its propagation or impacts. The result is likely to be a reduction in the amount of water available for infiltration to ground water, rivers and water bodies. Thus, while meteorological drought conditions that will increase the vulnerability of PWS are likely to increase in the future, the actual impact will be a function of many factors include catchment storage capacity and type of PWS. It is likely that for each individual PWS and catchments, there will be other contributing factors such as water used for irrigation, land use change (e.g. addition tree planting to meet net-zero carbon emissions targets) that will affect the amount of water available.

Solutions to improve the resilience of PWS to drought, including connection of rural properties in areas at risk from drought to mains, will also need to take into account the carbon footprint of changes. Such assessments will need to consider full life cycle analysis to understand the complete balance of greenhouse gas emissions costs and benefits between options.

Water quality issues are outwith the scope of this report, but it is important to recognise risks from potential future changes to the patterns of precipitation leading to hydrological droughts, that may also have impacts on water quality, e.g. resuspension of sediments with falling water levels in rivers and decreased dilution of microbiological and chemical contaminants entering watercourses. Conversely, flooding events may alter the processes of erosion and movement of faecal matter and risk increasing contaminants enter watercourses.

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Appendix I: Materials and methods

Phase 1. Literature review approach

Computerised searches were performed using web-based search engines such as Google Scholar (GS), Web of Science (WoS), and Science Direct (SD). The reason for using three different search engines was to take advantage of the different benefits arising from the use of each one of them such as detection of (i) published peer-reviewed and grey literature on the basis of full document searches including results drawn from references (GS); (ii) peer-reviewed articles tagged for their high scientific impact and close relevance of their title and keywords with the search terms (WoS and SD). Only articles and reports in English were selected. Search terms used included (search output from GS in parentheses):

- "vulnerability to drought", "Scotland OR UK" "drinking water" excluding the terms "water -quality" -"public -health" NO ASIA, NO AFRICA (561) and
- Resilience "drinking water" decentralised, OR rural, OR well, OR borehole, OR spring OR flow, OR river-intake "vulnerability to drought " NO ASIA, NO AFRICA (9)

Overall, approximately 80 peer-reviewed articles and reports were used for compiling the key evidence on the processes rendering the sources of small water supplies vulnerable to below-normal river and groundwater levels (hereafter reported as hydrological drought in line with the findings of the literature review) and identifying indicators and early warning systems to improve PWS resilience to hydrological drought.

Climate projections

Climate Data: Future probabilities for changes to precipitation were assessed spatially at a 5km resolution. Input data used were taken from the UKMO gridded observed daily data (Perry, Hollis and Elms 2009) for the period 1960 to 2018 and from UKCP18 generated from HadRM3[25] for 2020 to 2080. The original HadRM3 future projection data were estimated at a 12km spatial resolution, but here they have been downscaled and bias corrected[26] to 5km (based on Rivington *et al.* 2008). The future climate projection data are for the global rate of greenhouse gas emissions we are currently on – see text Box App I.1 for summary.

25 HadRM3 is the model applied to produce the UK Met Office projections

26 Bias correction is a mathematical means of downscaling a spatial dataset to a finer resolution. Without bias correction, critical variables, e.g. temperature, would under- or overestimate the actual observed temperature at locations at the finer resolution.

Box App I.1. Summary of the origins of the climate projections and greenhouse gas emissions rate scenarios.

Climate projections and emissions pathways:

The climate change research community has for many years developed a range of possible future scenarios linking economic development pathways, called Shared Socio-economic Pathways (SSPs) and greenhouse gas emissions pathways and their effect on radiative forcing (the amount of 'greenhouse effect') called Representative Concentration Pathways (RCPs). See Riahi et al. 2017.

There are 5 RCPs for which there are climate projections, ranging from RCP2.6 (low rates of emissions) to RCP8.5 (high rates). Only the RCP 8.5 data is available at the appropriate resolution for this work.

The UKCP18 climate projections are produced by modelling using a global scale climate model (HadGEM3) which in turn provides input into a Regional Climate Model (HadRM3). The HadRM3 is run 12 times using slightly different parameterisations that aim to capture the range of uncertainty associated with climate modelling. This creates a 12-member ensemble of climate projections.

The UKCP18 climate projections cover the range of RCPs, with estimates of future climate conditions presented as probabilities (e.g. temperature increase could be between 0.7°C to 4.4°C in the winter by 2070 (at the 10% and 90% probability levels), depending on emissions scenario (RCP2.6 to RCP8.5). further information about the UKCP18 use of the RCP can be found here: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance---representative-concentration-pathways.pdf

However, the UK Met Office have only released daily data for the RCP8.5 simulations. The snow model used in this study needed daily data.

Even if emissions ceased now, there will still be some locked in warming leading to some further climate change.

Climate scenarios other than the RCP8.5 used in this study have been generated for different emissions rates and associated temperature increases, but only the high emissions scenario is currently available for analysis of daily data. Other RCP scenarios with lower climate forcing (RCP1.9. 2.6, 4.5 and 6.0), represent lower rates of global warming that might result in lower levels of risk to PWS. These climate projections used are the best available for the UK and have been further assessed and improved through downscaling and bias corrected against long-term observed data to increase the spatial resolution (from 12 to 5km) (Rivington *et al.* 2008). This helps understand any biases that may impact use of the data and improves the utility of the projections.

Appendix II.1: Climate change terms and trends

Climate change. Climate change is the systematic, large-scale, long-term change in average weather and temperature patterns that have come to define Earth's local, regional and global climates (Met Office 2019). In the present day, climate change is anthropogenic (IPCC 2018) and the term is used interchangeably with the term global warming, i.e. the long-term heating of Earth's climate system observed since the pre-industrial period (1850-1900) due to human activities, primarily fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere. On a global level, average human-induced warming from pre-industrial levels to the decade 2006–2015 is assessed to be 0.87°C (likely between 0.75°C and 0.99°C) (Allen *et al.,* 2019). There is strong evidence that anthropogenic activity is driving rise in global and regional temperatures (Bindoff *et al.,* 2013), as well as global and regional scale rise in sea level, e.g. Church *et al.,* 2013; and atmospheric moisture content, e.g. Santer *et al.,* 2007) (see also Appendix II.2).

Predictions vs Projections. A distinction must be made between the climate predictions and climate projections (Kirtman *et al.,* 2013; IPCC 2018):

- A climate prediction refers to an event that is likely to occur based on what is known today and is an attempt to produce an estimate of the actual evolution of the natural climate in the future, for example, at seasonal, inter-annual or long-term time scales. Since the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. Climate predictions may also be made using statistical methods which relate current to future conditions using statistical relationships derived from past system behaviour. For decision makers, a prediction is a statement about an event that is likely to occur no matter what they do.
- The term forecast is related to climate prediction. Forecast quality measures the success of a prediction against observation-based information. Ensembles of individual forecasts can be used to predict the most probable outcome and to maximize forecast skill. For a decision maker, the credibility of the forecast depends critically on the credibility of the forecasting technique as well as on the inevitability of the event.
- Climate projections are assumptions that depend upon emission/concentration/radiative forcing scenarios, which are based on assumptions concerning, for example, future socioeconomic and technological development scenarios that may or may not be realised and are therefore subject to substantial uncertainty. Projections refer to the statement: "if these conditions develop, then this event could happen". These projections are often made with models that are the same as, or similar to, those used to produce climate predictions and forecasts. A climate projection is neither a prediction nor a forecast of what will happen independent of future conditions. For a decision maker, a projection is an indication of a possibility, and normally of one that could be influenced by the actions of the decision maker.

Science of attribution: detection and attribution of climate change impacts. Detection of impacts of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterises its behaviour in the absence of climate change (Stone *et al.,* 2013). "Attribution" addresses the question of the magnitude of the contribution of climate change to a change in a system (Cramer *et al.,* 2014). In practice, an attribution statement indicates how much of the observed change is due to climate change with an associated confidence statement and requires the evaluation of the contributions of all external drivers to the system change, such as solar variations, volcanic eruptions, natural modes of variability (e.g. El Nino Southern Oscillation or Atlantic Multi-Decadal Oscillation) and other confounding variables such as regional or local climatic variations and changes in land use (such as deforestation, urbanisation, agricultural development (Cramer 2014; Otto *et al.,* 2016; James *et al.,* 2019). We must also recognise the significant disparity between the vulnerability of countries, regions, and social groups, related to differences in adaptive capacity (Willbanks *et al.* 2007), which may also confound the impact of anthropogenic climate change in attribution studies (Otto *et al.* 2016; James *et al.* 2019).

Detection and Attribution of Observed Climate Change Impacts in Natural Systems. To respond to climate change, it is necessary to predict what its impacts on natural and human systems will be. As some of these predicted impacts are expected to already have occurred, detection and attribution provides a way of validating and refining predictions about the future (Cramer *et al.,* 2014). The detection in historical data of a climate-related shift in the availability of water resources would lend credence to this prediction, and the assessment of its magnitude would provide information about the likely magnitude of future shifts. Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands, including the UK, with different characteristics of change in different regions. On a global and regional level, changes in frozen components of freshwater systems and higher frequency of extreme phenomena (e.g. heavy rain or drought) tend to show much higher confidence in detection of change and attribution to anthropogenic climate change than components that are strongly influenced by non-climatic drivers, such as river flows, groundwater levels and water quality, which have very low confidence (Cramer *et al.,* 2014); see Appendix II.2. Detection and climate attribution of trends in atmospheric and hydrological variables across the UK are summarised in Appendix II.3.

Appendix II.2 Key global trends of climatic variables

Predicted impacts of climate change on water resources. Increased likelihood of more heat and high-precipitation extremes due to the thermodynamic consequences of a warming world are predictable, on average, in any specific location or circumstances (Otto *et al.* 2016). This is because warmer air can hold more water vapor (moisture) and causes more evapotranspiration, which is also affected by increasing atmospheric carbon dioxide levels, leading to changes in plant productivity and affecting plant transpiration and water available for river discharge and infiltration to the aquifer (Forkel *et al.,* 2016; Schulte-Uebbing *et al.,* 2015; Prudhomme *et al.* 2014; Herrera-Pantoja and Hiscock 2008). Thus, global warming accelerates the water cycle at global, regional and local scales leading to frequent periods of heavy rainfall and flooding interspersed by warm, dry periods and a shortened winter groundwater recharge season, soil moisture deficit, melting glaciers and to low river flows when population, crops and ecosystem needs for water are greatest (Watts *et al.* 2015; Herrera-Pantoja and Hiscock 2008; IPCC, 2012a, 2014; IPCC 2018[27]; Schewe *et al.,* 2014; Döll *et al.,* 2018; Prudhomme *et al.* 2014). This cascade of events increases the risk of water stress[28] and water scarcity[2] .

II. 1 Key observations on climate change-driven changes in the water cycle refer to:

- Globally and regionally (Cramer *et al.,* 2014):
- Meteorological variables:
    - High confidence of detection and attribution to anthropogenic climate change for increase in air and sea surface temperature, air moisture and frequency of heavy precipitation events and for reduction in annual snowfall.
    - Uncertainty (low confidence) over trends in annual precipitation and evapotranspiration.
- Hydrological variables:
    - High confidence of detection and attribution to anthropogenic climate change for lake and river ice duration or thickness in the Northern Hemisphere.
    - Medium confidence in detection of earlier timing (e.g. early spring) and decreasing magnitude of snowmelt floods but high confidence in attribution of these observations to climate change and especially to decreasing snow pack.
    - The role of climate change in river flows is uncertain, as trends of reduced flows in the world's major rivers and some parts of the world may reflect decadal climate variability and be affected by other confounding factors such as human alteration of river channels and land use.
    - Both increases and decreases in floods have been found (medium confidence in detection).
    - Since the 1950s some regions of the world have experienced more intense and longer dry periods, although a global trend currently cannot be established.
    - Changes in groundwater storage are generally difficult to attribute to climate change, due to confounding factors from human activities.
    - Confounding factors do not permit attribution of observed changes in water quality to climate.

