CREW CENTRE OF EXPERTISE FOR WATERS

Future predictions of water scarcity in Scotland: impact on distilleries and agricultural abstractors

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Report and Appendices

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Glossary/Acronyms

Term	Definition
Abstraction	The process of removing water by mechanical means from a body of water, either temporarily or permanently, including where water is transferred across or within bodies of water.
Abstraction Licence	A person specific authorisation required for higher risk water abstraction activities.
Adaptation	Adaptation measures refer to long-term actions that aim to enhance the resilience of a system.
Agri-Environment Climate Scheme (AECS)	Rural payment scheme that funds specific measures aiming to improve water quality, manage flood risk and mitigate and adapt to climate change and can be accessed by farmers who meet specified criteria.
Agroclimatic Zone	Geographic area characterised by specific climatic conditions suitable for certain agricultural practices.
Aquifer	A geological formation that can both store and transmit water.
Arable	Land used for growing crops.
Attenuation	Increasing water storage capacity to prevent water rapidly running off land into water courses.
Borehole	A hole drilled into the ground to access water for abstraction.
Business Reference Number	Unique identifier assigned to businesses that's required to use the Scottish Governments Rural Payments and Services.
Burns	A term used in the UK for describing smaller streams, often found in upland areas.
Carcass Weight	The weight of livestock animals after the removal of inedible parts.
Catchment	Area of land from which water drains into a river, lake, or reservoir.
Climatic Water Balance (CWB)	Indication of the changes in available water, specifically soil water availability, calculated as precipitation minus reference evapotranspiration.
Controlled Activities Regulations (CAR)	The Water Environment (Controlled Activities) (Scotland) Regulations 2011 governing activities that have an impact on the water environment, often requiring permits.
County Parish Holding Number	Unique identifier required for land and buildings used to keep livestock.
Crystalline Aquifer	Igneous or metamorphic rock aquifer, where water is hosted in fractures and weathered horizons.
Cycling	A stage in the livestock reproduction process.
Deficit	Climatic Water Balance situation where evapotranspiration is greater than precipitation.
Distilling	Process of the production of alcohol by heating fermented barley and yeast to create steam which is then turned back into an alcohol.
Data Protection Impact Assessment (DPIA)	Data Protection Impact Assessment is an evaluation to ensure data protection obligations are met.
Drain Upper Limit (DUL)	The maximum amount of water a soil can hold.
Drain Lower Limit (DLL)	The minimum amount of water that can be left in soil.
Drought Risk and Assessment Tool (DRAT)	Drought Risk and Assessment Tool operated by SEPA which provides a live data feed of the number of days a monitored river flow station experienced flows under the Q95 threshold to trigger significant water scarcity.
Drought	Prolonged period of abnormally low rainfall, leading to water scarcity and environmental stress.
Enhanced future flows and groundwater (eFLAG)	A dataset of river flow and groundwater projections for the United Kingdom (UK) created using the latest UK climate projections provided by the UK Climate Projections programme.
Evaporative Cooling	A licensed abstraction type that uses water for cooling process that relies on the evaporation of water to lower temperature, often used in the distilling process and then returned to the water body.
Evapotranspiration	Combined process of water evaporation from soil and transpiration from plants.
Exposure	Degree to which a system is exposed to a particular hazard, such as flooding or drought.
Flooding	Inundation of land by water, usually due to heavy rainfall, overflowing rivers, or storm surges.
Furrow	Trench or groove made in the ground for planting seeds or directing water for irrigation.
Grid-2-Grid (G2G)	National-scale grid-based hydrological model which typically operates on a 1 km × 1 km grid.
General Binding Rules (GBR)	Activities covered by GBRs do not need to be notified to SEPA. There are a series of generic conditions contained in the Controlled Activities Regulations that must be complied with.
Grain Development	Growth and maturation process of cereal grains such as wheat, corn, or rice.

Term	Definition
Grass Swards	Area of land covered with a dense growth of grass.
Groundwater (GW)	Water stored underground in porous-permeable rock layers or aquifers.
Groundwater recharge	Process by which water infiltrates the soil and reaches the water table thus replenishing groundwater resources.
Groundwater storage	Amount of water held in underground aquifers or rock formations.
Headwaters	Source area of a river or stream, usually high in elevation.
Horticulture	Cultivation of fruits, vegetables, flowers, and ornamental plants.
Lowlands	Geographical areas characterised by relatively low elevation and flat terrain.
Infiltration	Process of water soaking into the soil or porous rock layers from the surface.
Irrigation	Artificial application of water to land to assist in the growth of crops or plants.
Irrigation Lagoons	Man-made water reservoirs or ponds used for storing water for irrigation purposes.
Land Cover Map	Map showing the different types of land cover in a particular area.
Leaky Barriers	Structures designed to control water flow or contain pollutants while allowing some leakage or percolation, often using woody debris.
LTA	Long-Term Average, a statistical measure calculated over an extended period to represent typical conditions.
Livestock Agriculture (Extensive)	Farming practices involving animals raised primarily on pasture or rangeland with minimal inputs.
Livestock Agriculture (Intensive)	Farming practices involving animals raised in confined spaces with high levels of inputs such as feed and medication.
Live weight	The weight of livestock animals before it has been prepared as a carcass.
Mains Water Supply	Water provided by a centralised system, usually through pipes, to residential, commercial, or industrial areas.
Maltsters	Businesses or facilities engaged in the production of malt from barley or other grains.
Mash	Mixture of crushed grains and hot water used in brewing or distilling processes.
Mechanical Vapor Recompression (MVR)	Energy-efficient method of vapor compression used in industrial processes.
Meteorological Drought	Drought defined by meteorological indicators such as rainfall deficits and temperature anomalies.
Nature Based Solutions	Strategies or techniques that use natural processes to address environmental or societal challenges.
Non-evaporative cooling	Cooling process that doesn't involve evaporation, such as air conditioning systems.
Non-mains Water Supply	Water supply not provided by a centralised system, often sourced from wells, springs, or rainwater harvesting.
Nutrients	Substances essential for the growth and development of plants and organisms, such as nitrogen and phosphorus.
Precipitation	Any form of water, such as rain, snow, sleet, or hail, that falls from the atmosphere to the Earth's surface.
Private Water Supplies (PWS)	Sources of water that are not delivered by Scottish Water but are the responsibility of owners, there are approximately 22, 500 PWS in Scotland, servicing around 70,000 people.
Q95 (the 5-percentile flow)	The flow which was equalled or exceeded for 95% of the flow record. The Q95 flow is the parameter used to determine a significant low flow or water scarcity event.
Regional Climate Model (RCM)	Numerical climate prediction model that simulates atmospheric and land surface processes.
Representative Concentration Pathway (RCP)	Used in climate change projections and assessments.
Rainfed	Agriculture relying solely on natural rainfall for irrigation.
Rainwater Harvesting	Collection and storage of rainwater for later use, typically in agriculture or domestic settings.
Registration	A registration notifies SEPA of medium risk activities and enables SEPA to monitor cumulative impacts of water abstractions.
Resilience	The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance.
Rural Payments and Inspections Division (RPID)	Rural Payments and Inspections Directorate, responsible for administering agricultural subsidies and schemes.

Term	Definition
Runoff Projections	Predictions or estimates of the amount of water flowing overland or through channels after rainfall.
Sedimentary Aquifer	Underground layer of sedimentary rock with porous spaces that contain water.
Scottish Environment Protection Agency (SEPA)	Scottish Environment Protection Agency, responsible for environmental regulation in Scotland.
Socio-economic	Pertaining to the social and economic factors or conditions influencing an area or community.
Soil Water Holding Capacity (SWHC)	Maximum amount of water that soil can retain.
Soil Hydraulic Properties	Characteristics of soil related to its ability to transmit and retain water.
Sowing	Planting seeds or crops in soil to initiate growth.
Spatial	Pertaining to the arrangement or distribution of objects or phenomena in space.
Springs	Natural sources of water that flow or seep from the ground, often originating from underground aquifers.
Superficial Deposits	Unconsolidated sediments, such as gravel, sand, silt and clay that rest on older consolidated deposits or rocks referred to as bedrock.
Surface Water (SW)	Water located on the Earth's surface in streams, rivers, lakes, or other bodies of water.
Surface Water Discharge	Release or outflow of water from a surface water source, often into a river, lake, or ocean.
Surface water drought duration	The duration in which surface water flows fall below the long term Q95 threshold (2007-2018).
Surface water drought frequency	A count of the total number of droughts events divided by the 12-year time series (2007-2018).
Surplus	Climatic Water Balance situation where precipitation is greater than evapotranspiration.
Temporal	Relating to time or the sequence of events.
Thermal Vapor Recompression (TVR)	Process of using heat to generate vapor and then compressing it to increase its temperature. Mechanical Vapour Recovery (MVR) is a similiar technology.
Time series data	Data collected and arranged in chronological order, often used for analysing trends or patterns over time.
UK Centre for Ecology & Hydrology (UKCEH)	An organisation conducting research and providing expertise on environmental issues.
Uplands	Areas of high elevation, often characterised by rugged terrain and sparse vegetation.
Vegetative Phase	Stage in the growth cycle of plants characterised by leaf and stem development.
Vulnerability	The propensity of a system to be adversely affected by water scarcity and is determined not only by that potential impact but also by the capacity of the system to adapt
Water Resources	Natural sources of water, including surface water bodies, groundwater, and precipitation.
Water Scarcity	A long-term imbalance between water supply and demand in a region (or in a water supply system)
Water Security	Assurance of access to adequate and safe water resources for various purposes, including drinking and agriculture.
Water Shortage	Temporary insufficient supply of water to meet demand, leading to restrictions or rationing.
Water Stress Indicator (WSI)	Measurement or index indicating the degree of water scarcity or stress in a particular area or region.
Yields	Amount of agricultural or horticultural produce harvested per unit area.

Executive Summary

Purpose of research

The aim of this project was to provide summaries of future predictions of water scarcity in Scotland and the impacts this may have, tailored to three groups of abstractors: crop producers, livestock producers and distilleries.

The key questions addressed included:

1. How will water scarcity in Scotland impact the availability of surface waters and groundwaters for abstraction?
2. Considering question 1, how will this impact crop producers, livestock producers and distilleries in Scotland in the short (<5 years) and long term (>5 years)?

Key findings

- Most of the crop irrigation in Scotland occurs along east coast areas such as East Lothian, the Borders, Angus, and Fife (SEPA, 2013), mainly to support potato growing, soft fruits, and vegetable production (Scottish Government, 2010). Other crops, such as spring barley, are mainly dependent on rainfall. In 2016, 26,000 crop hectares were irrigated – 0.5% of the total crop area for the year – with on-farm groundwater being the main source of irrigation (48.3%), followed by mains water supply (26.2%), off-farm surface water – water sourced outside the farm boundary – (23%), on-farm surface water sources (19.4%) and other sources (10.5%) (Scottish Government, 2016).
- Sixty percent of land area in Scotland is used for livestock farming (Visser-Quinn *et. al.,* 2021) and is dependent on water (Köseoğlu, 2017) for both livestock drinking requirements and for cleaning purposes (Moran *et. al.,* 2007).
- A large quantity of water is needed for cooling processes during whisky production (Creaney *et. al.,* 2021; Carmen and Waylen, 2023). One analysis of water needed for whisky production in Scotland shows that to produce 1 litre of pure alcohol, roughly 114 litres of water were needed (Schestak *et. al.,* 2022). Of these, 66 litres were for cooling, 27 litres for boiling, 19 litres for mashing, and 2 litres for cleaning (Schestak *et. al.,* 2022).
- Compared to the baseline period 1960 – 1989, there has been an overall increase in precipitation from 1990 – 2019, with the area of Scotland experiencing higher precipitation being larger than experiencing decreases. There has also been a spatially variable change in Climatic Water Balance (CWB) compared to the baseline period. For the 2020 – 2049 period, there is agreement that between October and March, Scotland will remain in CWB surplus (precipitation is greater than evapotranspiration), but that Eastern Scotland will remain in CWB deficit between May and August.
- Observed shifts from water surpluses to water deficits in late summer and early autumn are the main drivers of the degree of exposure of most land cover types to climatic stress, depending on their spatial distribution in relation to west vs east geographical gradient. For cultivated land, arable land, mostly located in the eastern part of Scotland, and to a lesser extent improved grasslands were found to be most exposed to climatic water stress. The impacts on all types of agricultural abstractions were similar to those for arable land, although a greater proportion of agricultural abstractions fell into areas under future climatic water balance deficit in April and September than was the case for arable land alone.
- Based on observed data for the recent 1990 – 2019 period, 20% and 88% of distillery abstractions were in water deficit in March and August, respectively, while almost all distillery abstractions were in continuous water stress between April to July. For the future period 2020 – 2049, these statistics ranged from no change to almost universal water surplus in March and 95% deficit in August, depending on the specific climate model scenario. While only c. 20% of distillery abstractions were in water deficit in September, this increased up to 85% when CWB was based on the EM05 dry future scenario.
- An increase in mean, minimum and maximum frequency and duration of surface water hydrological droughts was found between the baseline (2007 – 2018) and future periods (2019 – 2050). By the middle of the century, the mean drought frequency and duration will almost double, from 0.33 to 0.65 events per

year for drought frequency and from 31 to 51 days for drought duration, across 23 catchments included in this study.

- Long term groundwater level monitoring by SEPA in East and Southwest Scotland suggests that summer groundwater levels have been lower in recent years compared to previous decades, but within or above normal ranges during the winter months. The spatial extent of the current groundwater monitoring network is insufficient to capture the full range of responses across all hydrogeological and climatic contexts in Scotland.
- In the east of Scotland, where long-term average potential recharge is relatively low, abstractions from high-storage sedimentary aquifers will be more secure through drought periods, while abstractions from lower-storage crystalline aquifers and localised superficial aquifers will be more vulnerable to drought. In the west of Scotland, where long-term average potential recharge is relatively high, low-storage aquifers will still be vulnerable to drought.
- Projected changes in the frequency and intensity of droughts may increase the future vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers. Eastern and central Scotland are likely to experience continued or accentuated reductions in long-term average potential groundwater recharge, with possible insignificant to moderate increases in winter recharge unlikely to offset the summer deficits.
- Feedback from our focus groups combined with information from the literature review suggest that droughts seem to have mostly had economic impacts on the rainfed agricultural sectors – arable and livestock. The rainfed agricultural sectors currently appear to be more vulnerable to future increase in water scarcity as few available and profitable adaptation strategies seem to have been identified, beyond the benefits of soil health management.
- Where irrigation is already being used, farmers seem to have been able to avoid large production losses, while bearing additional irrigation costs. The more widespread availability of irrigation infrastructures for the horticultural sector might provide some resilience to the sector when facing reductions in soil moisture. Additional irrigation needs generated by reduced soil moisture levels may increase the pressure on surface water systems. Where these additional pressures lead to restrictions on water abstraction, the sector could face high losses given the high value of production.
- Distilleries face potentially high costs if abstraction bans require them to stop production. However, there is currently little evidence on the potential associated costs, and how these would vary with the duration, frequency and location of restrictions. Switching to groundwater sources may be a viable adaptation strategy for surface water abstractors in some areas, but more data on groundwater systems in Scotland is needed to determine the longer-term sustainability of such a solution in different contexts.
- It was clear that even forward-looking farmers and distillers were often unaware of how much water they were using (demand) nor how much water they could rely upon from rainfall, surface or groundwater sources (supply) and therefore were not able to factor this into their business planning - there is a lack of water calculation tools for both sectors.
- Margins for adaptation through increased water use efficiency seem to be higher in the distilling sector than in the agricultural sectors. Most adaptation strategies in the agricultural sector appear to rely on a substitution approach, replacing current water resource with alternative sources or adapting farming practices (e.g. new grass varieties). A complete transformation of the production system (e.g. stopping growing a certain crop, or from intensive to extensive production) was uncommon beyond livestock number reductions mentioned by focus group participants.
- Our findings confirm the review on climate change communication (Environment Agency, 2023) that messaging needs to be framed as business risk and resilience issue, be part of a long-term and sustained conversation and focus on enabling actions. Here attention to how the barriers to adaptation can be overcome is essential.

Background

Climate change, in Scotland, will increase the frequency and severity of water scarcity and this will impact a range of water users, including those businesses that depend on water abstraction. The frequency of drought events in Scotland is projected to increase from one in every 20 years (1981 – 2001) to one in every three years by 2040, with areas on the east coast most likely to be most affected (Kirkpatrick *et. al.,* 2021). These scientific predictions are indeed starting to bear out, with recent significant drought events recorded in 2018 and 2022, with large parts of Scotland experiencing moderate to significant drought conditions. Scotland's climate has already changed and further changes in seasonal precipitation patterns and frequency of extremes affecting water shortages are expected (Rivington and Jabloun, 2023).

Drought conditions will have direct consequences for water users as more regions in Scotland become vulnerable to water shortages (Gosling, 2014). Climate change in Scotland will increase the frequency and severity of water shortages and this will impact a range of water users, including those businesses that depend on water abstraction. In this project, we reviewed current understanding of future water availability and demand from non-mains water supplies related to three economically significant sectors; arable, livestock and distilling.

The review addresses the following questions:

Q1: How are water resources currently used by each of the three sectors?

Q2: What future changes in water shortages can we expect to see?

Q3: What do future projections mean for the three sectors?

Recommendations

Improved data on water resources demand and supply

1. **There is a clear need for better data on actual abstraction volumes and water source types** (including estimates of those using surface and groundwater under general binding rules). Drinking water supply-related abstraction data currently cannot be shared by SEPA due to security limitations. However, seamless integration of this data with abstractions returns held by SEPA would streamline data analysis and prevent discrepancies in data formats, as well as minimize delays caused by preprocessing datasets. The SEPA abstraction licences database should explicitly attribute the sources of abstractions (surface water or groundwater) rather than relying solely on keywords from location descriptions to distinguish between the two. It is also essential to address missing location coordinates and water body names associated with the SEPA licenses. Improved abstraction licencing records by SEPA should also include information on the depth of groundwater sources.

2. **Improved integration of licensed abstraction data** with farm census data would allow areas to be identified where water demand is high and vulnerability to water deficit is also high (either in situ or upstream/downstream); this would allow targeted support (advice, incentives) to farmers to prepare for and cope with severe water shortages; and planning to prevent environmental damage from low water levels upstream/downstream of production areas. This information could be collected as part of a supplementary module within the annual June agricultural census, that farmers already complete (thus reducing the administrative burden on the farmer) and used to generate benchmarks (e.g. Standard Water Requirements, analogous to Standard Labour Requirements or Standard Output). Having farmers can estimate their risk of exposure to future water scarcity and increase the demand for water scarcity adaptation advice. An interim measure could be an updated survey on the use of irrigation to understand the actual abstraction volumes used and how much water is used for what purpose.

3. **There is an urgent need for improved groundwater monitoring across Scotland.** The National Water Scarcity Plan highlights the potential for groundwater to provide more drought-resilient water supplies in response to future water scarcity. However, the lack of information regarding the status of these resources at a catchment scale needs to be addressed to understand where, when and to what extent groundwater is a viable substitute in the long term. A cost-benefit analysis of exploiting deeper groundwater, or the potential for augmenting recharge through, for example, nature-based solutions such as managed aquifer recharge need to be explored.

4. **To improve local understanding of conditions for the onset of significant drought, spatial resolution of drought risk assessment could be refined**. Focus group participants reported that on occasion, whilst river flows may be above severe drought levels, water resources in upstream locations were already in drought. Therefore, other metrics and data sources, additional to SEPA gauging stations, should be explored, including the use of remote sensing data.

Informed adaptation options

5. **Encouraging all farmers and small scale distilleries** (not just the licenced abstractors) **to consult the** Water Situation Report that highlights potential water scarcity before the higher tiers of the National Water Scarcity Plan are reached is useful to allow businesses to proactively adapt (e.g. planning stocking rates, installing rainwater tanks). Continued promotion of the website and status of surface water availability using social media would help embed this as part of good practice business management (see also recommendation 6).
6. **Tools (Water Calculators to estimate demand) are needed to help farmers and distillers make strategic decisions** about what and how to produce in future conditions. Forward looking focus group participants stressed the need to move from reaction to adaptation to future water scarcity – and advice on the costs, benefits and practicalities of adaptation options is needed. However transformation from current farming or distilling practices to alternative climate resilient practices (e.g. switching crops or grazing regimes) is not yet common.
7. **There is a pressing need for further work to understand the likely response of different groundwater systems to future pressures** and subsequent impacts on future groundwater availability to ensure that groundwater remains a viable substitute in the long term. The National Water Scarcity Plan promotes the use of groundwater as a temporary, more resilient resource when there are drought conditions affecting rivers and streams. However, there is a lack of information regarding the status and vulnerability of these resources at a catchment scale. This is particularly important for both low and high storage aquifers in Eastern Scotland, which are critically important for economic activities such as agriculture and distilling and which are expected to see a decrease in future long term average recharge. But it also applies to low storage aquifers in Western Scotland, which are locally important for small-scale water supply. We found that many participants were already using groundwater and experienced problems with scarcity during drought events. An improved understanding of Scotlands' regional groundwater resources could be achieved through an expansion of the long-term groundwater monitoring network, further collation and analysis of existing groundwater data, including the development of numerical models of strategically important aquifers, and more detailed localised studies to collect new data in areas where future pressures are expected to be greatest.
8. **Future work into potential adaptation measures** would be beneficial for future water security planning. This might include an assessment of areas where groundwater could provide more resilient supplies compared to other source types, a cost-benefit analysis of exploiting deeper groundwater, or the potential for augmenting recharge through, for example, nature-based solutions such as managed aquifer recharge. Swapping from surface to ground water options should only be explored in areas that have high water security. This improved understanding could be achieved through an expansion of the long-term groundwater monitoring network, further collation and analysis of existing groundwater models of strategically important aquifers, and more detailed localised studies to collect new date in areas where future pressures are expected to be greatest.

Clear adaptation pathways

9. **There is a need for a cross-sector process of preparing for a future of water extremes**, as also found in the parallel CREW project by Gosling *et. al.* (2024).
10. Promoting water scarcity in terms of business resilience to risks makes the topic relevant but also requires a **clear pathway to options that can be implemented by a variety of businesses.** Farmers recognise the importance of soil management and appropriate seed varieties to respond to extremes of flood and droughts, so this can be reinforced through the advice and demonstration networks. Sector-specific awareness raising is needed for rainwater harvesting, natural water retention measures,

such as wetlands and on-farm irrigation ponds to illustrate potential returns on investment and how they can fit with rotations and existing farm practices. Clarity on funding opportunities for these interventions in the new Agricultural Payments Tiers would be welcomed, however farmers may also need to consider commercial loans.

11. **The work of catchment management partnerships** that can provide a coordination mechanism, act as a trusted intermediary and reduce the need for busy farmers or distillery managers to undertake relationship building and maintenance activities **needs more visibility and support to co-ordinate water resources use at landscape/catchment level.** As water is a common pool good, collective action responses can help mitigate scarcity, however there was limited support for these from farmers or distillers. In some cases, focus group participants reported not being able to use their full licence allocation (there is too much permitted given changing climatic conditions) and this could be addressed through periodic licence review and allocation sharing, or even trading, at a catchment scale.

12. **The costs of adaptation strategies should be compared to potential costs of water scarcity** to the sectors, at the individual business level to support decisions to invest in adaptation strategies, and at the national scale when assessing (i) abstraction restriction requirements and (ii) potential interventions to support adaptation of the sector to future climate conditions. However, this is currently hindered by the lack of relevant data at the micro level (individual business) (see recommendations 1 and 2). An assessment of the effect of droughts for individual businesses would require access to and monitoring of micro-level data such as: production levels for each crop, their production costs, linked to irrigation systems and uses, water storage capacity and pedo-climatic data. This assessment, pooling together micro-level data from a large sample of farms and over time, could allow to statistically determine the effect of droughts on farms that have already experienced them. This assessment would provide useful information for (i) farms with more limited data or evidence to support their adaptation strategy, (e.g. having less experience of water scarcity until now), (ii) anticipate effects at regional or national scales.

Conclusions

Through literature review, modelling and stakeholder focus groups, this research project summarises future projections of water scarcity in Scotland and their impacts on crop, livestock and distilling sectors. First, we identified how water use differed by the three sectors, with rainfed sources critical for arable crop producers, surface water and groundwater sources abstracted for irrigation, as well as cooling and process water in distilling processes, and mains or private sources utilised for health and welfare of livestock. Despite identifying 1,601 abstraction licences and 472 registrations there is a need for better data on abstraction volumes, including abstractions under General Binding Rules (GBR), to give true understanding of water use.

Modelled projections to 2050 indicate that central and eastern Scotland are likely to be at increasing risk of CWB deficit from May through to September. Increasing deficits would lead to soil water stress impacts for crops, as demonstrated in our analysis of soil water holding capacity and the negative impacts on barley yield. We indicate how deficits may propagate to surface water and groundwaters. Frequency and duration of surface water droughts are projected to approximately double by 2050, which would trigger further licence restrictions and impacts on horticulture and distilling sectors. For groundwater, monitoring suggests that, in some areas, summer groundwater levels have been lower in recent years compared to previous decades, but within or above normal ranges during the winter months. Projected increases in the frequency and intensity of droughts may increase the future vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers.

In our experience of discussing current and projected water scarcity across the different sectors, the direction of travel in terms of the increasing frequency of water scarcity events and related impacts were understandable to participants. We find that rainfed agricultural sectors currently appear to be more vulnerable to future increases in water scarcity as few available and profitable adaptation strategies seem to have been identified for the sector. However, good soil management was seen as an important part of climate resilience and something that all farm businesses can implement.

Although we identify adaptation measures already being taken by participants, particularly in the distilling sector, there is less consensus on how to respond to scarcity, with cost of efficiency and substitution measures being cited as major barriers to uptake. Promoting water scarcity in terms of business resilience to risks makes the topic relevant. Once awareness is raised, the sectors require a clear pathway to options that can be implemented by a variety of businesses and are flexible enough to respond to differences between and within sectors. The costs of adaptation strategies should be compared to potential costs of water scarcity to the sectors, at the individual business level to support decision to invest in adaptation strategies.

These conclusions and recommendations imply a systemic approach, requiring multi-level actions from individual businesses to national institutions; and crossing different policy directorates. Adapting to future climate challenges, in the context of current headwinds related to inflationary input costs and tight profit margins, can be challenging to achieve, however building capacity to improve understanding of how sectors use water and can respond to change needs to begin now to equip us for the future.

1 Introduction

1.1 Background and scope

Climate change, in Scotland, will increase the frequency and severity of water scarcity and this will impact a range of water users, including those businesses that depend on water abstraction. The frequency of drought events in Scotland is projected to increase from one in every 20 years (1981 – 2001) to one in every three years by 2040, with areas on the east coast most likely to be most affected (Kirkpatrick *et. al.,* 2021). These scientific predictions are indeed starting to bear out, with recent significant drought events recorded in 2018 and 2022, with large parts of Scotland experiencing moderate to significant drought conditions. Scotland's climate has already changed and further changes in seasonal precipitation patterns and frequency of extremes affecting water shortages are expected (Rivington and Jabloun, 2023).

Drought conditions will have direct consequences for water users as more regions in Scotland become vulnerable to water shortages (Gosling, 2014). Climate change, in Scotland, will increase the frequency and severity of water shortages and this will impact a range of water users, including those businesses that depend on water abstraction.

Responding to these risks, Scotland's National Water Scarcity Plan was developed to provide water users with guidance on how water resources will be managed before, during and after drought events (SEPA, 2020). Recent CREW project by Gosling *et. al.* (2024) recommended mitigation and adaptation actions to address future water scarcity challenges in Scotland. The aim of this project was to provide summaries of the future predictions of water scarcity in Scotland and the impacts this may have, specifically tailored to three groups of abstractors: crop producers, livestock producers and distilleries to understand:

1. How will water scarcity in Scotland impact the availability of surface waters and groundwaters for abstraction?
2. How will this impact crop producers, livestock producers and distilleries in Scotland in the short (<5 years) and long term (>5 years).

1.2 Project objectives

To answer the above project brief, firstly we reviewed current understanding of future water availability and demand from non-mains water supplies related to these three economically significant sectors; followed by structured engagement with stakeholders in four focus groups to understand:

Q1: How are water resources currently used by each of the three sectors?

Q2: What future changes in water shortages can we expect to see?

Q3: What do future projections mean for the three sectors?

1.3 Structure of the report

In section 3.1 we provide a brief overview of how water is currently used by agricultural and distilling sectors based on literature and the findings from stakeholder focus groups. Then in Section 3.2 we present summaries of a range of detailed analyses of current and future climate projections on water scarcity. We start with future changes to the climatic water balance (CWB) (precipitation minus reference evapotranspiration) to provide an indication of the changes in available water. The second part shows spatial distribution of soil water holding capacity (SWHC) in arable areas. The third part presents a current and future analysis of national groundwater security. Finally, we present an analysis of water abstractions by the agriculture and distilleries sectors across Scotland and simulate the likely change in the frequency and duration of surface water drought events under current and hypothetical abstraction scenarios in 23 catchments with available data. In section 3.3, we bring together our findings from literature and from the structured stakeholder focus groups to understand what future projections mean for these sectors and what are their adaptation options. Detailed findings and methodology are presented in Appendices 1–6.

2 Research undertaken

2.1 Literature review

A rapid scoping and evidence review was undertaken to address the above research questions and inform future interactions with the distilling, livestock and crop sectors. Scoping reviews are a suitable method for collecting evidence when time is limited (Arksey and O'Malley, 2005), making them a suitable and robust way to collect and synthesise known literature. The rapid nature of the review means information may be missed, which could have been captured as part of a full in-depth and systematic review. However, literature on the impact of future climate change on water scarcity and sectoral abstractions in Scotland is quite limited, therefore we anticipate to have captured most relevant sources. In addition, to ensure the review is as robust as possible, it was informed by expert knowledge from within the project team, as well as ongoing work in parallel projects, such as the Scottish Government funded Strategic Research Program 2022 – 27.

2.2 Modelling

Past and future trends in water availability that can lead to water limitation and occurrence of meteorological drought were assessed using a Climatic Water Balance indicator (CWB), defined as the difference between precipitation input (P) and reference evapotranspiration (ETo) output. Previous analysis by Rivington and Jabloun (2023) and Gagkas *et. al.,* (2023) was extended to understand the impact of climatic changes on arable and intensive grassland land uses as well as agricultural and distilling abstractions. Presented results (Appendix 2) show the areal extent of cultivated land and number of abstractions occurring within areas of observed and projected climatic water deficits or surpluses, defined as both direction of change and actual CWB ratios, with CWB ratios >2 indicating a Strong Surplus and CWB ratios <2 indicating a Strong Deficit.