27 This refers to evidence cited in Chapter 2.

28 See Box 1 in main document.

Appendix II.3 Trends in meteorological and hydrological variables in the UK

Variable	Observed trend	Confidence in detection	Confidence in attribution to anthropogenic climate change	Climate driver	Reference
Air temperature					
Precipitation	Little increase in rainfall totals in Scotland (1961-2000)	Significant	Insufficient evidence		Afzal *et al.*, 2015; Watts *et al.*, 2015; Garner *et al.*, 2017
	Increase in the magnitude of extreme rainfall events (maxima) in the north and especially Scotland (1961-2010)	Significant	Insufficient evidence		Prosdocimi *et al.*, 2014; Watts *et al.*, 2015; Garner *et al.*, 2017
	Increase in winter rainfall (amount and maxima) throughout the UK, with greatest change in Scotland (over the 20th century to 2010)	Significant	Insufficient evidence		Simpson and Jones 2014; Wilby and Quinn 2013; Watts *et al.*, 2015; Garner *et al.*, 2017
	Dry spells have been observed in both England and Scotland since the 1870s, and the longest dry periods are likely to become shorter and less severe but also less rare	Significant	Low	Natural climatic variability	Wilby *et al.*, 2015; Garner *et al.*, 2017
Potential Evapotranspiration (PE)	Increase in PE across the UK, annually and in spring	Significant	High	Decrease in relative humidity and increasing short and long wave radiation, especially in Spring	Robinson *et al.*, 2017 ; Kay *et al.*, 2013
River flow	High degree of seasonal variability in seasonal river flow trends (1969-2008)				Hannaford and Buys 2012
	Increase of winter runoff in upland and western areas	Significant	Insufficient evidence		Hannaford and Buys 2012
	Increase of autumn flows across the UK	Significant	Insufficient evidence		Hannaford and Buys 2012
	Decreasing spring flows since 1960	Weak trend	Insufficient evidence		Hannaford and Buys 2012
	No clear pattern for summer flows but some observations point to downward trends in south UK and upward trends in the north and west UK				Hannaford and Buys 2012; Prosdocimi *et al.*, 2014
	Increase in annual flow maxima in the north	Significant	Insufficient evidence		Hannaford and Marsh 2008; Prosdocimi *et al.*, 2014
	Despite many studies, there is no evidence for long-term increase in flood frequency potentially because of declines in snowmelt contributions to major floods and occurrence of flood-rich and flood-poor periods in the record				Watts *et al.*, 2015; Garner *et al.*, 2017
	Few studies on low flows and drought, generally been inconclusive showing marked spatial variation and interdecadal variability in long-term records of low-flow, with some droughts in the 19th century being longer and more severe than those of the 20th century.*				Watts *et al.*, 2015; Barker *et al.*, 2019
Groundwater levels	Decline at chalk aquifers (England)	Significant	Low to medium	Groundwater levels are linked strongly to water vapour transport and precipitation but England's chalk aquifers are also influenced by changes in abstraction and resource management	Jackson *et al.*, 2015;
	No systematic studies of change in non-chalk aquifers in the UK				Watts *et al.*, 2015; Garner *et al.*, 2017
River water temperature	Increase over recent decades across the UK	Significant	Low		Watts *et al.*, 2015; Garner *et al.*, 2017; Pohle *et al.*, 2018
Groundwater temperature	No systematic studies				
River water quality	Improved river water quality	Significant	Low		Watts *et al.*, 2015; Garner *et al.*, 2017
Groundwater water quality	Deterioration of groundwater quality since 1950s but further change will be linked to the degree of recharge	Significant	No link to climate change		Watts *et al.*, 2015; Garner *et al.*, 2017

Table II.3.1. Observed trend, confidence of detection, confidence in attribution to anthropogenic climate change and key climate driver of change for key meteorological and hydrological variables.

Appendix III. Hydrological drought generation and propagation

III.1 Meteorological drivers

The atmospheric processes that are the starting point of hydrological drought development are related to a prolonged precipitation deficiency which generates less input to the hydrological system. Precipitation deficiency in the UK can be caused by blocking high-pressure systems (blocks) (Fleig *et al.* 2010) and temperature anomalies which can both be associated with large-scale atmospheric or ocean patterns like ENSO, NAO, and sea surface temperatures (Kingston *et al.*, 2013).

High pressure blocks

Blocks are areas of high pressure (anticyclones) that remain nearly stationary and distort the usual eastward progression of atmospheric pressure systems*.* Blocking events cause cold spells, heat waves, and droughts because of the anomalous clear-sky radiative forcing (under the anticyclonic circulation) and horizontal thermal advection; additionally, in summers, subsidence at the blocks' central region contributes to surface warming (Nabizadeh *et al.*, 2019). Therefore, larger blocks are expected to lead to anomalous radiative forcing and subsidence over a greater area and thus likely extreme events (e.g. droughts) with larger spatial extents.

For most of the year, Euro-Atlantic blocks enhance the likelihood of heatwaves beneath the anticyclonic region in the summer and of cold spells equatorward and downstream of the high pressure block in winter and early spring (Brunner *et al.*, 2018). Exceptionally, high pressure blocks can persist for months around mid-summer, as in 1976 (Met Office n.d.), or from late spring to late summer, as in 2018, when May, June and July were dominated by high pressure near or over the UK (Kendon *et al.*, 2019). Local feedbacks from anomalies in soil moisture can clearly amplify the surface heat during summer blocks (Seneviratne *et al.*, 2010). It is not clear to what extent soil moisture feeds back to influence the blocking circulation pattern itself, although some studies report potential effects (Woollings *et al.*, 2018). Outside the blocked regions, the opposite effects can take place leading to, for example, abnormally high precipitation. Winter blocks may be associated with prolonged cold spells, as in March 2018 when a blocking high over Scandinavia lead to funnelling of bitterly cold air over the UK from eastern Europe/Russia (Kendon *et al.*, 2019).

Forecasting atmospheric blocking in weather and climate models remains a challenging task. One major contributing factor is the lack of a complete theory to explain the onset, persistence and decay of atmospheric blocking events (Woollings *et al.*, 2018). For example, the influence of large-scale circulation patterns on features such as block persistence and surface effects (e.g. precipitation and surface temperature) is not fully understood. However, some studies suggested that, on average, a decrease in solar activity can promote an increase in atmospheric blocking, as in March 2018 (Schwander *et al.*, 2017). Further, a recent study suggested that winter blocks are likely to get bigger due to climate change but understanding of summer blocks and how larger blocking events might affect the size, magnitude and persistence of extreme-weather events like heat waves needs further research (Nabizadeh *et al.*, 2019).

Temperature anomalies

Temperature anomalies leading to drought refer to phenomena such as prolonged freezing conditions in winter in snow-dominated catchments (van Loon and van Lanen, 2012), or low temperatures in summer in glacier-dominated catchments (van Loon *et al.*, 2014). However, flow seasonality in Scotland is generally dominated by rainfall rather than snowmelt (Ferguson 1984; Hannaford and Buys 2012). Only alpine catchments in the Scottish Highlands experience substantial snow accumulation in most winters, although there is large variation (Kay 2016). It has been shown that patterns of snow accumulation and snowmelt can strongly influence the hydrology of alpine streams leading to low baseflow (i.e. the portion of the river discharge that is sustained between rainfall events or during prolonged dry weather, fed to streams via springs and seepages by natural discharge of groundwater from an aquifer) during cold periods of snow accumulation and snowmelt in early spring (Soulsby *et al.*, 1997) and low flows in the absence of a substantial snow pack in mild winters (Helliwell *et al.*, 1998). Snowmelt in Scotland affects seasonal river regimes mainly in rivers in the east and north-east of Scotland having their head waters in the Cairngorms (i.e. the rivers Spey, Dee, Don, Sourth-Esk (Clova), Prosen Water, West Water and the Tay and its tributaries Garry and Tilt), which may show a secondary maximum runoff in April when precipitation is least (Ferguson 1984).

Winter precipitation variation across Northern Europe, and by inference over Scotland, is strongly positively correlated with North Atlantic Oscillation (NAO) fluctuations (Rust *et al.*, 2018). Snowfall in Scotland generally occurs in distinct cold weather events interspersed by warmer periods when much of the lying snow can melt (Dunn *et al.*, 2001). Isolated and sheltered snow patches can also remain from one winter to the next (e.g. Cameron *et al.*, 2014). However, there is evidence of decreasing trends in long-term observations post-1969 of snowfall and snow cover at all elevations in the Cairngorms (Rivington *et al.*, 2019), with a significant decrease in the number of days with snow cover since the late 1970s (Harrison *et al.*, 2001). Climate model projections suggest a continuation of this trend in upland Britain (Kay 2016).

The question arises whether climate change will affect flow in the snow-affected catchments in Scotland. Changes in snow cover below the 600m elevation have occurred in conjunction with increases in precipitation between October and March, a marked spring warming, and a more frequent occurrence of heavy daily rainfalls and strong winds (Harrison *et al.,* 1999). In the UK, flow changes in small catchments heavily affected by declining snow cover are likely to involve increases in winter flow due to winter snowmelt and decreases in spring flow (Harrison *et al.,* 2001). The effect on catchments with more variable snow cover and on larger catchments is less clear, as is the effect on winter flooding and summer flows. For example, an analysis of long-term flow observations (i.e. 1929-2004) in the River Dee showed increases in spring flows and decreases in summer flows, coincident with seasonal rainfall trends, but the decrease in summer flows was considered to be linked to declining snow cover in the Cairngorms (Baggaley *et al.,* 2009). Snowmelt is however a key factor in flooding in late winter and spring on several rivers in Scotland (Black and Werritty 1997). Hannaford and Buys (2012) found that the Dee has higher spring flows because spring snowmelt from the Cairngorms can be a major flow regime component, whereas it is less important in the other upland sites. A study of the River Tay, Scotland, suggests that snowmelt was more influential in late winter floods in the 18th and 19th centuries than more recently (McEwen, 2006).

Reduced snow cover can also affect groundwater recharge. Upslope areas in upper latitudes of the Northern hemisphere are areas of transition to more freely draining soils that serve as groundwater recharge zones (Spence and Woo, 2003). Subsurface permeability and hillslope connectedness to riparian areas and the stream network are also important determinants of hydrological catchment response (Tetzlaff *et al.,* 2015). It must be also borne in mind that frozen soils before snow fall generally increase the amount of snowmelt runoff by decreasing soil permeability and thereby impeding infiltration to groundwater (Bayard *et al.,* 2005). This then leads to less recharge to the groundwater system, which can eventually enhance a summer drought in groundwater (see Appendix III.4: cold-snow season drought). However, evidence suggests that the effect of soil frost enhancing surface runoff during snow melt is limited, at least in forested catchments (Nyberg *et al.,* 2001).

III.2 Catchment factors and water storage

Current state for knowledge about the relationship between soil moisture and groundwater recharge in the UK.

Several stores (e.g., soils, groundwater, bogs, lakes and snowpack) control drought propagation (van Lanen *et al.,* 2013). The generic role of catchment stores can be described in the following series of events:

1. Below-normal precipitation (see Appendix III.3 for how precipitation at different seasons can affect drought propagation), often in combination with higher potential evapotranspiration (ET), causes depletion of soil moisture storage and lowers water levels in bogs lakes and reservoirs.

2. Low soil moisture eventually leads to lower than normal or negligible infiltration of water from the soil to the groundwater system, i.e. low or negligible groundwater recharge (Van Lanen *et al.,* 2004). In cold regions, drought can also occur due to either lower than normal temperatures (in particular longer periods below zero) or higher temperatures (periods above zero that normally are frost times), which is related to snow accumulation and melt (e.g., Van Loon *et al.,* 2011; Staudinger *et al.,* 2011; Van Loon and Van Lanen, 2012); see also Appendix III.1.

3. A hydrological drought develops when groundwater recharge is below-normal because it causes:

(i) Low water table levels (i.e. groundwater drought). Actual groundwater levels are dependent on the pre-event conditions and the rate of decline of the levels, which again depends on the amount of recharge and discharge and the storage characteristics of the aquifer (van Loon 2015).

(ii) Low river discharge in groundwater-fed rivers (i.e. river discharge drought). During drought the main contribution to discharge is via baseflow. The fast pathways that contribute to discharge during wetter periods (i.e. surface runoff, interflow) are usually limited during drought (van Loon 2015).

4. A hydrological drought will end when groundwater recharge returns to normal (or above normal) for a sufficient period of time. This can be triggered by rainfall or snowmelt (van Loon and van Lanen 2012; van Loon 2015).

Groundwater is largely recharged by winter precipitation after satisfying soil deficits and before they begin to develop again in spring as a result of a higher rate of evaporation (Arnell 1998). However, Yawson *et al.* (2019) found significant variations in potential groundwater recharge from spring barley crop fields between fourteen UK administrative regions and the high, medium and low emissions scenarios. They observed a decline in spring-summer groundwater recharge by 2030 only for Northeast and Northwest Scotland under the high emissions scenario whilst all areas of Scotland displayed increases in potential spring-summer recharge by 2030 over baseline values for the low and medium scenarios. While this shows the direction of travel for spring-summer groundwater recharge in Scotland towards increased recharge with important implications for management,[29] it provides no information about the actual groundwater storage, which takes longer to build up, or about the proportion of recharge needed for storage. Further studies are required to fully quantify the effect of precipitation, evapotranspiration, crop type and management, soil management and topographic changes on potential recharge throughout the year (Yawson *et al.,* 2019).

Studies of surface water-groundwater interactions at Eddleston catchment, Scotland, suggested that soil water storage in the catchment has the potential to buffer smaller volumes of rainfall infiltration, and that water transfer to the saturated aquifer and/or the river only occurs above a rainfall threshold (O'Dochartaigh *et al.,* 2012; Archer *et al.,* 2012). Improved grazed grassland was found to hinder rainfall infiltration, whereas the mature deciduous forest provided the best conditions for storing storm rainfall into deeper soil layers thus preventing sub-surface flow / interflow to the river (Archer *et al.,* 2012).

Prior international research suggests that groundwater response and not soil moisture determines the number and duration of droughts as well as the water volume deficit for catchments in the same climatic region (van Lanen *et al.* 2013; Peters *et al.,* 2003; Van Lanen *et al.,* 2004; Fleig *et al.,* 2006; Van Lanen and Tallaksen, 2007; Van Loon and Van Lanen, 2012). Here, we report the results of a modelling experiment by Van Lanen *et al.* (2013) using three different representative soil types[30] (covered with permanent grassland) with respect to soil moisture and three different aquifer types representative of fast, medium and slow response with respect to how long it takes an aquifer to naturally drain into streams. Modelling showed that:

(i) The number of droughts, duration and standardized deficit volume are hardly affected by the soil moisture for the selected moderately thick soil types. This finding can be explained by the limited impact of the selected soils on the temporal variability (intra- and interannual) of the modelled hydrographs. Types of soils not included in the modelling study by van Lanen *et al.* (2013) may give a different result. For example, hydrophobic soils or heavy clay soils with strong preferential flow, can generate a more irregular discharge (Bouma *et al.,* 2011), and, hence, might play a more prominent role on hydrological drought characteristics.

(ii) the responsiveness of groundwater systems had a large effect on drought characteristics.

a. Flashy hydrographs, associated with quickly responding groundwater systems, displayed a high number of drought events of short durations. For instance, the median number of droughts (D50) for a quickly responding groundwater system (high transmissivity[31]) was about three times higher than for a slowly responding system. It must also be noted that the standardized deficit volume of the quickly responding groundwater systems was about two and half times higher than that of the slowly responding system.

b. Hydrographs representative of slowly responding groundwater systems were rarer but lasted longer than flashy hydrographs. They were smooth, showing a delayed and attenuated response to rainfall or snowmelt. Further, differences in median drought duration were rather small (many minor droughts), but the lower number of droughts for the slowly responding system resulted in a duration that was about twice as long as for a quickly responding system.

Precipitation and surface runoff: an example from Scotland.

Afzal *et al.* (2015) projected changes in precipitation and evapotranspiration under climate change and their impacts on the reliability of six public water storage reservoirs and two public river intake schemes in Scotland are examined. A conceptual rainfall–runoff model was used to simulate catchment runoff which, together with evapotranspiration, served as inputs into a reservoir model. Outputs from a regional climate model coupled with a weather generator indicated an increase in rainfall variability and evapotranspiration throughout the 21st century. This resulted in a decrease in both the time-based and volumetric reliability of the reservoirs under the assumption of an unchanging demand. It was found that the variability of rainfall had the greatest effect on reservoir reliability, outweighing the positive effect of an increase in total annual precipitation, while evapotranspiration had a lesser impact. A more drastic reduction in reliability was observed for the river intake schemes given their lack of storage capacity. The increase in water demand based on demographic projections further reduced reservoir reliability, especially when monthly variations in demand were taken into account. Afzal *et al.* (2015) suggested adaptive strategies to deal with the projected changes in the public supply and demand for water.

A study on the effects of afforestation on runoff at the Monachyle basin (Highlands) – with an annual precipitation of more than 2000mm - showed that

29 For example, it might be necessary to reduce the magnitude or duration of soil saturation and mitigate flood risk (Yawson *et al.* , 2019).

30 They selected representative soils with a medium soil moisture supply capacity (light silty loam soil) and soils with low and high supply capacity, i.e., a coarse sandy soil and a sandy loamy soil, respectively).

31 Transmissivity refers to how much water can be transmitted horizontally.

afforestation resulted in minor changes in the low flow conditions, leading to an increase in drought duration by 10%, i.e. 10% more days with streamflow (Q) below normal (Q70).

Soil moisture and groundwater recharge-discharge in Scotland

As far as we know very few studies have examined the role of soil and by extention agricultural land use on groundwater storage and recharge in Scotland. For example, Hererra-Pantoja-Hiscock (2008) studied the effects of climate change[32] on potential groundwater recharge in Paisley in west Scotland and found that despite precipitation increases during the wet season in the 21st century, the potential groundwater recharge decreases steadily from 2011 to 2100 as a result of an increase in actual evapotranspiration and soil moisture deficit, particularly during the dry season. Further, drier summers leading to increased soil moisture deficit extending into the autumn will have the effect of shortening the winter recharge season, requiring recharge to occur during longer periods of steady rain rather than by the predicted short, intense rainfall events.

Groundwater in Scotland

In Scotland, groundwater provides baseflow to rivers and lochs throughout the year but is particularly critical in dry summers and in the east of Scotland where lochs do not provide significant alternative sources of water storage (O'Dochartaigh *et al.,* 2015).

- **Background.** Scotland's aquifers[33] vary markedly in their hydraulic characteristics, thickness, and extent. Some aquifers are capable only of supplying small amounts of groundwater, enough to support dispersed small domestic demand, whilst others can provide yields sufficient to supply towns such as Dumfries and Aviemore (MacDonald *et al.,* 2005). Some aquifers have large natural storage which can buffer low rainfall over periods of several months or years, whilst others cannot (MacDonald *et al.,* 2005; O'Dochartaigh *et al.,* 2015). The geological mapping DiGMapGB-50 dataset developed by the British Geological Survey forms the basis of aquifer productivity[34] (i.e. the potential of an aquifer to sustain various levels of groundwater flow and/or abstraction from a properly sited and constructed borehole), bedrock aquifer groups, superficial aquifer groups (aka 'drift' or Quaternary deposits), and subsequent groundwater body classifications, used for the management of the groundwater resources in Scotland. The maps use two key physical properties of aquifers (i.e. the dominant groundwater flow type in an aquifer, and the aquifer's potential for sustaining various levels of borehole water supply) to classify aquifers into three groundwater flow categories types:

- significant inter- granular flow (which is important in only a few sandstone formations);
- mixed fracture/intergranular flow (which characterises all superficial deposits); and
- fracture flow (which is important in bedrock aquifers).

Bedrock aquifers were grouped first according to their rock type: calcareous rocks; dominantly non-calcareous sedimentary rocks; and fractured igneous or metamorphic ('hard') rocks. All superficial deposit — or unconsolidated — aquifers in Scotland were deposited in the last 20 000 years during the Quaternary geological period, during and after the latter part of the last glacial period and are deposits of gravel and coarse sand, including alluvial sand and gravel, raised beach and blown sand deposits, and glaciofluvial sand and gravel.

Table III.1 presents information on flow paths of each aquifer group to inform assessments of vulnerability of PWS to drought. Analysis of transmissivity (see footnote 13), borehole yield[35] and specific capacity[36] on data from the Scottish Aquifer Properties Database showed that aquifers of Quaternary and Permo-Triassic age are the most productive in Scotland, followed by those of Carboniferous and Devonian age (Graham *et al.,* 2009). O'Dochartaigh *et al.* (2015) report that aquifers of Pre-Cambrian (e.g. Aberdeenshire) and Silurian-Ordovician age as well as calcareous and volcanic igneous and mixed igneous-sedimentary aquifers have low productivity.

Spring-fed PWS were the most affected water sources during the Summer 2018 drought. Springs as sites of aquifer discharge are mainly associated with the following types of aquifers: Silurian and Ordovician, Calcareous, Volcanic igneous and mixed igneous-sedimentary aquifers.

32 A regional climate model was used as an input to a stochastic weather generator, the results from which were incorporated in a soil moisture balance model that considered crop characteristics and hydrogeological conditions.

33 A geological formation that is sufficiently porous and permeable to yield a significant quantity of water to a borehole, well or spring. The aquifer may be unconfined beneath a standing water table, or confined by an overlying impermeable or weakly permeable horizon. In Scotland, due to its particular geological history and to its rainfall, all rock types and most unconsolidated superficial deposits can be aquifers. Groundwater that can be abstracted for human use therefore occurs underneath most of Scotland. Source: O'Dochartaigh *et al.* , 2015.

34 A dataset describing the potential of bedrock aquifers across Scotland to sustain various levels of borehole water supply, and the dominant groundwater flow type in each aquifer was published under license by BGS on 1st April 2020 (BGS, 2020).

35 The volume of water pumped or discharged from a borehole, well or spring (O'Dochartaigh *et al.* , 2015).

36 The rate of discharge of water pumped from a borehole divided by the resulting reduction of the pressure head in a aquifer due to withdrawal of groundwater and the lower water level in the borehole (O'Dochartaigh *et al.* , 2015).

- Silurian and Ordovician aquifers: Springs can be found on hillslopes where relatively unimpeded recharge can take place through absent, thin, and/or permeable superficial deposits. (MacDonald *et al.*, 2008 cited in O'Dochartaigh *et al.*, 2015). They are found in Southern Scotland, their northern boundary being marked generally by the Southern Uplands Fault.
- Calcareous aquifers: Dissolution of the calcareous carbonate rock along fractures can produce secondary karstic permeability. Major springs can occur in areas where limestones show significant karst development and downstream of areas where superficial cover is absent, thin and/or permeable and therefore focused recharge through swallow holes and rapid flow paths can take place. Minor springs can be fed by the fracture system in areas of slow groundwater flow. Calcareous rocks occur within the Highlands as well as in the Appin (West Highlands), Argyll and Southern Highland Groups of the Dalradian Supergroup within the Precambrian South aquifer group (Strachan *et al.*, 2002 cited in O'Dochartaigh *et al.*, 2015).
- Volcanic igneous aquifers. Volcanic rocks in Scotland typically form low productivity aquifers, the main controls on aquifer permeability are the degree and nature of rock fracturing, and the degree of weathering along junctions between individual lava flows (O'Dochartaigh *et al.*, 2015). Recharge can take place through absent, thin and/or permeable superficial deposits. Springs are found where fracture zones meet ground surface highly fractured/weathered zones at junctions of lava flows. These formations support several notable abstractions for mineral water from Scottish volcanic rocks, and the aquifer is also used locally for PWS. A number of springs from Tertiary lavas in the Highlands, particularly on Skye, are used for public water supply.
- Mixed-igneous sedimentary rocks. Springs mainly occur at sites of volcanic rock within narrow, highly weathered, fractured zones where groundwater flow can be faster (O'Dochartaigh *et al.*, 2015). They are found in the south of Scotland.

There are very few studies on groundwater storage in Scotland, therefore it is difficult to infer the vulnerability of each aquifer type to a meteorological or hydrological drought. For example:

- Breccias in Permian age aquifers showed a limited groundwater storage (MacDonald *et al.* 2003), lower than that of Sandstone aquifers (MacDonald *et al.*, 2005).
- Studies on groundwater-surface water interactions at the Findhorn catchment revealed the complex role of groundwater on the catchment hydrology (MacDonald *et al.*, 2014). For example, groundwater level response to rainfall and river stage varied across the floodplain: there was close coupling to river stage within 250 m of the river, a delayed integrated response to river and rainfall in the centre of the floodplain, and a rapid response to intense rainfall events (daily totals >30 mm) at the edge of the floodplain, close to the surrounding hillslopes.