To improve the understanding of the surface water drought frequency and duration, we designed a drought profiling framework using data on actual abstractions from SEPA and Scottish Water. First, raw abstraction data comprising daily licensed sectoral abstractions from 2007 – 2022 (please note 2008 – 2018 is a complete dataset, 2019 was lost because of the cyber-attack and 2020 – 2021 is a partial dataset for prioritised catchments) was combined with catchment level daily abstractions for public water supply for the year 2017 – 2022 from Scottish Water. Then future hydrological projections derived from the Grid-to-Grid (G2G) model (Hannaford *et. al.,* 2023), based on UKCP18 Representative Concentration Pathway (RCP) 8.5 'dry' ensemble member 05 were used to simulate the impact of future abstraction scenarios on drought frequency and duration in 23 study catchments for the period 2019 – 2050. These scenarios ranged from no increase in abstraction (using the historical abstraction time series repeated until 2050) and increasing abstractions by 5%, 10%, 15%, 20%, to a worst-case scenario of 25%.

To improve the understanding of potential future risk to groundwater availability in Scotland, a water security framework was developed to analyse the relationship between groundwater storage, groundwater recharge and groundwater abstraction. Using existing national-scale groundwater datasets for Scotland, a new groundwater storage map for Scotland was developed, showing areas where aquifers have the ability to store relatively large or small volumes of groundwater, which respectively increases or decreases their capacity to continue to support groundwater supplies during drought. This storage map was then combined with a map of long-term average potential groundwater recharge derived from the eFLaG (enhanced Future Flows and Groundwater) dataset (Hannaford *et. al.,* 2022), which gives an indication of the renewability of the groundwater resource. The combined analysis highlighted those parts of the country that are relatively more or less resilient to drought and long-term groundwater depletion to assess risk based on their importance for groundwater abstraction. Although no new analysis of future groundwater recharge scenarios was made, the available projections from the eFLaG dataset were summarised, providing an assessment of what climate change might mean for future groundwater availability and risk in different parts of the country.

2.3 Stakeholder focus groups

Stakeholder focus groups were conducted to gain insight on how the three sectors currently use water, understand how the future projections will impact the three sectors and how stakeholders might adapt to the projected changes. An initial focus group with national scale representative organisations for the three sectors informed the selection of four main focus group engagements spatially distributed in key areas across Scotland:

- North East of Scotland focusing on mixed agriculture
- Fife Region focusing on arable and horticultural agriculture
- National focusing on livestock and dairy farming
- Speyside region focusing on the distilling sector

In total 59 stakeholders attended the focus groups, 11 of which attended the North East focus group 9 attended the Fife focus group, 13 attended the national livestock and dairy focus group and 26 attended the Speyside distilleries focus group. Full details of the focus group methodology and findings are presented in Appendix 5, including a breakdown of all the stakeholder participants and their unique identifier codes which are used throughout the report.

3 Findings

3.1 How are water resources currently used by the agricultural and distilling sectors?

Drawing on our review of literature and stakeholder responses during focus groups, we detail how water is currently used by the three sectors. Further information identified during the review of literature can be found in Appendix 1, while greater detail of stakeholder responses can be found in Appendix 5.

Surface and groundwater abstractions are regulated by the Controlled Activities Regulations (CAR). The level of authorisation required under regulation is dependent on the effect an activity will have on the water environment. Levels of authorisation include 1) General Binding Rules (GBR) where activities are considered to be at low risk and don't require a specific permit, 2) Registration for activities that pose low individual risk but may collectively affect the environment, and 3) Licence activities that pose moderate to high risk to the environment. Activities requiring abstractions greater than or equal to $10m^3$/day and less than $50m^3$/day are subject to Registration, while Simple and Complex licence activities are regulated under CAR licences according to abstraction volumes (>50 and >$2000m^3$/day, respectively). Surface water abstractions less than $10m^3$/day and some other exemptions, for example groundwater abstractions <200m depth below Registration and Licence level abstraction, do not require authorisation.

Information from SEPA on licenced abstraction activities indicate there are:

- 1,205 surface water licences for agricultural irrigation
- 187 groundwater licences for agricultural irrigation
- 25 surface water licences for agricultural activities other than irrigation (these are likely to be used for livestock watering)
- 9 groundwater licences for agricultural activities other than irrigation
- 145 surface water licences for distilling purposes
- 30 groundwater licences for distilling purposes

Of the identified licences, 1,375 were for surface water sources (85.9%; see Figure 1) and 226 were from groundwater sources (14.1%; see Figure 2).

In addition, SEPA registration level abstractor data shows that there are approximately 132 registrations for agricultural irrigation and 340 registrations for agricultural activities other than irrigation.

The spatial distribution of abstraction points are important (supply) and to get an overall picture of water scarcity impacts, the abstractions need to be associated with the demand for water discussed in sections 3.1.1 – 3.1.4. Integration of licenced abstraction data with available farm business data would allow areas to be identified where water demand has the potential to be high and vulnerability to water deficit is also high (either in situ or upstream/downstream) to allow targeted support (advice, incentives) to farmers to prepare for and cope with severe water shortages; and planning to prevent environmental damage from low water levels upstream/downstream of production areas (see Recommendations). This information could be collected as part of a supplementary module within the annual June agricultural census, that farmers already complete (thus reducing the administrative burden on the farmer) and used to generate benchmarks (e.g. Standard Water Requirements, analogous to Standard Labour Requirements or Standard Output). To enable data integration with the SEPA abstraction licences held under CAR (and potentially the Scottish Water public water supply abstraction data) it would be useful to ask for either the Business Reference Number or ideally the County Parish Holding number to be associated with the licence number, as this can link the licence to data held by Scottish Government on farm type and other farm management information and allow these data to be integrated without identifying personal data. Voluntary industry standards or supply chain requirements may also encourage individuals to keep records on water use; and if these could be streamlined with agricultural compliance reporting, that would further reduce administration for farmers. Having such benchmarks would allow online farm water calculators to be developed, so farmers can estimate their risk exposure to future water scarcity and increase the demand for water scarcity adaptation advice. An interim measure could be an updated survey on the use of irrigation to understand the actual abstraction volumes used and how much water is used for what purpose.

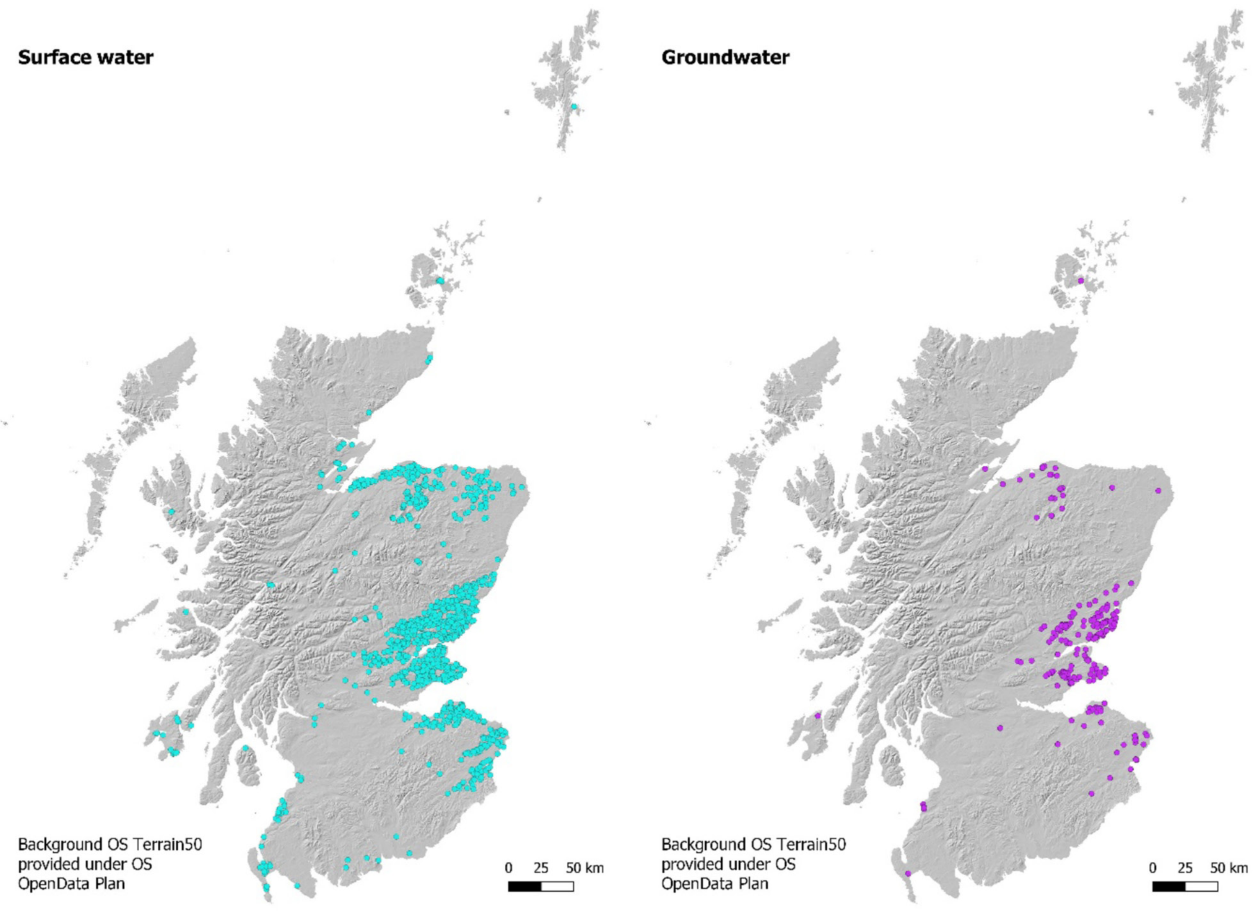

Figure 1: Map of licensed groundwater and surface water abstractions across Scotland for agricultural and distilling purposes.

3.1.1: Water use by the crop sector

Most crop irrigation in Scotland occurs along east coast areas such as East Lothian, the Borders, Angus, and Fife (SEPA, 2013), mainly to support potato growing, soft fruits, and vegetable production (Scottish Government, 2010), or what we will refer to as 'horticultural' crops. Other crops, such as spring barley, are mainly dependent on rainfall and rely on soil moisture for crop growth, which we refer to as 'arable' crops.

Irrigation needs are highly dependent on agroclimatic zone and soil moisture. Based on figures from the survey of farm structure and methods published by the Scottish Government (2016), 26,000 crop hectares were irrigated, which was 0.5% of the total crop area for the year. The 2016 report indicates the main source of irrigation being on-farm groundwater (48.3%), followed by mains water supply (26.2%), off-farm surface water – water sourced outside the farm boundary – (23%), on-farm surface water sources (19.4%) and other sources (10.5%). Water is typically applied using sprinkler irrigation (57.2%) surface irrigation – flooding of the field surface or furrows in the soil – (30.5%) and drip irrigation (17.8%) (Scottish Government, 2016).

3.1.2: Water use by the livestock sector

Sixty percent of the land area in Scotland is used for livestock farming (Visser-Quinn *et. al.,* 2021) and is dependent on water (Köseoğlu, 2017) for both livestock drinking requirements and for cleaning purposes (Moran *et. al.,* 2007). Livestock water footprints mainly consider green water (water used to (rainfall used by feed crops and grasses) and blue water (surface or groundwater used for drinking, washing and irrigation) (Chatterton *et. al.,* 2010).

There are limited studies, information or data on livestock water use in Scotland. Global figures suggest that the average water footprint for animals (live weight) across various production systems was 4,325 m^3/ton for chicken meat, 5.988 for pig meat, 10,412 m^3/ton for sheep meat, and 15,415 m^3/ton for beef (Mekonnen and Hoekstra, 2012). However, the majority of this water is needed for growth of animal feed (green water), with only an average of 1.1% of these amounts required for drinking water (blue water) (Mekonnen and Hoekstra, 2012). Water footprints are sensitive to different livestock production systems, for example the systems in Scotland will be different to systems in the USA. The study of pasture-based farms in Ireland by Murphy *et. al.,* (2018) developed carcass weight average water footprints for beef (8391 l/kg or 8,526 m^3/ton) and sheep (7,672 l/kg or 7,795 m^3/ton), and may be more representative for Scottish systems. Future research is required to increase understanding of water use within both livestock and crop sectors.

3.1.3 Water use by the distilling sector

Although a range of alcohol is produced within the sector, whisky production is dominant in Scotland. The river Spey is home to the greatest concentration of Scottish distilleries and is considered a drought hotspot (Visser-Quinn *et. al.,* 2021). The main uses of water in the distilling sector are for the production of alcohol and required cooling process. The cooling process requires larger volumes of water (Creaney *et. al.,* 2021; Carmen and Waylen, 2023) that is often abstracted from rivers and then returned to the water source (SEPA, 2018). One analysis of water requirements for whisky production in Scotland shows that to produce 1 litre of pure alcohol, roughly 114 litres of water is needed (Schestak *et. al.,* 2022), of which 66 litres were for cooling, 27 litres for boiling, 19 litres for mashing, and 2 litres for cleaning. Sourcing water for cooling is a considerable problem within the sector, as higher water temperatures lead to a need for greater abstraction volumes to cool the abstracted water before its use in distillation or return to the river.

3.1.4 How focus group participants use water

During stakeholder focus groups, participants were first asked to identify their sources of water (Figure 2). A large amount of water was sourced from groundwater by the agricultural sector (91% of participants used groundwater in the Northeast, 100% in Fife, and 90% in the livestock focus group). When compared to the proportion of licensed groundwater abstractions in Scotland presented in Figure 2, it seems the majority of groundwater abstractions are covered by registrations, or GBRs. There were relatively high levels of mains water usage by the Fife farmers (21% of respondents) and by distilleries (23% of respondents; see Figure 3), indicating the importance of accounting for abstraction under GBRs and registrations as well as licenced abstractions.

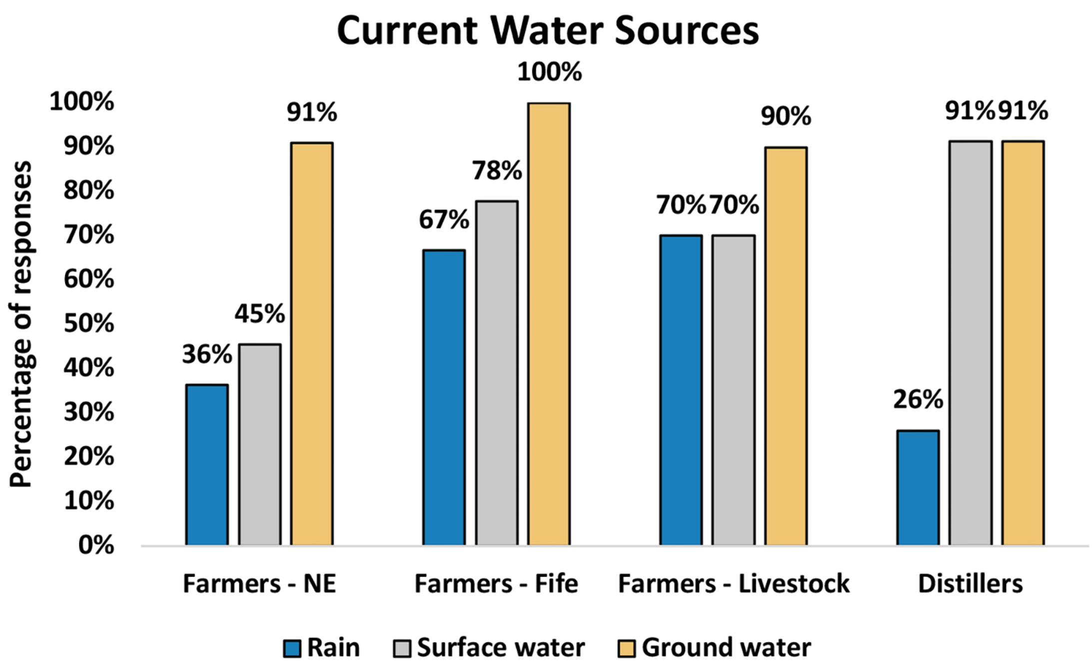

Figure 2: Percentage of focus group participants using different sources of water used by sector and location. Note that the figures do not add up to 100% as participants could select more than one option, as most had multiple sources of water.