Table III.2.1. Summary of aquifer characteristics, i.e. flow type, aquifer productivity, flow path length, groundwater age and permeability. Modified from: O'Dochartaigh et al., 2015.

Aquifer	Dominant groundwater flow type	Dominant aquifer productivity	Dominant1 groundwater flow path length	Dominant groundwater age	Dominant overlying strata
Permo-Triassic	Significantly intergranular (sandstone); Fracture (breccia)	Moderate to very high	1 km + Geological control usually dominates over catchments	Years to millennia	Variable.
Carboniferous – not extensively mined for coal	Fracture (minor intergranular), except Passage Formation – significantly intergranular	Moderate (except Passage Formation) to high	1–10 km Geological control usually dominates	Years to millennia	Generally thick and low permeability.
Carboniferous – extensively mined for coal	Fracture (minor intergranular) and through mined voids	Moderate	1–10 km Dominated by impacts of historical mining	Months to millennia	Generally low permeability. Thick in valleys, thinner elsewhere.
Old Red Sandstone North	Fracture (minor intergranular)	Low to high	1 km + Usually follows main river body catchments	Decades to centuries	Variable: thick and low permeability in Caithness; generally higher permeability elsewhere.
Old Red Sandstone South	Fracture (minor intergranular)	Moderate to very high	1 km + Usually follows main river body catchments	Decades to centuries	Generally thick, moderate to high permeability
Silurian-Ordovician	Fracture	Low	0.1–1 km + Usually follows local surface water catchments	Years to centuries	Thin, low permeability on hillslopes; thicker and permeable in valleys.

Table III.2.1. Summary of aquifer characteristics, i.e. flow type, aquifer productivity, flow path length, groundwater age and permeability. Modified from: O'Dochartaigh et al., 2015.

Aquifer	Dominant groundwater flow type	Dominant aquifer productivity	Dominant1 groundwater flow path length	Dominant groundwater age	Dominant overlying strata
Precambrian North	Fracture	Very low to low	-1 km Usually follows local surface water catchments	Years to decades	Thin, low to moderately permeable on hillslopes; thicker and permeable in valleys.
Precambrian South	Fracture	Very low to low	0.1-1 km Usually follows local surface water catchments	Years to decades	Thin, low-moderately permeable on hillslopes; thicker and permeable in valleys.
Igneous Volcanic	Fracture	Low	0.1-1 km Usually follows local surface water catchments	Months to decades	Generally thin or absent.
Igneous Intrusive	Fracture; sometimes weathered intergranular	Low	100s m Usually follows local surface water catchments	Years to decades	Generally thin and permeable, or absent.
Igneous/ sedimentary	Fracture (minor intergranular)	Low to moderate	0.1-1 km + Sometimes geologically controlled	Years to centuries	Variable, generally low to moderate permeability.
Shetland low permeability	Fracture	Very low to low	0.1-1 km Usually follows local surface water catchments	Years to decades	Generally thin and low permeability.
Ayrshire basic	Fracture	Very low to low	0.1-1 km Usually follows local surface water catchments	Years to decades	
Superficial aquifers	Intergranular	Moderate to high	0.01-1 km Usually follows main river body catchments	Weeks to years	Generally absent.

III.3 Hydrological drought typology based on generation processes and propagation characteristics

Here we summarise the findings of peer-reviewed research on drought typology based on the review by: van Loon and van Lanen, 2012; van Lanen *et al.,* 2004; Van Loon *et al.,* 2010; Bierkens and van den Hurk (2007); Marsh *et al.* (2007); Van Loon *et al.* (2011).

Classical rainfall deficit drought. This type of drought is the most common around the world. It is caused exclusively by a prolonged lack of rainfall (meteorological drought) that propagates through the hydrological cycle and develops into a hydrological drought. It can occur in any season and catchment type (quickly or slowly responding), and in any climate region, as long as precipitation falls as rain and not as snow (see below for snow-related droughts). Classical rainfall deficit drought can have any possible duration. Its hydrological deficit volume depends on the: (i) rainfall deficit (one or pooled periods of lack of rainfall); and (ii) level of water storage in the catchment before the onset of a period of no rain (meteorological drought). Propagation features such as pooling, lag, attenuation, and lengthening depend on catchment characteristics; see Section 3.3 this report.

Rain-to-snow season drought. This type of drought starts as rainfall deficit (meteorological drought) usually in the season in which groundwater recharge normally takes place (usually autumn but also summer), resulting in deficits in soil moisture and groundwater storage. It ends with snowfall because temperature has dropped below zero usually in the winter. Therefore, the initial value of the winter baseflow (i.e. the portion of the streamflow that is sustained between rainfall events fed to streams by delayed subsurface runoff) is lower than normal and groundwater storage and river discharge stay below the threshold level until the snow melt peak of the next spring. Durations of rain-to-snow-season hydrological droughts are long and deficit volumes can be high (partly due to the long durations). Lengthening is the main drought propagation feature defining rain-to-snow season droughts. Other drought propagation features also occur (e.g. pooling and lag), but are less important. This type of drought occurs in catchments with a clear snow season, which can be catchments at high latitude or high elevation. These catchments have a low-flow season in winter due to the continuous snow cover that hampers recharge.

Wet-to-dry season drought. This type of drought is governed by the same principle as the *rain-to-snow-season drought*, but instead of a snowfall deficit, it is associated with a very high potential evaporation (PE) in the dry season. This drought is caused by a rainfall deficit (meteorological drought) in the wet season (usually winter) that continues into the dry season (usually summer). This prevents soil moisture and groundwater stores from being replenished by recharge in the wet season/winter. The meteorological drought ends with precipitation, which is completely lost to evapotranspiration because PE in this dry season/summer exceeds precipitation. Therefore, the initial value of summer groundwater levels is lower than normal and groundwater storage and discharge stay below the threshold level until the next wet season. Wet-to-dry season drought occurs in catchments with

a clear wet and dry season, e.g. monsoon climatic regions and the Mediterranean. This type of drought is not further discussed here.

Cold-snow season drought. This type of drought is caused by a low temperature in the snow season. In catchments with a very cold winter, subtypes A and B occur, which are caused by an early beginning of the snow season and a delayed snow melt, respectively. In catchments with temperatures around zero in winter, subtype C occurs, which is caused by a lack of recharge due to snow accumulation. Here, we focus on type C because it is more relevant to the Scottish context, as explained in Appendix III.1. Subtype C cold-snow season drought occurs in catchments and climates where the snow season normally provides recharge to the groundwater system, due to occasional and partial melt of the snow cover. So, the normal winter situation is one of increasing storage and discharge. If, however, winter temperatures decrease to values well below zero and no melting of snow takes place, recharge decreases to zero. If low temperatures persist, a river and groundwater hydrological drought can develop before summer. A cold-snow season drought-subtype C typically has a duration of a few weeks to months. Again, drought propagation features are not applicable, although the reaction of groundwater can be different from that of river discharge, which can be delayed (lag) and attenuated.

Warm snow season drought. This type of drought is caused by a high temperature in the snow season. In catchments with a very cold winter (cold climates), subtype A occurs, caused by an early snow melt. In catchments with temperatures around zero in winter and some snow accumulation (temperate climates), subtype B occurs, and caused by a complete melt of the snow cover in combination with a subsequent rainfall deficit. Here, we are reporting on the characteristics of subtype B because it is more relevant to Scotland (as explained in Appendix III.1).

- Subtype B (aka Type 2 winter drought) : In catchments potentially influenced by this subtype the snow season normally provides recharge to the groundwater system, due to occasional and partial melt of the snow cover (see Appendix III.1). If, however, winter temperatures rise above zero and the snow cover melts completely, no snow store is left that can provide recharge. If, at the same time, a meteorological drought occurs, a hydrological drought can develop in late winter -early spring and can continue into summer. Durations can be long and deficit volumes high. Warm snow season droughts-subtype B can show all propagation features (i.e. pooling, lag, attenuation, and lengthening), mainly dependent on catchment characteristics.

Composite drought (multi-year drought). This type of drought is caused by a combination of hydrological drought events (of the same or different drought types) over various seasons and can occur in all climate types, but are most likely in (semi-)arid climates due to irregular rainfall patterns and in slowly responding catchments. A composite drought combines a number of drought generating mechanisms. In this hydrological drought type, a number of drought events (of the same or different type) in distinct seasons cannot be distinguished any more. The main feature of the composite drought is that the system has not recovered from a hydrological drought event, when the next event starts. Composite droughts only occur in catchments with considerable storage. This storage can be in e.g. aquifers, bogs, or lakes. The drought types that are combined differ per catchment and climate zone. Composite droughts have long to very long durations (often multi-year) and deficit volumes are high. The main drought propagation feature defining composite droughts is pooling, and this type of drought is especially displayed as groundwater drought and less as a river drought.

Appendix IV. Evidence on historical hydrological drought events.

IV.1 Timeline of meteorological and hydrological droughts in Scotland

Gosling *et al.* (2012) compiled a timeline of historic droughts and impacts, which is mainly based on anecdotal information, but also drawing on other peer reviewed literature, where available, grey literature and datasets. The drought catalogue is shown in Table IV.1.

Table IV.1.1. A drought timeline for Scotland from 1666 to present

Year	*Period*	*Description of drought*	*Location of impacts*	*Citation*
1666	May to mid-July	"phenomenal dryness"	England Wales and Scotland	Chronicle of the Frasers cited in CBHE*
1826	July - August	Extraordinarily dry and hot	Widespread. From Isle of Bute, to Tayside and Aberdeenshire	CBHE
1871	Not known	High rainfall deficiency index	Scotland	Marsh and Lees 1985
1887	Not known	"The capacity of those schemes which were in operation during 1887 was more severely taxed than in those of forty subsequent years".	NW England and Scotland	Brooks and Glasspoole (1928)
1902	Winter/Spring	"The lack of rain in the winter months began to be felt, the ground being very dry and the springs low."	Aberdeenshire	CBHE
1913	July to October	"Glasgow has only 77 days' water supply, the river Tay has reached the lowest level on record "".	Glasgow, Rivers Tay and Garry	Colonist, Volume LV, Issue 13808, 23 August 1913, Page 13808, 23 August 1913, Page 5
1933/4	Annual	Low rainfall totals across much of the UK	England Wales and Scotland	CBHE
1941	Spring/Summer	The January to June rainfall totals for Scotland in 1941 remained the lowest on record until 2010	Scotland	Source unknown
1955	Summer	Very sunny and hot during July and August	Scotland	Marsh and Lees 1985
1959	Summer	Gladhouse Reservoir was almost dry and standpipes were in use widely across Clackmannanshire.	Forth river basin	Pathe News 1959
1975/6	Peaking in summer 1976	Hot dry summer following 18 months of below average rainfall	South East Scotland	Rodda and Marsh 2011
1984	April to September	Considered an extremely severe drought with rainfall averages typically less than 70% of the LTA	Dumfries and Galloway, the eastern Cheviots, the Clyde Valley and Tayside	Marsh and Lees 1985
1995	April to August	Rainfall 68% of LTA	Highland and also Lothian Rivers	Marsh 1996
2003/4	Summer 2003 but extending to 2004 in E Scotland	Long-term rainfall deficiencies over this period were almost the lowest on record for many of catchments in North West Scotland.	Scotland and in particular Angus, Tayside and Dundee	Scottish Water 2005
2008	May and June	Very low rainfall and river flows	NW Highlands, Skye and the Western Isles	Scottish Water 2008
2010	May and June	Low rainfall during preceeding winter followed	Southern and Central Scotland	Scottish Water 2010