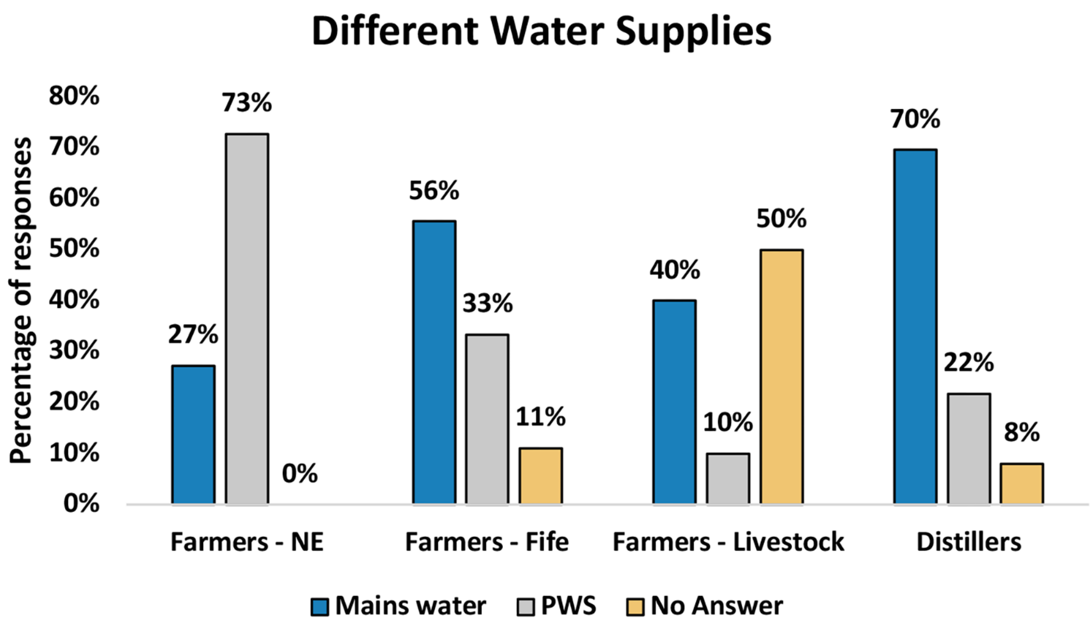

Figure 3: Number of focus group participants using either mains or private water supplies (PWS).

Generally, agricultural stakeholders had limited awareness of the volume of water used for different activities. Although licenced abstraction required an annual data return to SEPA informed by the amount of time irrigation pumps are in use, stakeholders in Fife reflected on a lack of knowledge of exact water abstraction volumes. Furthermore, farmers in Fife were sceptical of introducing metering due to the risk of being charged for their water use. Arable farmers confirmed that rainfed sources were key for crop growth, however, there were cases around Fife where grass and arable crops were being irrigated.

Most livestock farmers suggested they use less than 10,000 cubic meters of water a year, with one stakeholder commenting that they had been unaware of different types of abstraction licencing requirements. Participants confirmed water was used mainly for drinking by livestock, with some also used for cleaning. It was suggested that dairy production requires the highest level of water input by livestock farming, and that farms in Scotland expect to be milking for 6 – 8 months of the year, although this figure is lower than the industry norm (over 300 days per year).

In contrast to the farming groups, all of those present at the distillery focus group said that they used abstraction licences, reflecting a much higher water abstraction rate by this sector. Distilling stakeholders did point out that most of the water they abstract was returned to the water sources after use for cooling, which for SH37 was 95% of the abstracted water. SH52 estimated water use at their distillery as 40 million litres a week, ranging from 140 litres of water per litre of alcohol in winter to 230 litres of water per litre of alcohol in summer, when more water was needed due to the increased temperature of that used for cooling. Metering was more widely used by this sector to drive water use efficiency, meaning that distilling stakeholders had greater awareness of water use volumes.

3.2 What future changes in water shortages can we expect to see: what does future look like up to 2050?

Below we present summaries of a range of detailed analyses of current and future climate projections on water scarcity. We start with future changes to the climate water balance (precipitation minus reference evapotranspiration) to provide an indication of the changes in available water. The second part shows spatial distribution of soil water holding capacity in arable areas, with a focus on barley. The third part presents likely change in frequency and duration of surface water drought events under current and hypothetical abstraction scenarios in 23 catchments with available data. Finally, we develop a new water security framework to inform current and future groundwater availability.

3.2.1 How will climatic water balance change?

Future climate projections using RCP8.5 indicate that the climatic water balance (CWB) is likely to change in Scotland (Rivington and Jabloun, 2023). The CWB is an indicator of the potential for changes in soil water availability, on that basis that if evapotranspiration ETo > precipitation P, then there is less water input into soils, groundwater, and surface water bodies. CWB is therefore a metric of the combined impacts of changes in temperature and precipitation on water availability and its limitation that can lead to the occurrence of meteorological drought. The findings suggest that:

- There has been an observed change in CWB compared to the baseline period of 1960 – 1989, which is variable both spatially and temporally:
    - West coastal areas have become wetter (increased surplus water) between December to April.
    - Eastern Scotland has experienced a decrease in water availability between March to May, as has the whole of Scotland in September.
    - June to August have experienced an increase in average CWB (precipitation is greater than evapotranspiration) but the surplus is low (close to 0 mm) and variable, with deficits in the East.
- Projections show that there may be a shift in where and when parts of Scotland have a surplus or deficit of water.
    - Some upland areas of central Scotland are projected to shift from water surplus to deficit (Figure 4), especially in May in the central Highlands and in August in the eastern and southern upland areas plus southern Argyll, Islay and Jura and parts of the Outer Hebrides.
    - Large parts of eastern Scotland in September are projected to see a shift to CWB deficit.
- For the 2020 – 2049 period, there is good agreement between the 12 projections that October through to March Scotland will remain in CWB surplus (precipitation is greater than evapotranspiration), while May to August eastern Scotland will remain in CWB deficit.

There is large spatial and temporal variation in CWB for each of the 12 climate projections (ensemble members) used. To illustrate the degree of certainty in where and when these changes in CWB occur, Rivington and Jabloun (2023) produced ‘agreement maps’, showing where all 12 climate projections agree on whether there is a shift from water surplus to deficit, remains in surplus or deficit, or if there is no agreement (Figure 4). From this analysis, there is a strong indication that between October and March, Scotland is likely to remain in CWB surplus. However, from March through to September, it is likely that central and eastern parts of Scotland will be at increasing risk of CWB deficit. This will be variable between years, the implication being that in some cases the water deficit could be widespread and large.

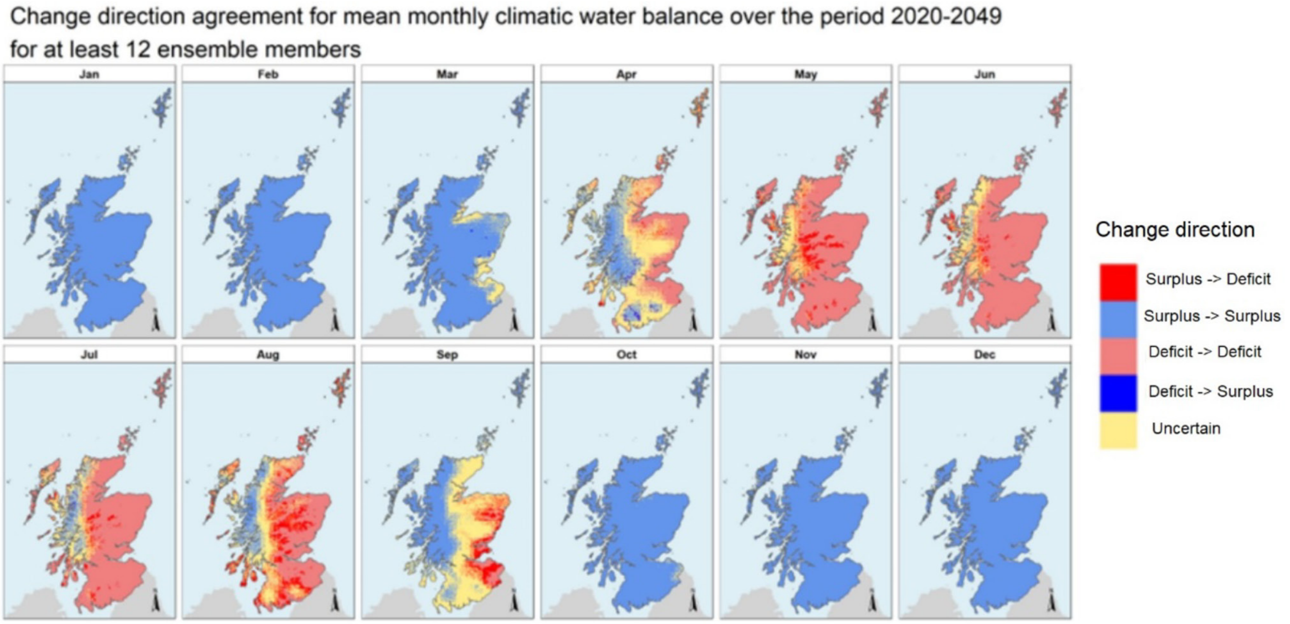

Figure 4: Agreement maps for the change direction (increase: blue/decrease: red) of the Climatic Water Balance for the period 2020 – 2049 for all 12 climate projections (ensemble members) relative to the baseline period 1960-1989. Yellow areas indicate no agreement between all 12 projections (Rivington and Jabloun, 2023).

To put this into context of impacts on land uses and land cover, Gagkas *et. al.* (2023) also looked at the direction of change in CWB for individual land cover classes, derived from UKCEH's Land Cover Map (LCM) for 2020 (Morton *et. al.,* 2021) for the observed and future climate, and found that, at a national scale, observed shifts from water surpluses to water deficits in late summer and early autumn are the main drivers of the degree of exposure of most land cover types to climatic stress, depending on their spatial distribution on a west vs east gradient. In this context, arable land, which is mostly located in the eastern part of Scotland, and to a lesser extent improved grasslands were found to be the most exposed habitat types to climatic water stress. Almost all arable land was found to be in constant climatic water deficit from May to August, whilst around of 70% to 85% of arable land (depending on which ensemble model is considered) was projected to be in water stress in September as well (see Appendix 2 for more detail).

3.2.2 How will soil water stress impact on crop yield: the case of barley?

Rivington *et. al.* (2022) used a crop simulation model and spatial weather, soil, and land use data to estimate barley growth across Scotland for multiple years under current climate and 12 future projected climates for the future periods of 2020 – 2049 and 2050 – 2079 (Figure 5). The study area of this analysis were the 1 km climatic grids covering areas where barley is currently being grown extended to adjacent areas (1 km buffer) in which barley could hypothetically be grown, specifically allowing for climate change.

A key element in the development of the crop simulation platform was the estimation of the soil's water holding capacity (SWHC), which was calculated as the difference between two main crop-related soil hydraulic properties, the drain upper limit (DUL) and the lower limit (LL). In addition, a Water Stress Indicator (WSI) was calculated where a WSI value of 0 represents no water stress and 1 is high water stress leading to crop failure. Values in the mid-range imply stress can occur that reduces yields. It was found that the timing of when water stress occurs in relation to the crop growth stage during a growing season is critical, e.g. low water availability between crop emergence and flowering will likely have more of a yield impact than between flowering and harvest.

The modelling utilised the climatic water balance data described above as indicator of water shortage and found that on average, barley reproductive phase will likely suffer from water shortage under most of the future climate model members. The soils' capacity to hold water will determine how barley yield is affected, as soils with high water holding capacity will benefit from water surplus during the vegetative phase and the surplus can be used during grain development.

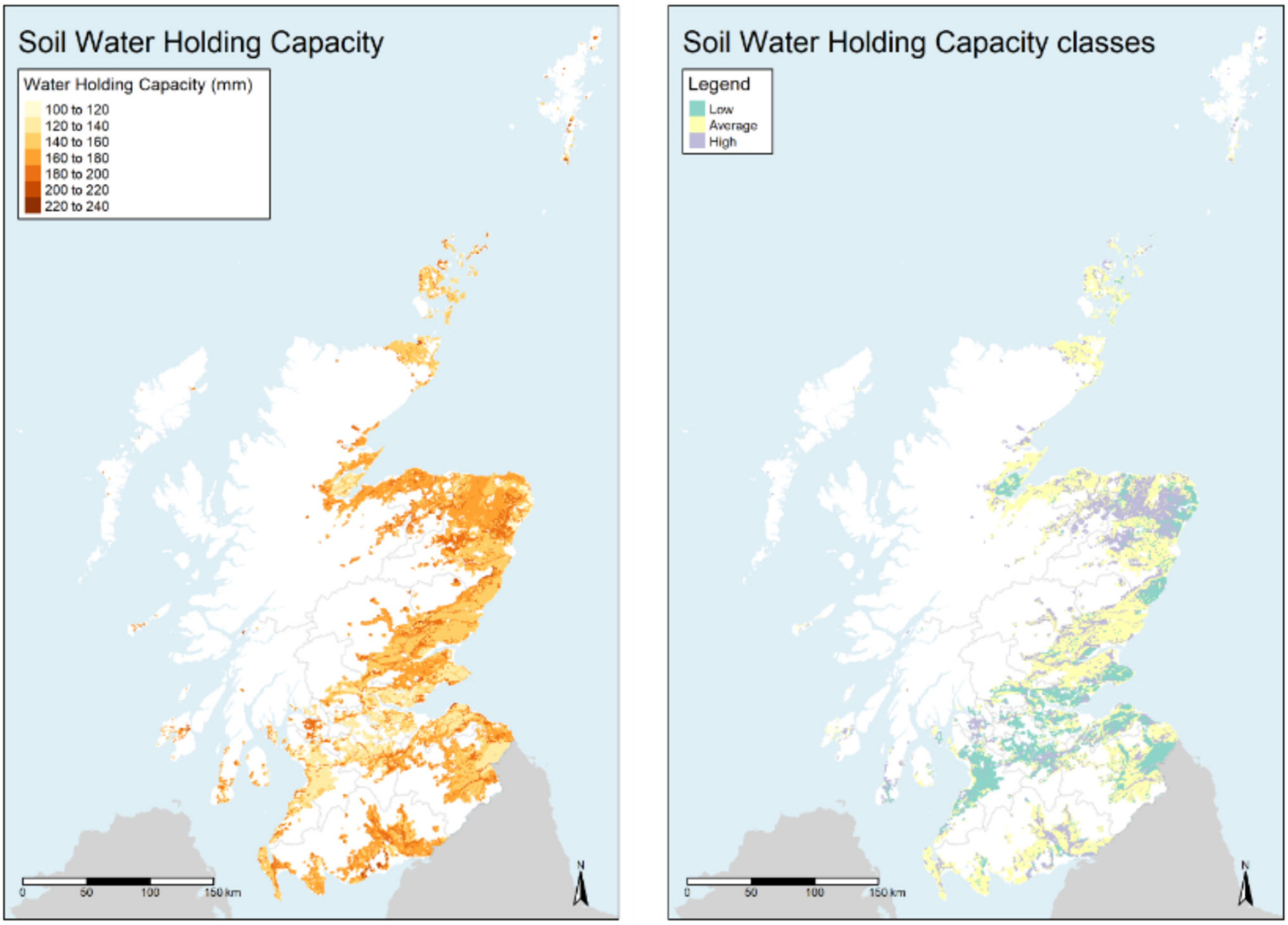

Figure 5: Spatial distribution of soil water holding capacity (WHC) (left map) and the different WHC classes (right, see text for explanation) (Rivington *et. al.,* 2022).