IV.2 Catchments with historical and current water quantity issues

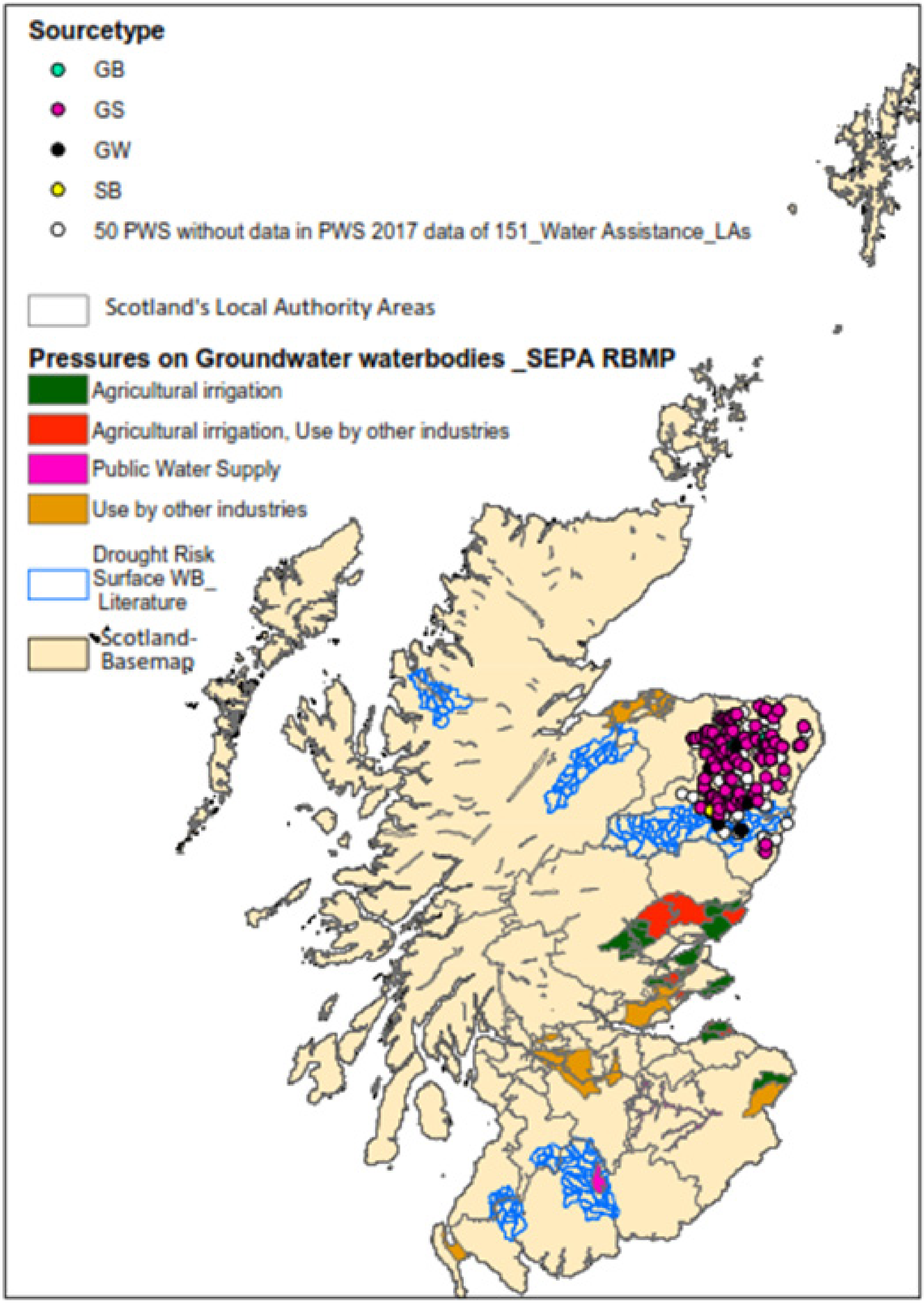

Figure IV.2.1. Surface waterbody catchments where historical river droughts had been evidenced (Wilby et al., 2015) in relation to anthropogenic pressures on groundwater water bodies and the location of PWS that required assistance during Summer 2018.

IV.3. Distribution of PWS by type of source in each Local Authority area.

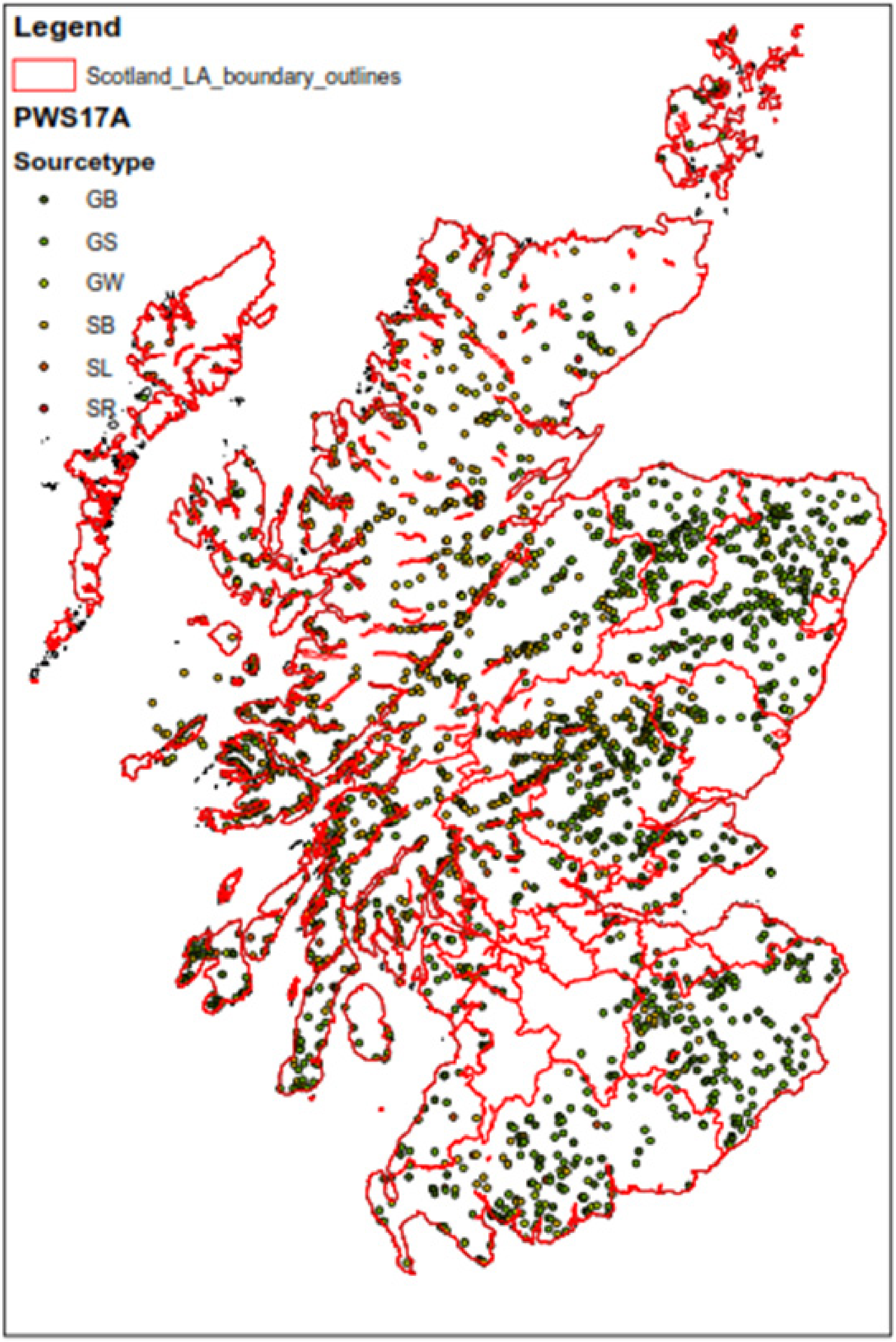

Figure IV.3.1. Distribution of PWS by type of source in each Local Authority area (Year 2017-18).

Appendix V. Hydrological drought indices and research questions

V.1 Summary of hydrological drought indices, their use and characteristics

Table V. 1. Indicators and indices applied for developing hydrological drought indices. Modified from: Svoboda and Fuchs 2016.

Hydrology	*Ease of use*	*Input parameters*	*Additional information*
Palmer Hydrological Drought Severity Index (PHDI)	Yellow	P, T, AWC	Serially complete data required
Standardized Reservoir Supply Index (SRSI)	Yellow	RD	Similar calculations to SPI using reservoir data
Standardized Streamflow Index (SSFI)	Yellow	SF	Uses the SPI program along with streamflow data
Standardized Water-level Index (SWI)	Yellow	GW	Similar calculations to SPI, but using groundwater or well-level data instead of precipitation
Streamflow Drought Index (SDI)	Yellow	SF	Similar calculations to SPI, but using streamflow data instead of precipitation
Surface Water Supply Index (SWSI)	Yellow	P, RD, SF, S	Many methodologies and derivative products are available, but comparisons between basins are subject to the method chosen
Aggregate Dryness Index (ADI)	Red	P, ET, SF, RD, AWC, S	No code, but mathematics explained in the literature
Standardized Snowmelt and Rain Index (SMRI)	Red	P, T, SF, Mod	Can be used with or without snowpack information

Key

Input parameters (indicators)

AWC: available water content

SF: streamflow

RD: Reservoir storage

S: Snowpack

Mod: Modelled data

ET: Evapotranspiration

P: Precipitation

T: Temperature

GW: Groundwater

Ease of use:

Yellow: Indices are considered to be yellow if one or more of the following criteria apply:

- Multiple variables or inputs are needed for calculations
- A code or program to run the index is not available in a public domain
- Only a single input or variable may be needed, but no code is available
- The complexity of the calculations needed to produce the index is minimal

Red: Indices are considered to be red if one or more of the following criteria apply:

- A code would need to be developed to calculate the index based upon a methodology given in the literature
- The index or derivative products are not readily available
- The index is obscure index, and is not widely used, but may be applicable
- The index contains modelled input or is part of the calculations

V.2 Research questions about the impact of drought on small rural supplies

Specific questions that may inform policy include (see also van Loon et al., 2016b):

- Drivers of drought:
  - To what extent can observed historic drought events be attributed to different drivers?
  - What are the dominant drivers of drought in different parts of the Scotland?
  - What are the implications for management for climate-induced, human-induced and human-modified droughts?
  - What is the most common and most severe type of hydrological drought (i.e. river or groundwater) in each region of Scotland?
- Human influences on the prevention, exacerbation or management of hydrological drought:
  - How do human interventions or modifications of drought enhance or alleviate drought severity?
  - How do we predict drought development, severity and recovery in human-influenced areas, taking into account relevant human drought modifiers?
- Collecting data on the impacts of hydrological drought:
  - o How should drought impacts be monitored and quantified?
  - o How do they depend on the physical characteristics of drought vs. the vulnerability of people or the environment?
- Modelling drought propagation, severity and recovery:
  - o Are there common responses of different catchments to different drought event typologies?
  - o To what extent are natural and human-influenced and induced drought processes coupled, and can feedback loops be identified and altered to lessen or mitigate drought?
  - o What are the links between practices of drought mitigation and alleviation in the context of PWS?
  - o What is the role of technology in current routines of water provision in rural areas?
  - o Are there tipping points in rural water use, e.g. build-up of large numbers of boreholes, abstraction for irrigation etc.?
- Drought awareness
  - o What are the reasons for a lack of public awareness of drought risk in view of climate projections and environmental water demands?
  - o What is the best approach to raising public awareness among PWS users about drought risk?
- Identifying "normal" in a constantly changing world:
  - o Is the normal situation actually changing or do we not have the data or understanding of natural variability to say anything about what is normal?
  - o How do long-term human influences on the water cycle change the normal situation?
  - o Would rural communities adapt to changes in the normal situation so that more severe droughts might lead to less impact in the future?
  - o How should we adapt our drought analysis to accommodate changes in the normal situation?
  - o Are current drought indices sufficient to identify risk from different types of droughts?

Appendix VI: 2018 anomaly maps

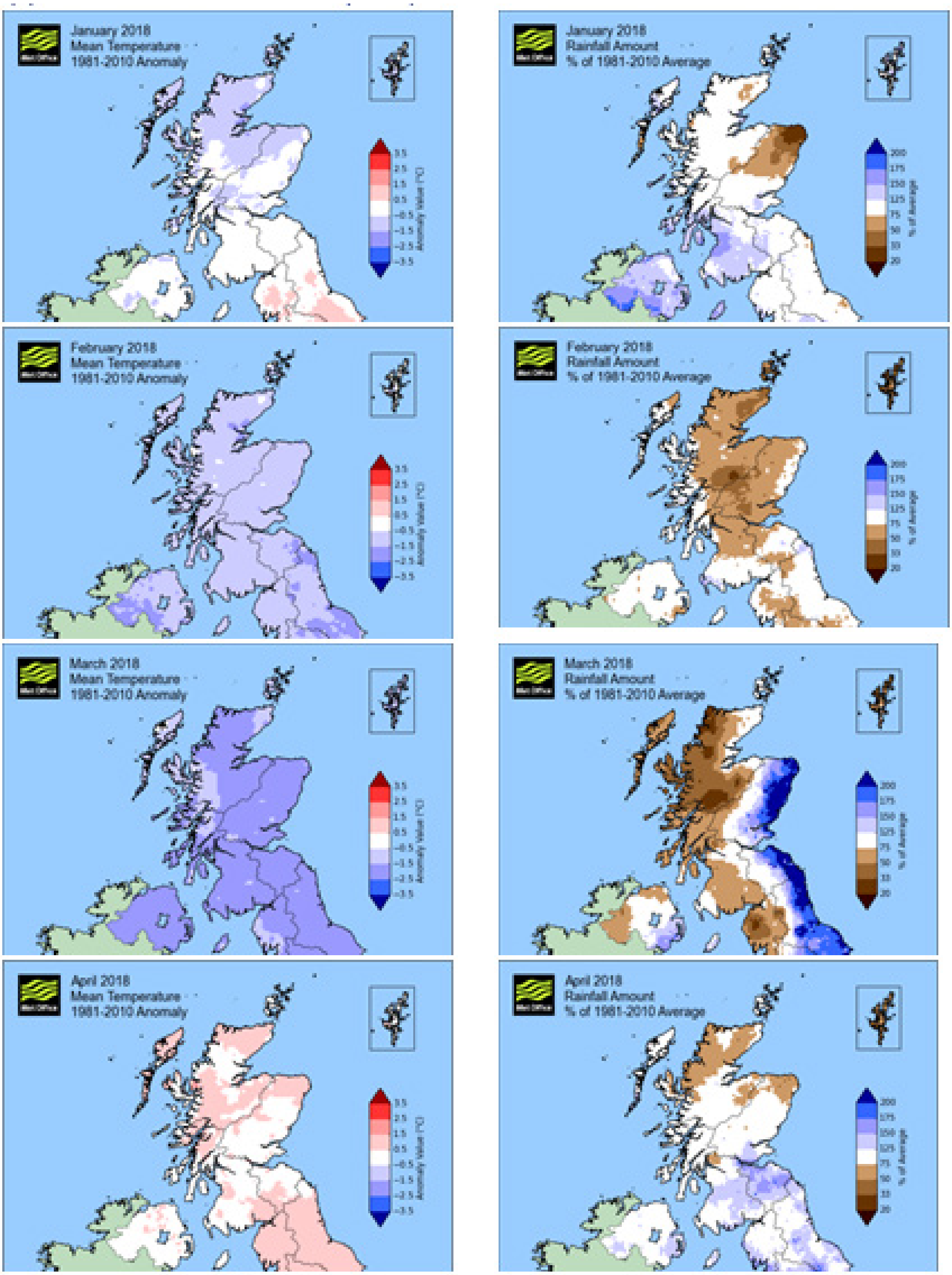

Figure VI.1a Mean temperature and rainfall anomaly maps for January – April 2018 (1981-2010 anomaly)

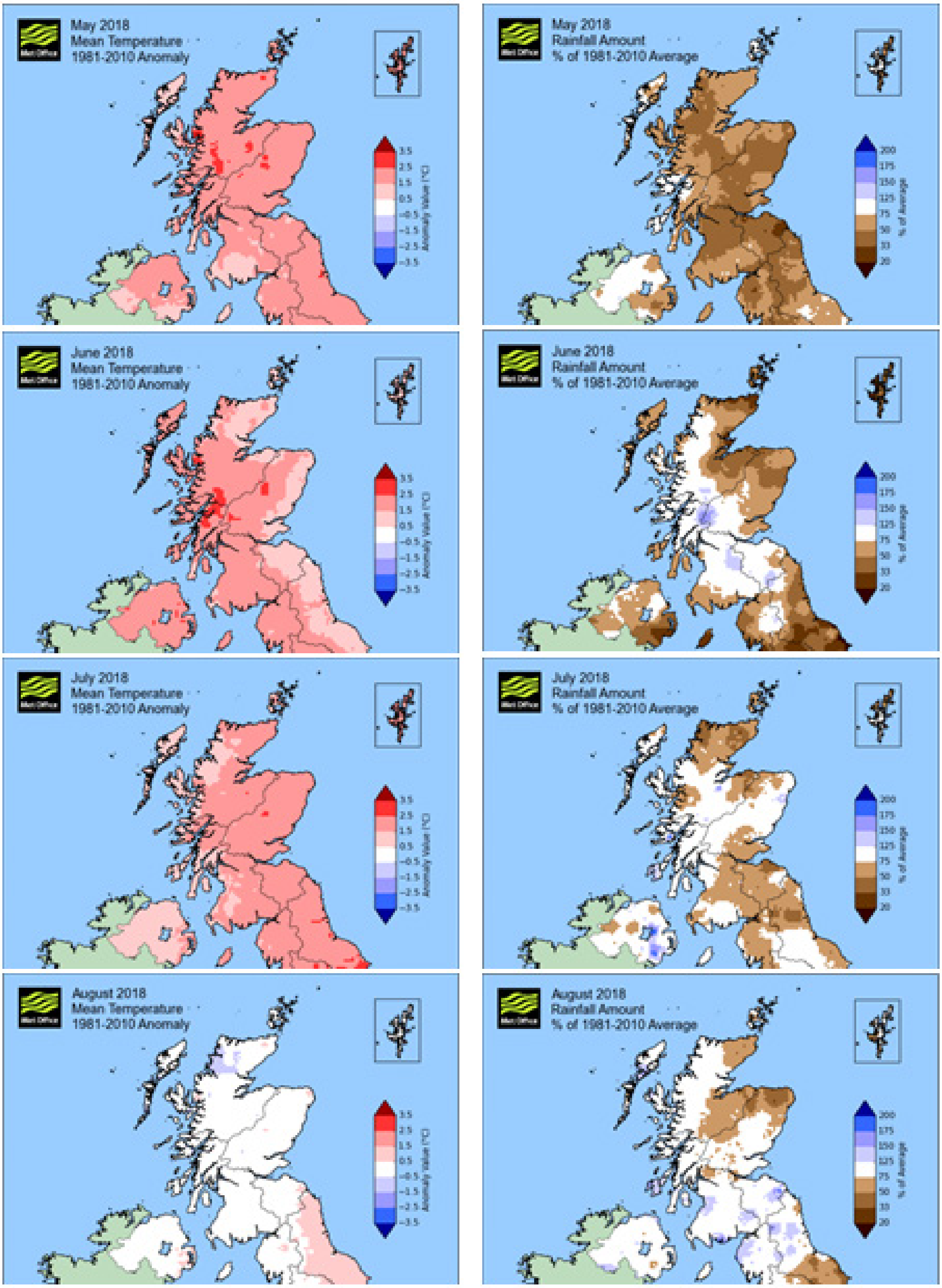

Figure VI.1 b Mean temperature and rainfall anomaly maps for May - August 2018 (1981-2010 anomaly)

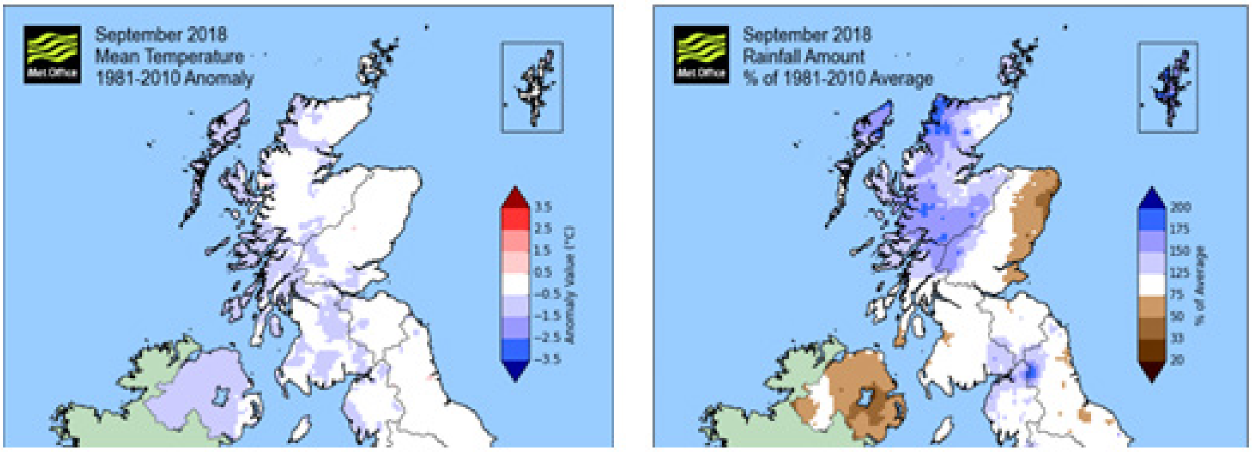

Figure VI.1c. Mean temperature and rainfall anomaly maps for September,

Appendix VII: Additional indicators of future change

The information below provides additional evidence as to how climate changes may affect water availability and input into PWS. The information is based on using the same observed and climate projection data as above applied to estimate and map a series of indicators based on analysis of weather data and communicated as maps (referred to as spatial Agrometeorological Indicators).

The Plant Heat Stress Indicator looks at the number of days in a year when the maximum temperature is above 25°C – the temperature generally considered to indicate when crops may experience heat stress that may affect growth and implies additional water requirements. The maps show the average number of days above 25°C. There has been a small increase in days when the temperature exceeded 25°C in the past, and this trend is projected to continue in the future. Currently the projections are for. 8-9 days increase, primarily in the lowlands (see Figure VII.1). Whilst not a substantial increase, this does indicate an overall warming trends that will increase evaporative loss from ground surfaces, thus reducing water available for infiltration to ground water or to feed springs from which PWS are sourced.

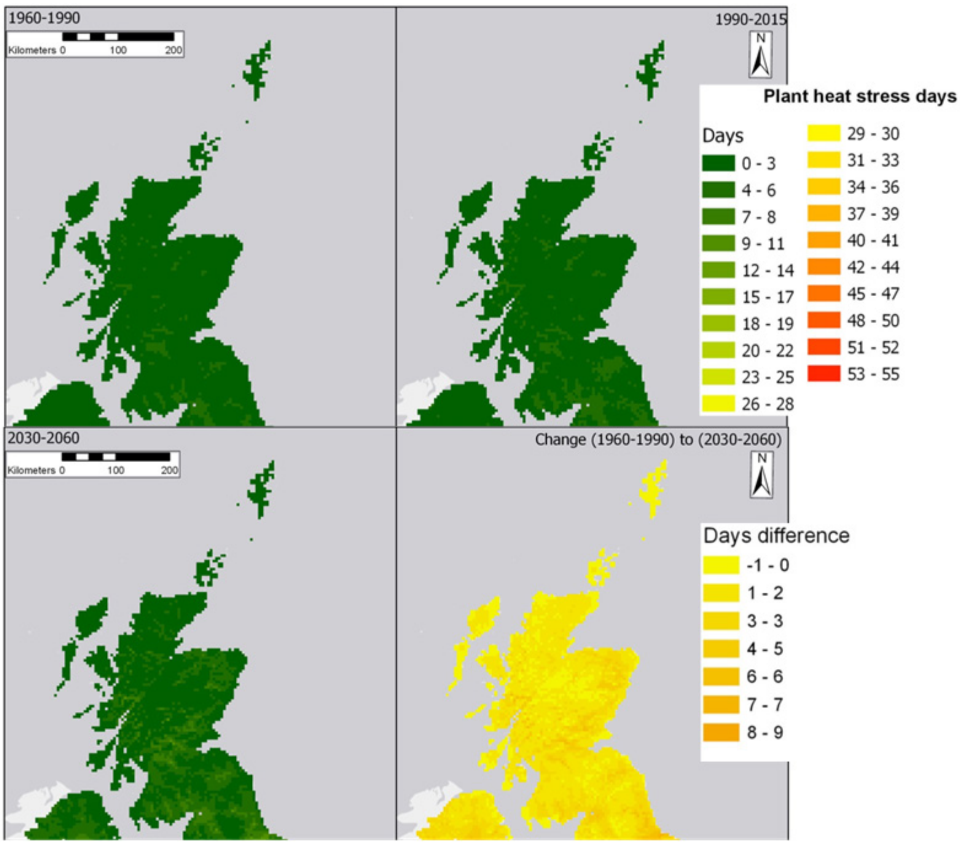

Figure VII.1. Plant Heat Stress Indicator (average count of days per year above 25°C) for the observed periods 1960-1990 and 1990-2015, and projected for 2030-2060 and difference between 1960-1990 and 2030-2060.