Overall, findings show that:

- With the high emissions scenario used (RCP8.5), climate change is likely to have both positive and negative impacts on barley growth and annual yields, but with an overall decrease in yields by the 2040s, which continues to worsen by the 2070s. It should be noted that there is little difference in estimated climate change impact between the low and high scenarios until c. 2040 – 2050, after which they start to diverge.
- Under the twelve climate projections used (which leads to temperature increases ranging from 1 to 3.5°C and 7% increase to 14% decrease in growing season precipitation), barley yields are likely to decrease in many parts of Scotland. This will likely be due to additional water stress, especially if water is limited in the spring to early summer periods.
- Future higher temperatures and potentially reduced precipitation are likely to lead to an increase in water deficit, where evapotranspiration loss of water to the atmosphere is greater than the precipitation input to soils. Areas with better soil water holding capacity appear to be more resilient and could potentially experience increase in yield when favourable climatic conditions permit.
- There is good agreement between the climate projections as to where these changes in yield may occur.
- There is likely to be increased annual variability, with some years potentially experiencing good yields when conditions are favourable.
- The spatial extent and temporal frequency of yield decreases is likely to cause substantial challenges to the barley supply chain and end users.
- Earlier sowing appears to be a viable adaptation option.

3.2.3 How will surface water availability change?

Daily time series data of total aggregated abstractions for a baseline period (2007 – 2018) were used to project future abstractions for the period 2019 – 2050. Scenarios analysed within the drought profiling framework to extract the drought frequency and average drought duration included: **Scenario 1** – a baseline using G2G model runs driven by observational meteorological data for 2007 – 2018; **Scenario 2** – G2G model runs driven by a regional climate change model (RCM) to simulate baseline conditions for 2007 – 2018 and **Scenario 3** – combining future runoff projections for 2019 – 2050 with six scenarios of future abstractions, including no increase in abstraction (using the same annual time series from the baseline applied to future until 2050) and increasing total abstractions by 5%, 10%, 15%, 20%, and 25% (Appendix 3).

The drought profiling framework was adapted from Visser-Quinn *et. al.* (2021) to calculate the volume of water available after abstraction in 23 catchments with available abstraction and modelled future flow data. Low flow events were defined as periods when the volume of available water, following actual abstraction, fell below the long-term Q95 threshold (i.e. flow that occurs less than 5% of the time). Following the drought definition from Visser-Quinn *et. al.* (2021), aligned with the Scotland National Water Scarcity Plan (SEPA, 2020), we defined drought as an event when

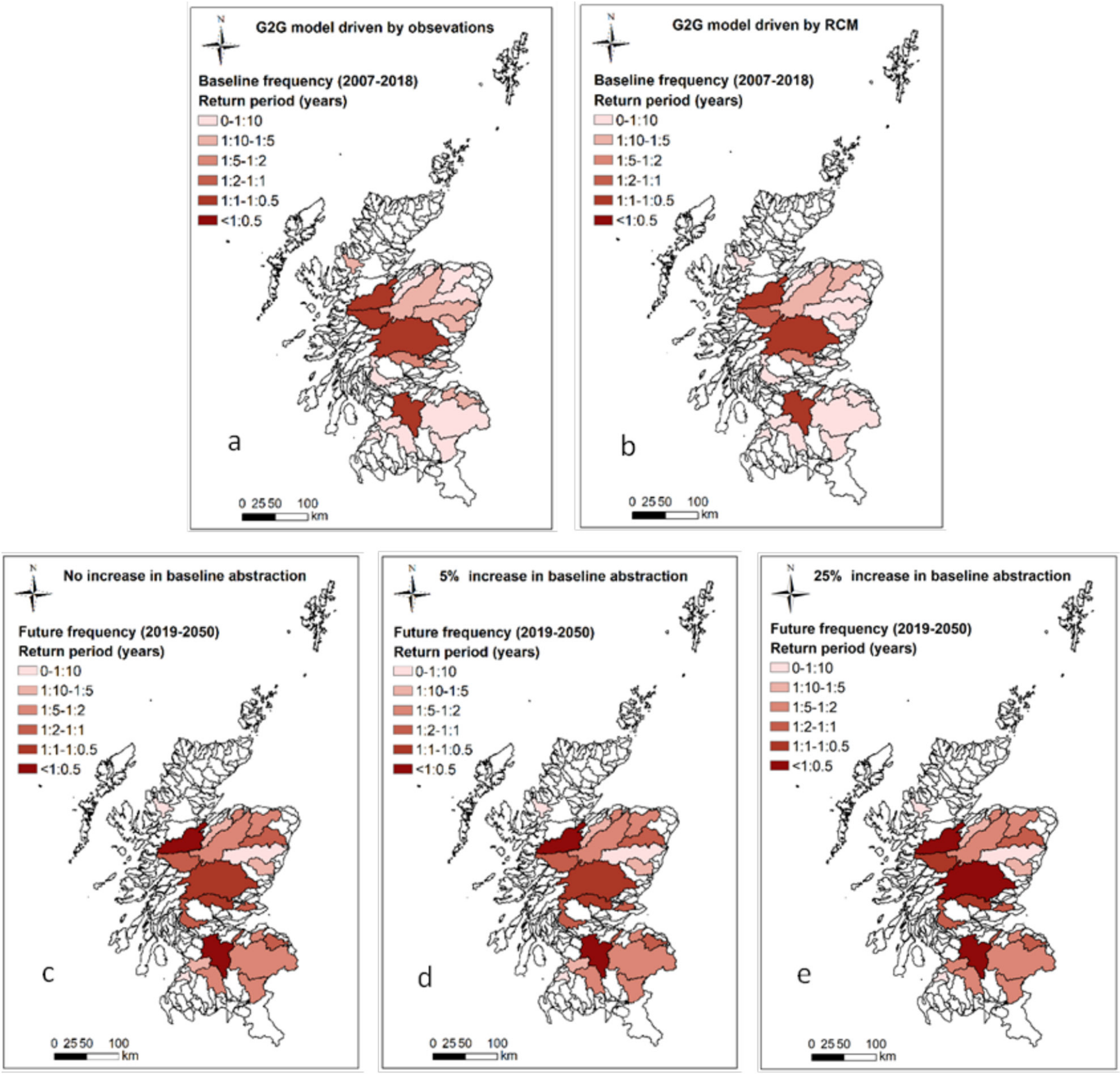

Figure 6: Drought frequency extracted from the drought profiling framework for the (a) historical period (2007–2018) driven by G2G model simulated flows using observations and baseline abstractions senario (b) historical period (2007–2018) driven by G2G model simulated flows using RCM and baseline abstractions (c) future (2019–2050) using G2G projected flows and baseline abstractions senario (d) future (2019–2050) using G2G projected flows and 5% increase in baseline abstractions. (e) future (2019–2050) using G2G projected flows and 25% increase in baseline abstractions. Catchments in white were not included in the analysis due to lack of data.

flow was below Q95 for 30-days or longer. We then calculated the frequency and duration of drought events for all scenarios across 23 catchments with available data. Frequency was defined as a number of droughts/year whilst Duration is a measure of the average event duration in days.

We observed an increase in both frequency (Figure 6) of drought events and average drought duration (Figure 7) in all future scenarios (2019 – 2050) in terms of mean, minimum and maximum. Mean drought frequency (events/year) was 0.33 and 0.65 across catchments in the baseline and the future, respectively. A maximum frequency of 1.92 and 2.31 in the baseline and future period respectively was seen in River Ness catchment. A minimum frequency of 0 events/year in the baseline period (i.e. no drought events) were seen in Esk, Nith, Water of Girvan, River Ayr, River Don, and Findhorn catchments, whereas 0.03 minimum number of events/year was observed in the future period at Water of Girvan, indicating an increased number of drought hotspots in the future. In the future scenario with an increase of 25% on baseline abstractions, a further increase in the maximum frequency of drought events up to 2.44 can be observed alongside an increase in mean event frequency of up to 0.7 per year.

We observed mean drought durations of 31 days and 51 days across all catchments during the baseline and the future respectively. Maximum

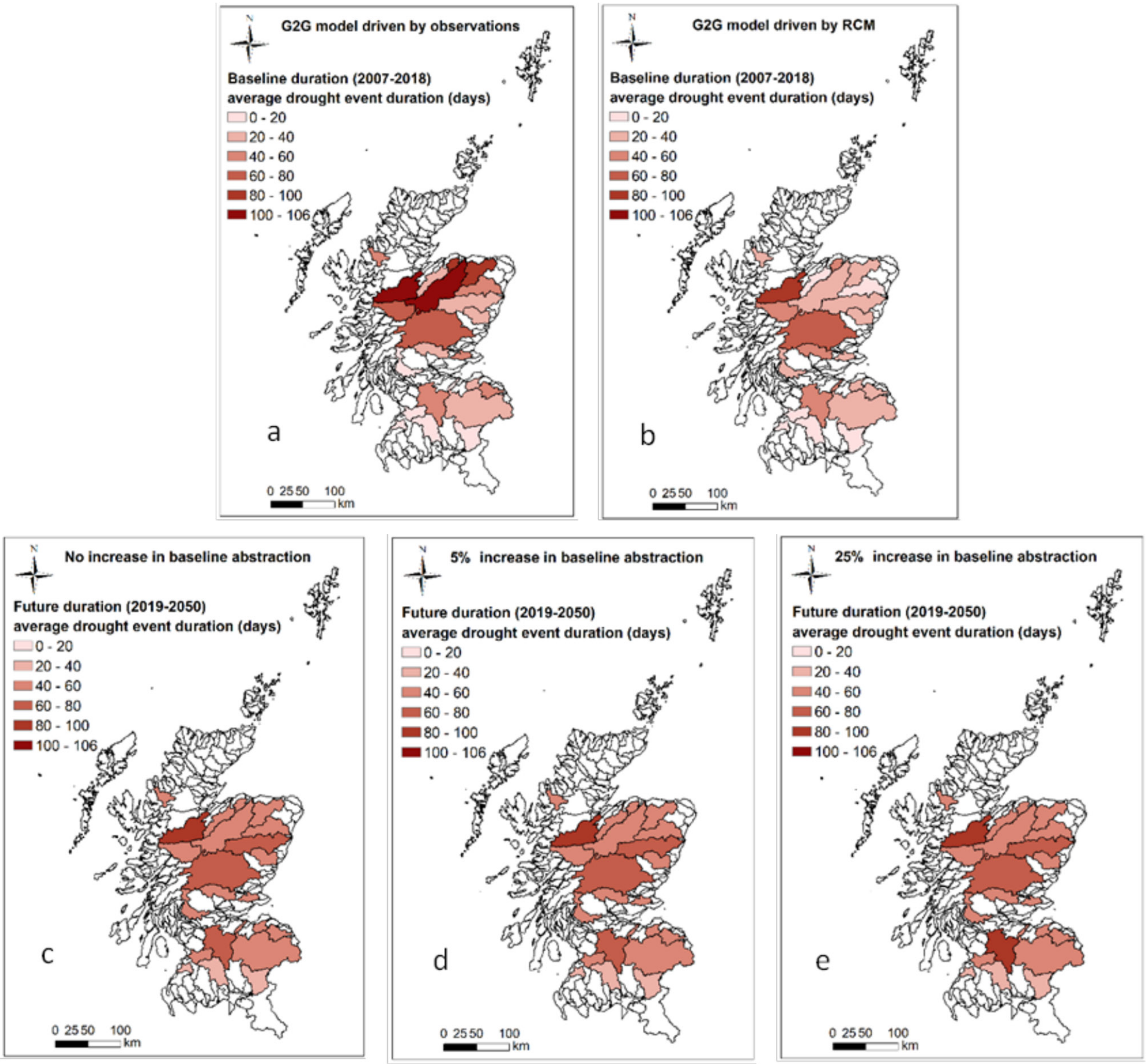

Figure 7: Average drought duration (in days) extracted from the drought profiling framework for the (a) historical period (2007–2018) driven by G2G model simulated flows using observations and baseline abstractions (b) historical period (2007–2018) driven by G2G model simulated flows using RCM and baseline abstractions (c) future (2019–2050) using G2G projected flows and baseline abstractions. (d) future period (2019–2050) using G2G projected flows and 5% increase in baseline abstractions.
(e) future (2019–2050) using G2G projected flows and 25% increase in baseline abstractions. Catchments in white were not included in the analysis due to lack of data.

average drought duration of 81 days and 86 days respectively was observed in Ness catchment in both baseline and future period. Similar to drought frequency, minimum average drought duration of 0 days was observed in the baseline period in Esk, Nith, Water of Girvan, River Ayr, River Don, and Findhorn catchments, whereas a minimum average drought duration of 31 days was observed in the future period at Water of Girvan, suggesting an increase in the length of drought events in the future. In the future scenario with an increase in baseline abstractions by 25%, maximum drought duration could further increase up to 95 days and mean drought duration up to 53 days.

3.2.4 Future groundwater resilience

We developed an initial assessment of the potential risk to future groundwater availability in Scotland due to climate change. This includes a review of the very limited published evidence on the (observed) past and (modelled) future changes in groundwater recharge and storage (level) under the effects of climate change. We highlight those areas where groundwater may be most vulnerable to drought and long-term depletion using existing national scale datasets of Scotland's aquifer properties and potential groundwater recharge. We do not consider groundwater quality dimensions or other pressures, such as increasing demand or land use change, which are also likely to have an influence on future groundwater availability in parts in Scotland. This new risk assessment uses a water security framework (Figure 8) to analyse the relationship between groundwater storage and groundwater recharge, highlighting parts of the country that are relatively more or less resilient to drought and long-term depletion. In parts of Scotland where long-term average potential recharge is relatively low (generally eastern Scotland), significant groundwater storage within sandstone aquifers can provide a buffer during dry periods, making abstractions from these aquifers potentially more resilient to drought. Conversely, large abstraction from relatively low-storage aquifers, such as those found within old crystalline rocks and many superficial deposits, will be more vulnerable to drought. An assessment of the eFLaG (enhanced Future Flows and Groundwater) dataset indicates that projected increases in the frequency and intensity of droughts may increase the vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers in eastern and central Scotland. Our analysis highlighted significant knowledge gaps in our understanding of the potential response of different types of aquifers to drought and long-term change in Scotland.