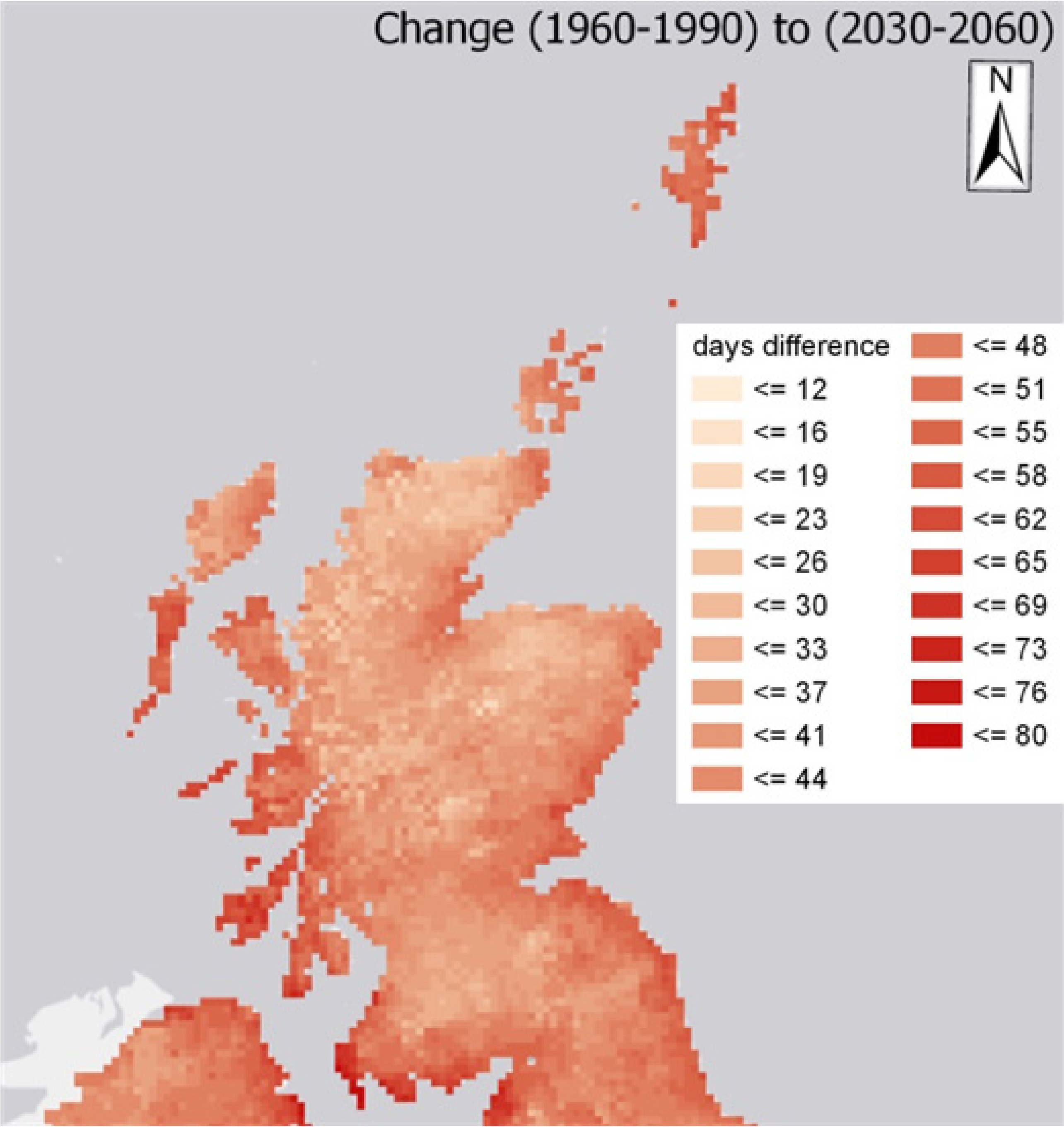

Figure VII.2. Heatwave Indicator difference map: estimate change between observed (1960-1990) and projected future (2030-2060).

Heatwave: The Heat Wave Indicator is the maximum temperature above the average maximum temperature (1960-1990 period) and an additional 3°C for at least 6 consecutive days. There has been an observed trend towards an increase in the number of heatwave days since 1960. This is projected to continue in the future (Figure VII.2), particularly on the west coast areas. These results imply an increased rate of evaporation over longer periods of time.

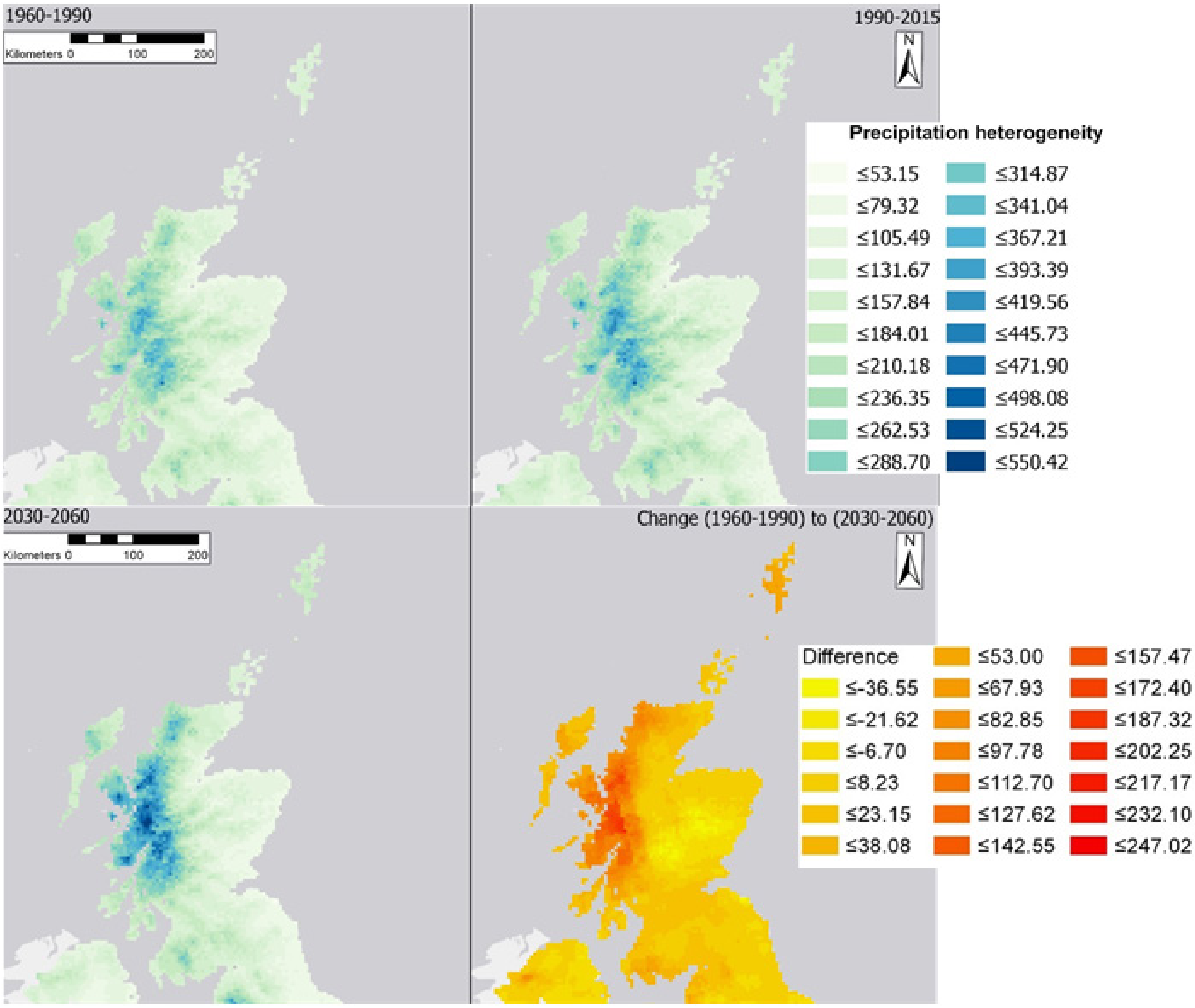

Figure VII.3. Precipitation Heterogeneity Indicator for the observed periods 1960-1990, 1990-2015 and projections for 2030-2060, and changes between 1960-1990 and 2030-2060.

Precipitation heterogeneity: The Precipitation Heterogeneity is a unitless Indicator and provides information about the erosivity of rainfall, which is more intense where there are high values (due to monthly precipitation concentration and total annual amounts). This tends to match spatially with rainfall total amounts and elevation. The maps in Figure VII.3 show this, with upland areas having higher indicator values. There has been some increase since the 1960-1990 period, with the north-west coastal areas of Scotland projected to have the largest increases but south-eastern Highlands may see a rain shadow effect giving a slight decrease in indicator values. The projected future increase in the Indicator implies more intense rainfall events and associated higher risks of erosion.

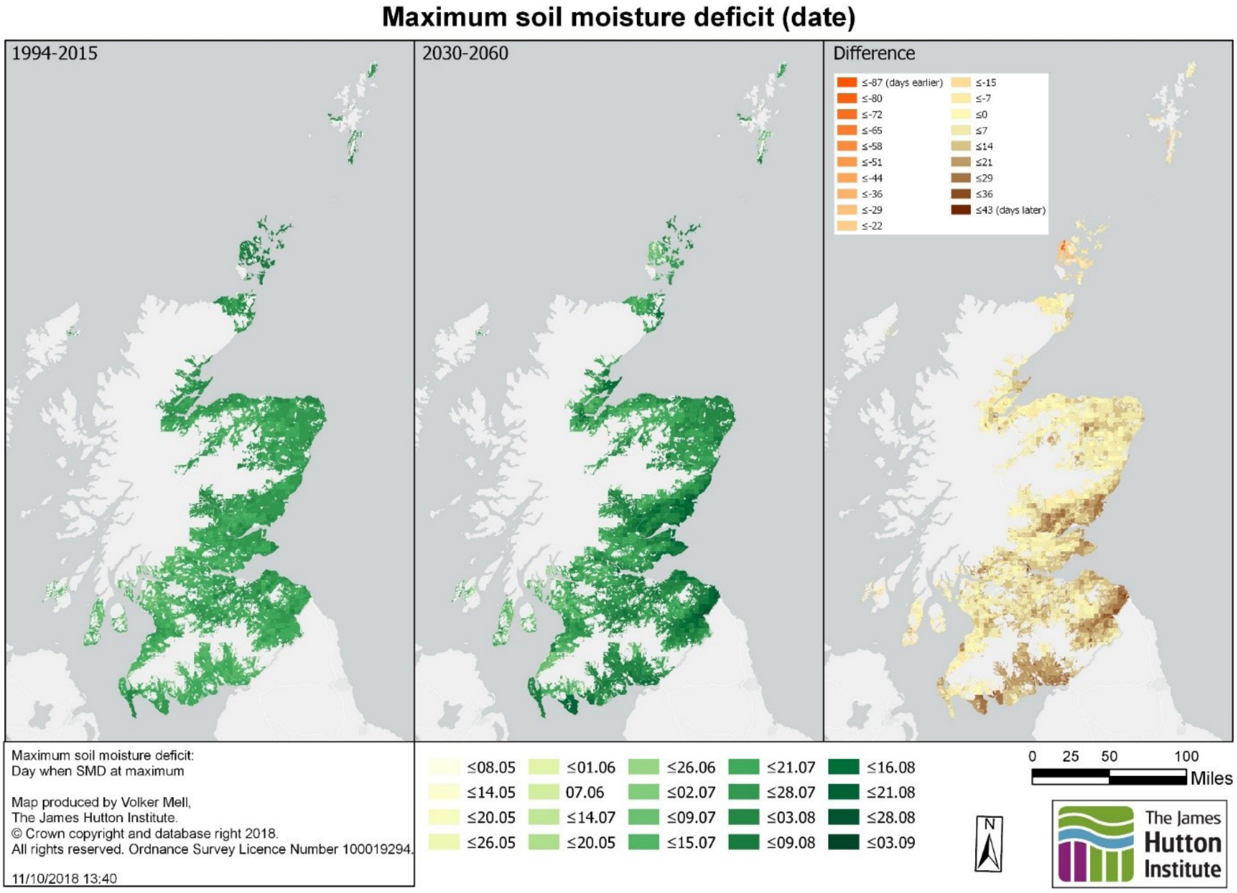

Figure VII.4. Date of maximum soil moisture deficit for the observed period of 1994-2015 and projection for 2030-2060 and changes between the periods.

Date of maximum soil moisture deficit: This Indicator tells us the day when the soil reaches its driest amount. The maps in Figure VII.4 show that in general the future date is estimated to occur at similar times to the present or later in the year (c. 30 days in some cases), varying with soil types. This is likely to be due to continued soil moisture loss from evapotranspiration and reduced summer period rainfall. A few soils (e.g. in Orkney) show an earlier date, possibly due to earlier and higher rates of soil water demand by crops. Note: these results are for arable and surrounding areas only and are derived from the spatial application of a crop simulation model (estimating the response of barley to climate change using soil series data and the UKCP09 climate projection data).

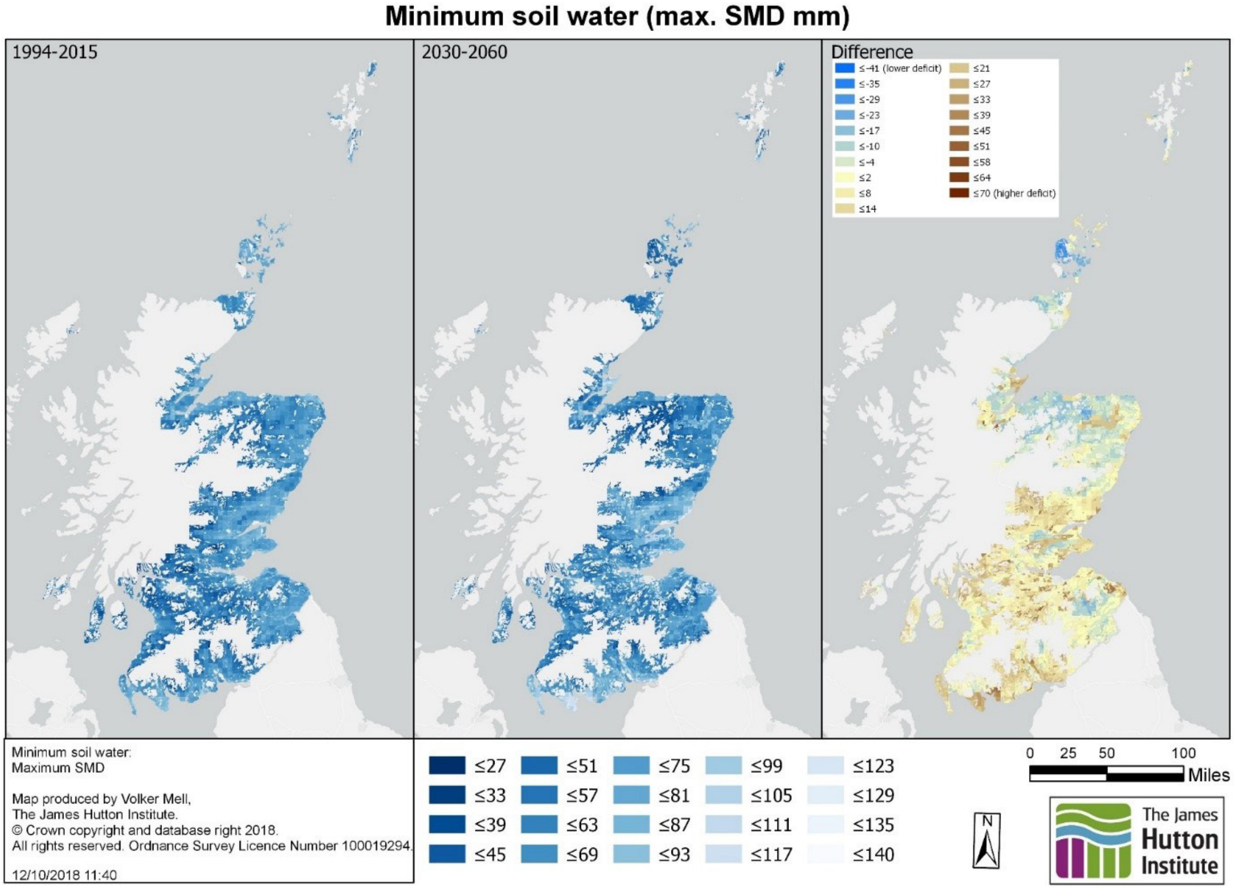

Figure VII.5. Minimum Soil Water (mm) for 1994-2015 and 2030-2060 periods and changes between them.

Minimum soil moisture amount: The Minimum Soil Water Indicates tells us how dry a soil may become. It is the maximum soil moisture deficit (SMD) value, with a higher deficit meaning that the soil becomes drier. Conversely a lower deficit means there is more water available in the soil. The change map in Figure VII.5 shows that generally soils show a range of higher, little or no change, or lower deficit responses, vary with soil type. Soils of a similar type (e.g. brown forest soils) with similar properties can have either higher or lower deficits, indicating that the change is climate driven. A low deficit (e.g. as seen in Orkney) indicates a higher rainfall input to the soils.

The combination of the Date of Maximum Soil Moisture Deficit and Minimum Soil Water Indicators implies soils will generally be drier and for longer in the future.

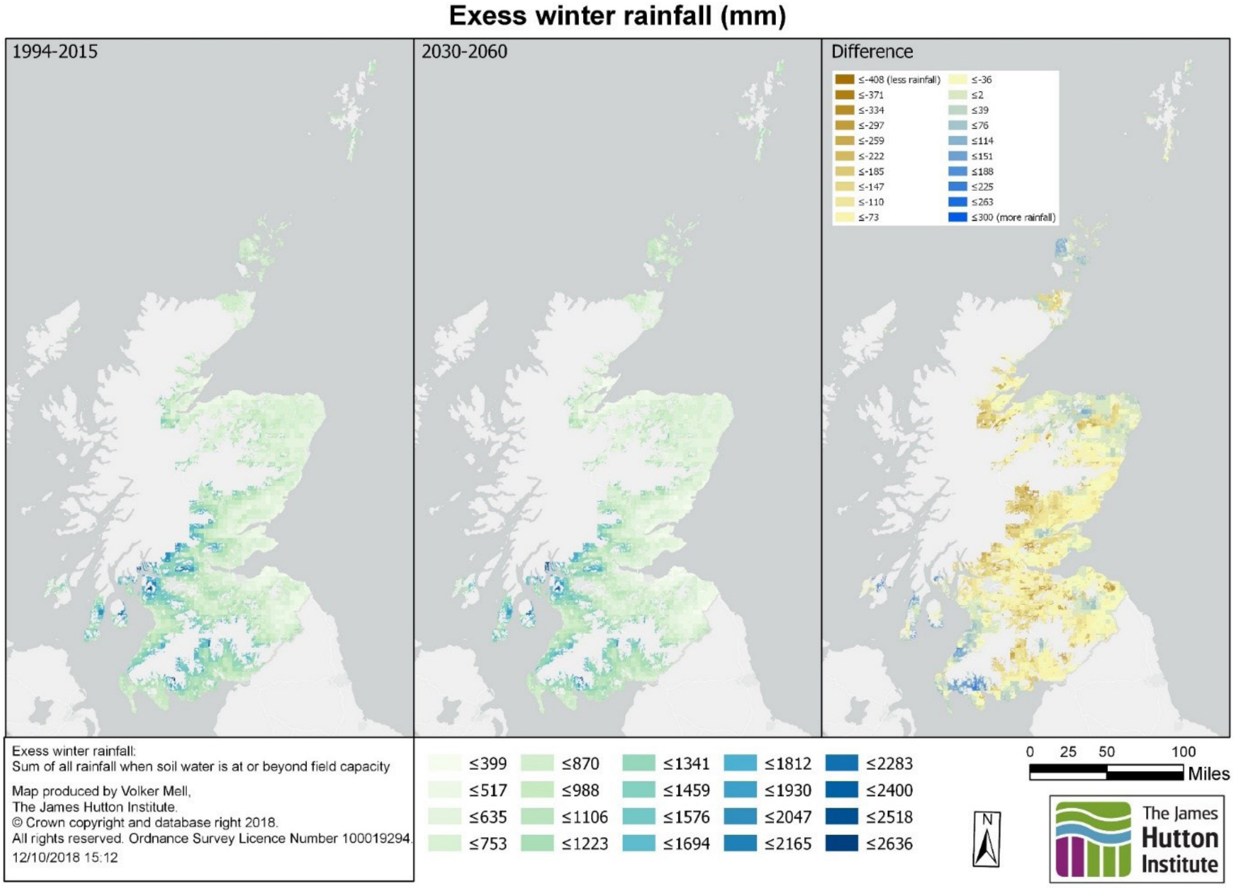

Figure VII.6. Excess winter rainfall amount (mm) between 1st October and 31st March

Excess winter rainfall: The Excess Winter Rainfall Indicator provides information about the amount of water that may result in risks of runoff or flooding. It is the total amount of rainfall between 1st October and 31st March and when soils are at field capacity. The maps in Figure VII.6 show that generally there may be a future reduction in the total amount of Excess Winter Rainfall. This may in part be due to soils being drier in the summer, requiring more autumn and winter rain to recharge to field capacity or saturation point.

Table VII.1: Water and Rain Indicators

	Indicator	Observed change	Future projection	Potential consequence	Risk and opportunity
Water and Rain	Dry Days (days)	Increasing number of dry days	Continued large increase in number of dry days, particularly in the west	Reduced water availability for longer time periods, possible increase in rainfall intensity on wet days.	Drier soils and increased soil moisture drought.
	Wet Days (days)	Reduction in number of wet days	Extenuation of rain shadow effect, with further reduction in wet days, particularly in north-east UK		
	Excess Winter Rainfall (mm, soil indicator, Scotland only) (Figure 23)	NA (estimates cover 1994 – 2015 only)	Most Scottish soils in arable areas show a reduction. This may be due to soils being drier and for longer in the summer, requiring more rain to recharge them to field capacity (or saturation point).	This will be temporally and spatially variable and associated with the intensity of rainfall events.	Possible increased flood and erosion risk if rainfall intensity is high.
	Precipitation heterogeneity (Index, no units) (Figure 20)	Slight increase in values (rainfall erosivity) in upland areas.	Intensifies particularly in north-west Scotland, but some areas see a reduction.	More intense rainfall events.	Increase in erosion risk.

Table VII.2: Heat Indicators

	Indicator	Observed change	Future change	Potential consequence	Risk and opportunity
Heat	Plant Heat Stress (days) (Figure 18)	Slight increase in lowland Scotland.	Further slight increase (+ c. 6-8 days)	Additional demand for water (crops, livestock, infrastructure etc.). Increased rates of transpiration and evapotranspiration giving increased surface water loss to the atmosphere.	Water stressed vegetation, reduced water input to groundwater, streams and surface water bodies.
	Growing Degree Days (thermal time accumulation) (days)	Slight increase in Scotland	Continued increase, particularly in lowland areas and southern UK		
	Heat Wave (days) (Figure 19)	Increasing number of heat wave days, particularly in southern UK.	Continued increase, particularly in lowland and coastal locations. Less change in Scotland than the rest of the UK.		

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