Groundwater recharge (along the horizontal axis of Figure 8) is the water that infiltrates from the land surface to reach the water table. Groundwater storage (along the vertical axis in Figure 8) is the total volume of water able to be held within an aquifer which can subsequently be released through surface water discharge (spring and river baseflow) or well discharge. In the bottom left quadrant of Figure 8, groundwater recharge and storage are both low. Aquifers in this context will have limited ability to sustainably support large levels of abstraction and limited capacity to buffer against the effects of drought and short- and long-term climate variability. As groundwater recharge increases along the horizontal axis, renewable

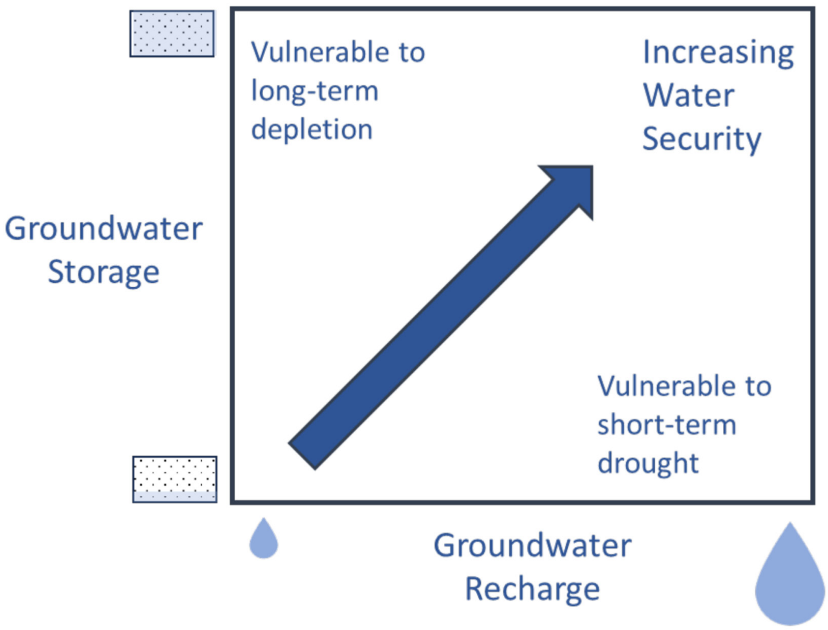

Figure 8: Groundwater security framework developed in this project, adapted from MacDonald *et. al.* (2021).

groundwater resources increase thus aquifers have greater capacity to sustainably support higher levels of abstraction in the long-term. However, limited storage means aquifers will still be vulnerable to drought. As groundwater storage increases along the vertical axis, aquifers have greater capacity to buffer against the effects of drought, however low recharge means aquifers in this context remain vulnerable to long-term depletion if levels of abstraction consistently exceed the renewability of the resource. In the top right, groundwater storage and recharge are high. Aquifers in this context will have the greatest capacity to support higher levels of abstraction in the long-term and to be able to continue to support abstraction during periods of drought.

Key findings from our analysis (Figure 9) show that:

Groundwater Storage, Recharge & Abstraction

- Scotland's aquifers are as diverse as its geology, encompassing regionally important, high-storage, high-productivity sedimentary aquifers to more localised, low-storage, low-productivity ancient crystalline and superficial aquifers.
- Potential groundwater recharge is strongly linked to rainfall showing a distinct west-east gradient.
- The majority of licensed groundwater abstractions for agriculture and distilling are in eastern Scotland, with most abstracting from high-storage sedimentary (sandstone) aquifers in Fife, Angus and Moray; abstraction from springs and relatively low-storage superficial aquifers is locally important for distilling in Speyside.
- Long term monitoring by SEPA across the various low to high productivity aquifers monitored in East and Southwest Scotland, suggests that summer groundwater levels have been lower in recent years compared to previous decades, but within or above normal ranges during the winter months.

Resilience to Drought

- In the east of Scotland, where long-term average potential recharge is relatively low, abstractions from high-storage sedimentary aquifers will be more secure through drought periods, while abstractions from lower-storage crystalline aquifers and localised superficial aquifers will be more vulnerable to drought.
- In the west of Scotland, where long-term average potential recharge is relatively high, low-storage aquifers will still be vulnerable to drought.
- Projected changes in the frequency and intensity of droughts may increase the future vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers.
- Evidence indicates that groundwater is critical to supporting river flow during droughts, particularly in upland areas.

Future Projections and Implications for Water Security

- Future projections indicate that eastern and central Scotland are likely to experience continued or accentuated reductions in potential groundwater recharge over most of the year, with possible insignificant to moderate increases in winter recharge unlikely to offset the summer deficits.
- In contrast, western Scotland is likely to experience a moderate increase in future groundwater recharge over most of the year apart from the summer months.
- Limited projections of groundwater levels at three sites across Scotland are consistent with recharge projections predicting an accelerated decrease in groundwater levels in the moderate to highly productive aquifers of eastern Scotland in the near and far future, while highly productive aquifers in southwest Scotland are likely to experience either no significant change or increasing groundwater levels.

3.3 What do the future projections mean for the three sectors?

The evidence collated in the previous section was presented to stakeholders during the four focus groups. In this section, we focus on stakeholder feedback on experiences with water scarcity, stakeholder perceptions of the impacts of future projections presented and how stakeholders might adapt to the projected changes. To supplement the impacts described by stakeholders, we conducted a socio-economic assessment of what is currently known about the potential costs of water scarcity to three sectors; as well as potential adaptation strategies. Full details of the socio-economic assessment are provided in Appendix 6.

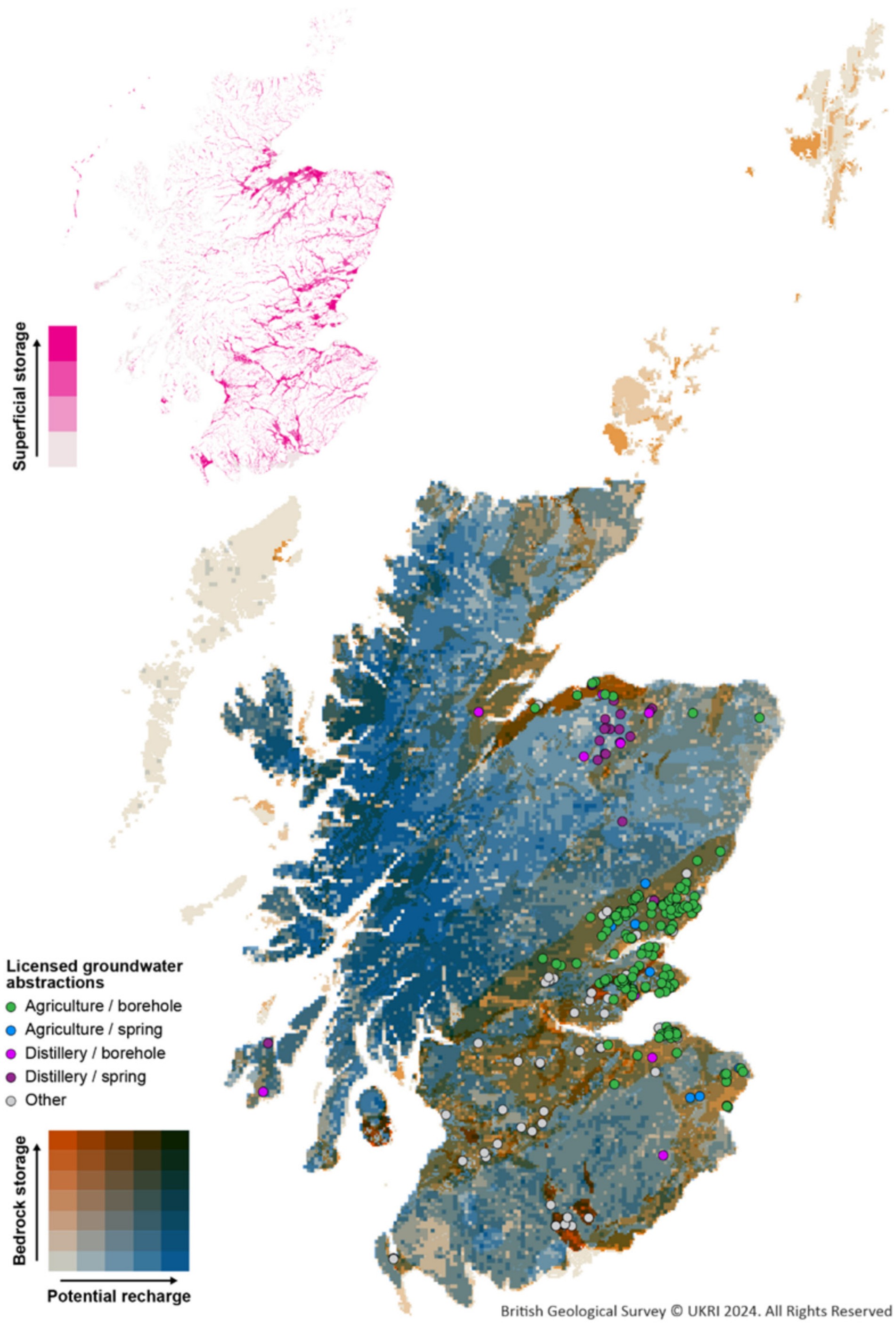

Figure 9: Water security analysis. Combined bedrock aquifer storage and long-term average potential recharge with licensed groundwater abstractions. Licensed groundwater abstraction records supplied by SEPA (Permissions received © SEPA 2024). Inset map shows superficial aquifer storage map. Note that potential groundwater recharge is only available for the mainland and larger islands of the Inner Hebrides.

3.3.1 Sector views on water scarcity

When asked if water scarcity impacted the farmers/businesses in their areas, most respondents said yes, farmers/businesses were impacted. In the livestock farmers focus group this figure rose to 100% of respondents (see Figure 10).

During discussion, all focus groups included stakeholders who believed that water shortages were becoming an increasing problem. In the national livestock focus group, SH12 pointed to increasingly dry summers, and felt that they would have once expected to see a dry summer 1 in every 10 years, whereas now they were seeing it 1 in every 2 or 3 years, consistent with the increased frequency of surface water drought expected in the future as presented in Section 3.2.3 (Figure 6).

In Fife, stakeholders raised concerns about fruit and vegetable crops, which can die within a day of water shortage. Distillers also mentioned problems with water scarcity, with one stakeholder commenting

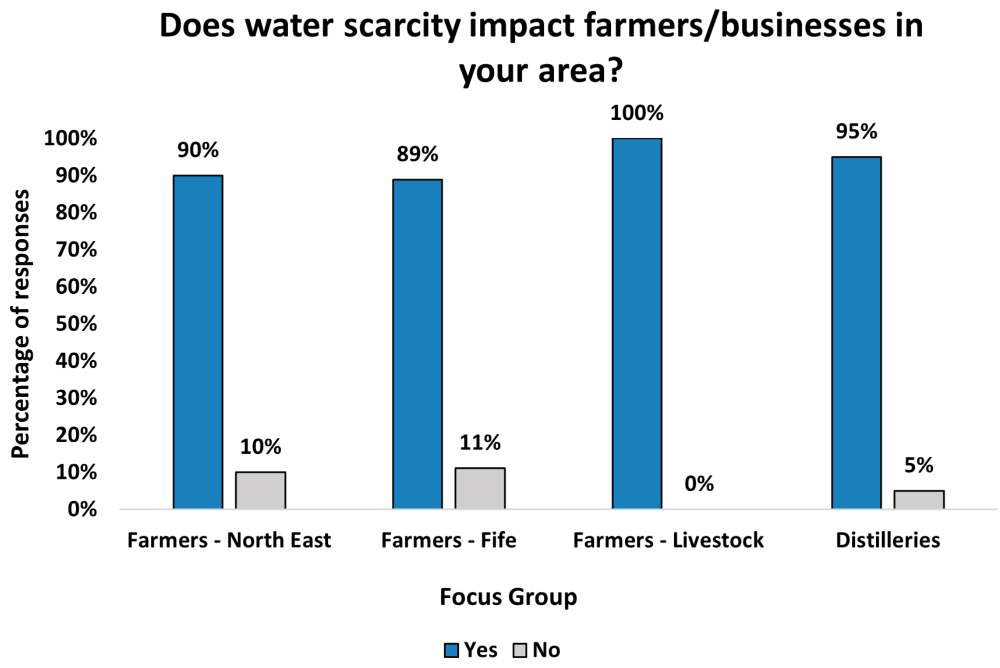

Figure 10: Stakeholder water scarcity impact perceptions different sectors in different locations across Scotland.

that they would be surprised if anyone in the room hadn't previously experienced this as a problem. There was a suggestion that attitudes within the distilling sector with regards to water scarcity changed recently; with SH58 suggesting that it has become important in the last 3 or 4 years.

Many of the experiences shared by stakeholders are consistent with the future projections presented in Section 3.2, Appendix 2. For example, Figure A2.11 indicates greater proportions of water deficits are projected in the months of September and October, which is consistent with the views of SH42 who noted the impact of dry periods on distilleries lasting longer into the calendar year. Although much of the evidence presented were projections to 2050, stakeholders across the three sectors indicated they had already felt the impacts, with SH 25, 28 and 29 from the Fife focus group agreeing that the projections were already being felt for the crop and horticulture sector. The Fife region experienced abstraction bans due to a significant water scarcity event as recently as 2022. The projected increased frequency of significant drought events in the Eden catchment changes from one in every 5–10 years to one in every year to 2050, risking further abstraction bans that could have significant impacts on vegetable and fruit growers who rely on abstraction for irrigation (see Figure 7).

In response to the evidence, a common comment across the focus group was the need for increased spatial resolution of the information provided. Participants, including SH32 and SH55 noted that SEPA monitor surface water flows at limited points of the river outlet when making decisions regarding significant water scarcity. It was suggested that expanding the monitoring across catchment would give a more representative view of water scarcity issues, particularly in headwaters and burns. Increased future soil moisture projections would also be welcome. Despite providing future impacts on soil water holding capacity in section 3.2.1 and the assumptions regarding soil water deficits in section 3.2.2, further research is required to consider the impacts on crops and vegetables other than barley. Further, although the research presented in section 3.2.4 advances the knowledge of groundwater security in Scotland, increased monitoring of groundwater storage and recharge tailored to local conditions is required to reduce uncertainty in decision-making around alternative abstraction sources.

Licenced abstractors were familiar with, and using, the information provided by SEPA on water levels and forecasts, but those reliant on water under registration and general binding rules were less aware of the information sources. They tended to rely on observing their local conditions (e.g. burns running dry) rather than using projections. This situation means that such water users are reacting to water scarcity, rather than proactively checking and adapting to the projected conditions.

3.3.2 Impacts of current and future water scarcity on the three sectors

At all focus groups, sectors believed that water scarcity would mean costs to their businesses. For livestock farmers, water scarcity would mean lower yields of forage. SH4 had experience of feed barley failing due to dry weather. Lack of quality fodder has an impact on livestock productivity, health and welfare; SH4 explained that drought in summer causes cows to stop cycling and therefore reduced calf numbers in spring, with implications for suckler enterprises given new restrictions on calving intervals under the Scottish Suckler Beef Support Scheme.

Arable farmers both in the North East and in Fife pointed to reduced production as a direct result of water scarcity. SH28 suggested that they may not want to be growing vegetables in three years' time if water scarcity patterns continue as predicted. SH30 talked about the costs of increased electricity use as the need for irrigation increases. Finding of our socio-economic assessment (Appendix 6) highlighted that rainfed agricultural sectors currently appear to be more vulnerable to future increase in water scarcity. Brás *et. al.* (2021) indicate that past droughts in the 1964-2015 period have caused an average yield loss of 9% for cereals, and 3.8% for non-cereal crops in the EU. The compounding impacts of this yield reductions in cereal crops on other sectors was described by focus group participants. SH1 said that a lack of water in arable lowlands is having a direct impact on the livestock systems in the uplands. Reduction in production of fodder leads to more feed being bought in, which in turn increases the cost of production. The increased demand for livestock feed was reflected in increased feed prices, affecting all livestock producers and leading to 20 to 25% higher input prices (UK HSA 2023, focus groups with farmers). For distilleries, increased barley prices due to the impacts of water scarcity on barely yields highlighted the compounding impact of water scarcity across the sectors.

Like livestock and arable farmers, water scarcity leads to reduced production and increased costs for the distillers. They said that the last two years have seen some sites forced to go to complete shut down due to water scarcity. SH34 pointed out that if they were forced to shut down for longer in the summer it would not only impact production, but also jobs, pay, and the ability to employ people year-round. SH37 expected impact on maltsters, which would in turn impact whisky distilleries. Further, increased energy costs associated with increased water scarcity were mentioned by the distilling sector. SH37 shared how their distillery had the means to pump water from an alternative source during low flows, but that as energy prices have gone up this has become increasingly unaffordable.

Our sector experts also raised the impacts that water scarcity can have on farmers' mental health (Yazd *et. al.,* 2020); particularly if they risk losing their crop, or experience cumulative negative impacts on their herd productivity. Furthermore, increased temperatures associated with dry summers can affect animal welfare and working conditions for distillers and farmers; whilst increased temperatures and dry conditions will amplify fire risks. It is possible that if there was more time in the focus groups, these impacts may.

3.3.3 How sectors can and are adapting to water scarcity

Stakeholders mentioned that they were already taking steps to address the water scarcity problem, particularly in the distilling sector, where latest innovations including thermal vapor recompression (TVR), mechanical vapor recompression (MVR) and chiller units would significantly reduce the amount of water abstracted for coolant in the distilling process and increase energy efficiency (Piller, 2024). Livestock farmers were also preparing for scarcity, one livestock farmer, SH4, has been working with technological advances to trial drought resistant grass swards on their farm, and other farmers felt that changing grass types could be a good way to cope with water scarcity in future.

Arable and horticultural farmers have invested in new boreholes to provide a guaranteed water supply when needed. Switching from surface to groundwater supplies is highlighted as an adaptation option in SEPA's National Water Scarcity Plan, however, our evidence in Section 3.2.4 highlights that this option should only be explored in areas that have high water security and further research will be required to understand where best to encourage groundwater abstraction. Improved soil management to increase moisture holding capacity was highlighted as a key approach for improving crop water availability, increasing groundwater recharge, attenuating surface water flows and ensuring applied nutrients were not lost through land run-off. Nature-based solutions (NbS), such as the creation of temporary storage ponds and runoff attenuation features (see Quinn *et. al.,* 2022; Roberts *et. al.,* 2023) can be implemented to disconnect storm runoff pathways, temporarily holding water and allowing it to infiltrate into the ground. Norbury *et. al.* (2017) found that willow-engineered log jams for a small (< $1km^2$) catchment in the Pennine uplands improved low flows by 27%. One key example for Scotland specifically involves leaky barriers that have been installed at the Glenlivet distillery to help improve low flows. Modelling work has shown that these measures have a positive impact on mitigating low and high flows (Fennell *et. al.,* 2023a) and thereby could be a cost-effective option for the distillery (Fennell *et. al.,* 2023b).

Looking to the future, livestock farmers were changing fodder crop varieties, noting a change to crop types may also be needed however, as with grass varieties, new crop varieties have to cope with extremes of flooding and drought. Although not mentioned in great depth by stakeholders during focus groups, Farming and Water Scotland and the Scottish Rural Development Programmes Farm Advisory Service provide ways of increasing drinking water use efficiency for extensive livestock production including alternative water systems such as solar and pasture pump systems (Audsley et. al., 2017).

Livestock farmers felt that there was room for improvement on current rainwater harvesting systems, including the use of new rainwater storage, although there were no grants to help with these adaptations. However, both the crop and distilling sector dismissed rainwater harvesting as a viable adaptation option, citing the method as not being sufficient to meet water needs and requiring additional treatment which would increase energy and chemical costs.

For the North-East and the Fife group, a combination of on farm and off farm (i.e., Scottish Water reservoirs) storage was called for. Although some participants had considered installing irrigation lagoons, there was common agreement across all farmer groups that the capital grants were too low and the application via the Agri-Environment Climate Scheme was too complicated and targeted meaning many farmers perceived they would not be eligible. Participants also recognised that current pump, or cannon, irrigation method was inefficient and alternative options such as trickle irrigation would increase efficiency.

Finally, SH29 felt that collective action could help to mitigate water scarcity effects. They said that they have licences that they don't use every year but are currently not allowed to irrigate their neighbours' land. If it were changed so they were able to share the allocation, then water scarcity impacts may be lessened. No abstractors from the agricultural sector were part of an abstractor group, with participants highlighting a lack of communication between farmers, leading in some instances to water sources running dry. In both irrigated farmed landscapes, and burns with more than one distillery, there is a need for co-ordination at landscape/catchment level (i.e. beyond the scope of a single business) at times of water scarcity. Rain-fed agriculture also benefits from measures designed to keep soil moisture at beneficial levels and to allow Groundwater recharge, and measures like wetlands and leaky barriers may need coordination across multiple holdings.

Overall, participants were aware of the challenges future water scarcity projections would pose for their sector. Despite many participants in the distilling sector indicating an awareness of adaptation measures and already acting, there was less consensus on how to respond to scarcity in the agricultural sector. The combination of lack of awareness of how much water they were using (demand) and the fact that those using water under registrations and General Binding Rules were not necessarily using projections of scarcity (such as found in the Water situation reports available on SEPA's Water Scarcity Website), meant that farmers still tend to react rather than proactively adapt to water scarcity. Participants cited cost of efficiency and substitutions as major barriers to adoption of adaptations. Clear pathways for adoption as the business level will be required to support decision-making.

Full descriptions of findings from the stakeholder focus groups are available in Appendix 5 and the socio-economic assessment can be found in Appendix 6.

4 Recommendations

Despite further developing knowledge of future water scarcity projections in Scotland, challenges were identified during modelling stages, and when talking to the different sectors, regarding the granularity of data available to reduce uncertainties in water abstraction volumes, future projections and their associated impacts. Although improving data collection would help improve decision-making, we identify further challenges related to adoption of adaptation measures in the agricultural sector. To overcome these challenges, we provide the following recommendations:

Improved data on water resources demand and supply

1. **There is a clear need for better data on actual abstraction volumes and water source types** (including estimates of those using surface and groundwater under general binding rules). Drinking water supply-related abstraction data currently cannot be shared by SEPA due to security limitations. However, seamless integration of this data with abstractions returns held by SEPA would streamline data analysis and prevent discrepancies in data formats, as well as minimize delays caused by preprocessing datasets. The SEPA abstraction licences database should explicitly attribute the sources of abstractions (surface water or groundwater) rather than relying solely on keywords from location descriptions to distinguish between the two. It is also essential to address missing location coordinates and water body names associated with the SEPA licenses. Improved abstraction licencing records by SEPA should also include information on the depth of groundwater sources.
2. **Improved integration of licensed abstraction data with farm census data** would allow areas to be identified where water demand is high and vulnerability to water deficit is also high (either in situ or upstream/downstream); this would allow targeted support (advice, incentives) to farmers to prepare for and cope with severe water shortages; and planning to prevent environmental damage from low water levels upstream/downstream of production areas. This information could be collected as part of a supplementary module within the annual June agricultural census, that farmers already complete (thus reducing the administrative burden on the farmer) and used to generate benchmarks (e.g. Standard Water Requirements, analogous to Standard Labour Requirements or Standard Output). Having such benchmarks would allow online farm water calculators to be developed, so farmers can estimate their risk of exposure to future water scarcity and increase the demand for water scarcity adaptation advice. An interim measure could be an updated survey on the use of irrigation to understand the actual abstraction volumes used and how much water is used for what purpose.
3. **There is an urgent need for improved groundwater monitoring network across Scotland.** The National Water Scarcity Plan highlights the potential for groundwater to provide more drought-resilient water supplies in response to future water scarcity. However, the lack of information regarding the status of these resources needs to be addressed to understand where, when and to what extent groundwater is a viable substitute in the long term. A cost-benefit analysis of exploiting deeper groundwater, or the potential for augmenting recharge through, for example, nature-based solutions such as managed aquifer recharge need to be explored.
4. **To improve local understanding of conditions for the onset of significant drought, spatial resolution of drought risk assessment could be refined**. Focus group participants reported that on occasion, whilst river flows may be above severe drought levels, water resources in upstream locations were already in drought. Therefore, other metrics and data sources, additional to SEPA gauging stations, should be explored, including the use of remote sensing data.

Informed adaptation options

5. **Encouraging all farmers and small scale distilleries** (not just the licenced abstractors) to consult the Water Situation Report that highlights **potential water scarcity** before the higher tiers of the National Water Scarcity Plan are reached is useful to allow businesses to proactively adapt (e.g. planning stocking rates, installing rainwater tanks). Continued promotion of the website and status of surface water availability using social media would help embed this as part of good practice business management (see also recommendation 6).

6. **Tools (Water Calculators to estimate demand) are needed to help farmers and distillers make strategic decisions** about what and how to produce in future conditions. Forward looking focus group participants stressed the need to move from reaction to adaptation to future water scarcity – and advice on the costs, benefits and practicalities of adaptation options is needed. However transformation from current farming or distilling practices to alternative climate resilient practices (e.g. switching crops or grazing regimes) is not yet common.

7. **There is a pressing need for further work to understand the likely response of different groundwater systems to future pressures** and subsequent impacts on future groundwater availability to ensure that groundwater remains a viable substitute in the long term. The National Water Scarcity Plan promotes the use of groundwater as a temporary, more resilient resource when there are drought conditions affecting rivers and streams. However, there is a lack of information regarding the status and vulnerability of these resources at a catchment scale. This is particularly important for both low and high storage aquifers in Eastern Scotland, which are critically important for economic activities such as agriculture and distilling and which are expected to see a decrease in future long term average recharge. But it also applies to low storage aquifers in Western Scotland, which are locally important for small-scale water supply. We found that many participants were already using groundwater and experienced problems with scarcity during drought events. An improved understanding of Scotlands' regional groundwater resources could be achieved through an expansion of the long-term groundwater monitoring network, further collation and analysis of existing groundwater data, including the development of numerical models of strategically important aquifers, and more detailed localised studies to collect new data in areas where future pressures are expected to be greatest.

8. **Future work into potential adaptation measures** would be beneficial for future water security planning. This might include an assessment of areas where groundwater could provide more resilient supplies compared to other source types, a cost-benefit analysis of exploiting deeper groundwater, or the potential for augmenting recharge through, for example, nature-based solutions such as managed aquifer recharge. Swapping from surface to groundwater options should only be explored in areas that have high water security. This improved understanding could be achieved through an expansion of the long-term groundwater monitoring network, further collation and analysis of existing groundwater data, including the development of numerical models of strategically important aquifers, and more detailed localised studies to collect new date in areas where future pressures are expected to be greatest.

Clear adaptation pathways

9. **There is a need for a cross-sector process of preparing for a future of water extremes**, as also found in the parallel CREW project by Gosling *et. al.* (2024).

10. Promoting water scarcity in terms of business resilience to risks makes the topic relevant but also requires a **clear pathway to options that can be implemented by a variety of businesses**. Farmers recognise the importance of soil management and appropriate seed varieties to respond to extremes of flood and droughts, so this can be reinforced through the advice and demonstration networks. Sector-specific awareness raising is needed for rainwater harvesting, natural water retention measures, such as wetlands and on-farm irrigation ponds to illustrate potential returns on investment and how they can fit with rotations and existing farm practices. Clarity on funding opportunities for these interventions in the new Agricultural Payments Tiers would be welcomed, however farmers may also need to consider commercial loans.

11. **The work of catchment management partnerships** that can provide a coordination mechanism, act as a trusted intermediary and reduce the need for busy farmers or distillery managers to undertake relationship building and maintenance activities **needs more visibility and support to co-ordinate water resources use at landscape/catchment level**. As water is a common pool good, collective action responses can help mitigate scarcity, however there was limited support for these from farmers or distillers. In some cases, focus group participants reported not being able to use their full licence allocation (there is too much permitted given changing climatic conditions) and this could be addressed through periodic

licence review and allocation sharing, or even trading, at a catchment scale.

12. **The costs of adaptation strategies should be compared to potential costs of water scarcity** to the sectors, at the individual business level to support decisions to invest in adaptation strategies, and at the national scale when assessing (i) abstraction restriction requirements and (ii) potential interventions to support adaptation of the sector to future climate conditions. However, this is currently hindered by the lack of relevant data at the micro level (individual business) (see recommendations 1 and 2). An assessment of the effect of droughts for individual businesses would require access to and monitoring of micro-level data such as: production levels for each crop, their production costs, linked to irrigation systems and uses, water storage capacity and pedo-climatic data. This assessment, pooling together micro-level data from a large sample of farms and over time, could allow to statistically determine the effect of droughts on farms that have already experienced them. This assessment would provide useful information for (i) farms with more limited data or evidence to support their adaptation strategy, (e.g. having less experience of water scarcity until now), (ii) anticipate effects at regional or national scales.

Conclusions

Through literature review, modelling and stakeholder focus groups, this research project summarises how future projections of water scarcity in Scotland and their impacts on crop, livestock and distilling sectors. First, we identified how water use differed by the three sectors, with rainfed sources critical for arable crop producers, surface water and groundwater sources abstracted for irrigation, as well as cooling and process water in distilling processes, and mains or private sources utilised for health and welfare of livestock. Despite identifying 1,601 abstraction licences and 472 registrations there is a need for better data on abstraction volumes, including abstractions under GBRs, to give true understanding of water use.

Modelled projections to 2050 indicate that central and eastern Scotland are likely to be at increasing risk of CWB deficit from May through to September. Increasing deficits would lead to soil water stress impacts for crops, as demonstrated in our analysis of soil water holding capacity and the negative impacts on barley yield. We indicate how deficits may propagate to surface water and groundwaters. Frequency and duration of surface water droughts are projected to approximately double by 2050, which would trigger further licence restrictions and impacts on horticulture and distilling sectors. For groundwater, monitoring suggests that, in some areas, summer groundwater levels have been lower in recent years compared to previous decades, but within or above normal ranges during the winter months. Projected increases in the frequency and intensity of droughts may increase the future vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers.

In our experience of discussing current and projected water scarcity across the different sectors, the direction of travel in terms of the increasing frequency of water scarcity events and related impacts were understandable to participants. We find that rainfed agricultural sectors currently appear to be more vulnerable to future increases in water scarcity as few available and profitable adaptation strategies seem to have been identified for the sector. However, good soil management was seen as an important part of climate resilience and something that all farm businesses can implement.

Although we identify adaptation measures already being taken by participants, particularly in the distilling sector, there is less consensus on how to respond to scarcity, with cost of efficiency and substitution measures being cited as major barriers to uptake. Promoting water scarcity in terms of business resilience to risks makes the topic relevant. Once awareness is raised, the sectors require a clear pathway to options that can be implemented by a variety of businesses and are flexible enough to respond to differences between and within sectors. The costs of adaptation strategies should be compared to potential costs of water scarcity to the sectors, at the individual business level to support decision to invest in adaptation strategies.

These conclusions and recommendations imply a systemic approach, requiring multi-level actions from individual businesses to national institutions; and crossing different policy directorates. Adapting to future climate challenges, in the context of current headwinds related to inflationary input costs and tight profit margins, can be challenging to achieve, however building capacity to improve understanding of how sectors use water and can respond to change needs to begin now to equip us for the future.

5 References

Afzal, M., and Ragab, R. (2020) 'Assessment of the potential impacts of climate change on the hydrology at catchment scale: modelling approach including prediction of future drought events using drought indices', *Applied Water Science*, 10 (10), pp. 1–19. DOI: https://doi.org/10.1007/s13201-020-01293-1.

AHDB (2018) 'Agricultural drought impact Summer 2018.' 23pp. Available online at: Agricultural drought impact summer 2018.pdf (ahdb.org.uk) (Accessed May 2024).

Angleitner, B., Kluge, J., Lappöhn, S., Plank, K., Mateeva, L. and Schnabl, A. (2021). The economic and ecological footprint of the spirits sector in the EU, the UK, Norway and Switzerland. Available online at: https://irihs.ihs.ac.at/id/eprint/5957/ (Accessed January 2024).

Arksey, H., and O'Malley, L. (2005). 'Scoping Studies: Towards a Methodological Framework.' *International Journal of Social Research Methodology: Theory and Practice, 8*(1), 19–32. DOI: https://doi.org/10.1080/1364557032000119616.

Audsley, R., Dunbar, D., Laird, B., Jones, A., McDonald, C., Ramsey, R., (2017). 'Technical note TN66: Alternative Watering for Field Grazed Livestock II – Pumping Systems', Farm Advisory Service. Available online at: fas.scot/downloads/alternative-watering-field-grazed-livestock-ii-pumping-systems/.(Accessed May 2024).

Boca, A.D., White, C.J. and Bertram, D. (2022). 'A review of the risks to water resources in Scotland in response to climate change. CD2021_02. *Centre of Expertise for Waters (CREW)*.' Available online at: A review of the risks to water resources in Scotland in response to climate change | CREW | Scotland's Centre of Expertise for Waters (Accessed January 2024)

Blasco, J., Navarro-Ortega, A., and Barcelo, D. (2015). 'Towards a better understanding of the links between stressors, hazard assessment and ecosystem services under water scarcity.' *Science of The Total Environment*, 503-504, 1-2. DOI: https://doi.org/10.1016/j.scitotenv.2014.08.022

Brás, T. A., Seixas, J., Carvalhais, N., and Jägermeyr, J. (2021). Severity of drought and heatwave crop losses tripled over the last five decades in Europe. *Environmental Research Letters*, 16(6), 065012. DOI: 10.1088/1748-9326/abf004

Cammarano, D., Hawes, C., Squire, G., Holland, J., Rivington, M., Murgia, T., Roggero, P.P., Fontana, F., Casa, R. and Ronga, D., (2019). 'Rainfall and temperature impacts on barley (Hordeum vulgare L.) yield and malting quality in Scotland.' *Field Crops Research*, *241*, p.107559. DOI: https://doi.org/10.1016/j.fcr.2019.107559.

Carmen, A.E., and Waylen, K., (2023). 'Considering Whisky – a rationale and plan for focusing on the Scotch whisky sector in order to understand how natural capital can unlock private-sector investment in nature-based solutions.' Available online at: https://www.hutton.ac.uk/sites/default/files/files/JHI-D5-3_WP4_M4_1_WhiskyPlan.pdf (Accessed January 2024).

Carson, A., Reichel, R., Bell, S., Collins, R., Smith, J. and Bartley, D. (2023), Haemonchus contortus: an overview. Veterinary Record, 192: 26-28. DOI: https://doi.org/10.1002/vetr.2613

Chatterton, J.C., Hess, T.M. and Williams, A.G., (2010). The water footprint of English beef and lamb production. Available online at: https://dspace.lib.cranfield.ac.uk/handle/1826/5425 (Accessed 8th of May 2024).

Creaney, R., Matthews, K., Miller, D., Wardell-Johnson, D., Gandossi, G., Hopkins, J., Chabdu, A., Rees, N., Blackstock, K. (2021). 'Report on MOVING Task 3.3 activities Vulnerability of the Speyside whisky industry to environmental change.' Available online at: https://www.hutton.ac.uk/sites/default/files/files/MOVING_T3_3%20report%20for%20stakeholders.pdf (Accessed January 2024).

Cuthbert, M.O., Gleeson, T., Bierkens, M.F.P., Ferguson, G. and Taylor, R.G. (2023). 'Defining renewable groundwater use and its relevance to sustainable groundwater management.' *Water Resources Research*, *59*(9), p.e2022WR032831. DOI: https://doi.org/10.1029/2022WR032831

DWQR. (2023). 'Private Water Supplies: Drinking Water Quality in Scotland 2022.' Drinking Water Quality Regulator (DWQR) for Scotland. Accessible online at: https://www.dwqr.scot/media/bv4go0kc/pws-annual-report-2022-november-2023.pdf (Accessed: January 2024).

Environment Agency. (2023). 'Annex to the review of the research and scientific understanding of drought.' Environment Agency. Available online at: https://assets.publishing.service.gov.uk/media/656f10920f12ef07a53e0229/Annex_to_the_review_of_the_research_and_scientific_understanding_of_drought.pdf (Accessed January 2024).

European Environment Agency. (2022). 'Europe's groundwater – a key resource under pressure.' European Environment Agency. Available online at: https://www.eea.europa.eu/publications/europes-groundwater#:~:text=Water%20abstraction%20for%20irrigation%20and,Hungary%2C%20southern%20Italy%20and%20Spain. (Accessed January 2024).

FAO. (2023). 'The Impact of Disasters on Agriculture and Food Security 2023 – Avoiding and reducing losses through investment in resilience.' Food and Agriculture Organization of the United Nations. Available online at: https://openknowledge.fao.org/handle/20.500.14283/cc7900en (Accessed April 2024).

Fennell, J., Geris, J., Wilkinson, M.E., Daalmans, R. and Soulsby, C., (2020). 'Lessons from the 2018 drought for management of local water supplies in upland areas: A tracer-based assessment.' *Hydrological Processes*, 34(22), pp.4190-4210. DOI: https://doi.org/10.1002/hyp.13867

Fennell, J., Soulsby, C., Wilkinson, M.E., Daalmans, R., Geris, J., (2023a). 'Assessing the role of location and scale of Nature Based Solutions for the enhancement of low flows.' *Int. J. River Basin Manag*. 21, 743–758. DOI: https://doi.org/10.1080/15715124.2022.2092490

Fennell, J., Soulsby, C., Wilkinson, M. E., Daalmans, R., and Geris, J. (2023b). 'Time variable effectiveness and cost-benefits of different nature-based solution types and design for drought and flood management.' *Nature-Based Solutions*, 3, 100050. DOI: https://doi.org/10.1016/j.nbsj.2023.100050

Fleming, A., O'Grady, A. P., Stitzlein, C., Ogilvy, S., Mendham, D., and Harrison, M. T. (2022). 'Improving acceptance of natural capital accounting in land use decision making: Barriers and opportunities.' *Ecological Economics, 200*, 107510. DOI: https://doi.org/10.1016/j.ecolecon.2022.107510

Foster, S., and MacDonald, A. (2014). 'The 'water security' dialogue: why it needs to be better informed about groundwater', *Hydrogeology Journal*, 22(7), pp. 1489–1492. DOI: https://doi.org/10.1007/s10040-014-1157-6.

Gagkas Z., Jabloun M., Udugbezi E., Rivington M. (2023). 'Assessment of Natural Capital exposure to current and future meteorological drought. Deliverables 2.1d and 2.3c for the Project D5-2 Climate Change Impacts on Natural Capital.' The James Hutton Institute, Aberdeen. Scotland. DOI: https://zenodo.org/records/8392470

Geris J., Loerke L., Valero D., Comte J.C., Marshall K., Rivington M., and Wilkinson M. (2023). 'Understanding the relationship between water scarcity and land use in private water supply catchments – Interim Report. CRW2022_05.' Scotland's Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/project/crw202205-understanding-relationship-between-water-scarcity-and-land-use-private-water (Accessed January 2024)

Gosling, R. (2014). 'Assessing the impact of projected climate change on drought vulnerability in Scotland.' *Hydrol. Res.* 45, 806–816. DOI: https://doi.org/10.2166/nh.2014.148

Gosling, R., Halliday, S.J., Brown, I., Black, A., and Hendry, S. (2024). Climate Crisis: informing Scotland's actionable mitigation and adaptation response to water scarcity project summary. CRW2022_07. Centre of Expertise for Waters (CREW)

Grafton, R.Q., and Wheeler, S.A. (2018). 'Economics of water recovery in the Murray-Darling Basin, Australia.' *Annual Review of Resource Economics*, *10*, pp.487-510. DOI: https://doi.org/10.1146/annurev-resource-100517-023039

Hannaford, J., Mackay, J., Ascott, M., Bell, V., Chitson, T., Cole, S., Counsell, C., Durant, M., Facer-Childs, K., Jackson, C., Kay, A., Lane, R., Mansour, M., Moore, R.J., Parry, S., Rudd, A., Simpson, M., Turner, S., Wallbank, J., Wells, S., Wilcox, A. (2022). 'Hydrological projections for the UK, based on UK Climate Projections 2018 (UKCP18) data, from the Enhanced Future Flows and Groundwater (eFLaG) project.' NERC EDS Environmental Information Data Centre. DOI: https://doi.org/10.5285/1bb90673-ad37-4679-90b9-0126109639a9

Hannaford, J., Mackay, J.D., Ascott, M., Bell, V.A., Chitson, T., Cole, S., Counsell, C., Durant, M., Jackson, C.R., Kay, A.L., Lane, R.A., Mansour, M., Moore, R., Parry, S., Rudd, A.C., Simpson, M., Facer-Childs, K., Turner, S., Wallbank, J.R., Wells, S., Wilcox, A. (2023). 'The enhanced future Flows and Groundwater dataset: development and evaluation of nationally consistent hydrological projections based on UKCP18.' Earth System Science Data, 15 (6). 2391-2415. DOI: https://doi.org/10.5194/essd-15-2391-2023

Hayes, R., Austin, H., Cadman, D., Bradley, D., Milner, N. (2017). Literature review of short-term flow reduction ecological impacts and recovery: R16115QQ. Available online at: https://www.sepa.org.uk/media/336665/sepa-literature-review-of-short-term-flow-reduction-ecological-impacts-and-recovery.pdf (Accessed: January 2024).

HDC. (2013). 'Water harvesting and recycling in soft fruit. A grower guide.' Horticultural Development Company (HDC). 30pp. Available online at: https://projectbluearchive.blob.core.windows.net/media/Default/Horticulture/Diseases/Recycling%20in%20soft%20fruit%20-%20website%20version.pdf (Accessed: April 2024).

Herrera-Pantoja, M. and Hiscock, K.M. (2008). 'The effects of climate change on potential groundwater recharge in Great Britain', *Hydrological Processes*, 22(1), pp. 73–86. DOI: https://doi.org/10.1002/hyp.6620.

Hughes, A., Mansour, M., Ward, R., Kieboom, N., Allen, S., Seccombe, D., Charlton, M. and Prudhomme, C. (2021). 'The impact of climate change on groundwater recharge: National-scale assessment for the British mainland.' *Journal of Hydrology*, 598, p.126336. DOI: https://doi.org/10.1016/j.jhydrol.2021.126336

Hydro Nation Scholar Programme. (2024). 'Scholar Biography Brady Johnson, The role of groundwater in adapting to climate change and increasing resilience to drought in Eastern Scotland.' Available online at: https://www.hydronationscholars.scot/scholars/brady-johnson (Accessed February 2024).

ITV News. (2022). 'Water scarcity levels in River Teviot threaten production of Borders Distillery Scotch whisky.' Available online at: https://www.itv.com/news/border/2022-08-12/water-scarcity-levels-threatens-production-of-scotch-whiskey (Accessed January 2024).

Kirkpatrick Baird, F., Stubbs Partridge, J. and Spray, D. (2021). 'Anticipating and mitigating projected climate-driven increases in extreme drought in Scotland 2021-2040.' NatureScot. Available online at: https://www.nature.scot/doc/naturescot-research-report-1228-anticipating-and-mitigating-projected-climate-driven-increases (Accessed December 2023).

Knox, J.W., Weatherhead, K. and Ioris, A.A.R. (2007). 'Assessing Water Requirements for Irrigated Agriculture in Scotland', *Water International*, 32(1), pp. 133–144. DOI: https://doi.org/10.1080/02508060708691970.

Köseoğlu, M.N. (2017). 'Optimisation and valuation of water use in Scotland.' University of Edinburgh. Available online at: https://www.era.lib.ed.ac.uk/bitstream/handle/1842/31243/Koseoglu2018_redacted.pdf?sequence=3andisAllowed=y. (Accessed January 2024).

Lawley, R. and Garcia-Bajo, M. (2010). 'The National Superficial Deposit Thickness Model (version 5).' *British Geological Survey Internal Report*, OR/09/049. 18pp. Available online at: https://nora.nerc.ac.uk/id/eprint/8279/1/SDTM_V5_UserGuide.pdf (Accessed February 2024).

MacAllister, D.J., MacDonald, A.M., Kebede, S., Godfrey, S. and Calow, R. (2020). 'Comparative performance of rural water supplies during drought.' *Nature communications*, 11(1), p.1099. DOI: https://doi.org/10.1038/s41467-020-14839-3

MacDonald, A.M., Lark, M.R., Taylor, R.G., Abiye, T., Fallas, H.C., Favreau, G., Goni, I.B., Kebede, S., Scanlon, B., Sorensen, J.P.R, Tijani, M., Upton, K.A., West, C. (2021). 'Mapping groundwater recharge in Africa from ground observations and implications for water security.' *Environ Res Lett* 16 DOI: https://doi.org/10.1088/1748-9326/abd661

Madsen, M. (2022). 'From Gin to Whisky - Scottish Whisky Distilleries Making Gin.' The Whisky Ardvark. Available online at: https://www.thewhiskyardvark.com/post/from-gin-to-whisky-scottish-whisky-distilleries-making-gincom (Accessed: January 2024).

Mansour, M.M., Wang, L., Whiteman, M., Hughes, A.G. (2018). 'Estimation of spatially distributed groundwater potential recharge for the United Kingdom.' *Quarterly Journal of Engineering Geology and Hydrogeology*, 51 (2). 247-263. DOI: https://doi.org/10.1144/qjegh2017-051

Meadows, S. and Strachan, P. (2015). 'Anaerobic Digestion and Resource Use within the Scotch Whisky and UK Beer Industries', University of Strathclyde Glasgow, pp. 1–96. Available online at: http://www.esru.strath.ac.uk/Documents/MSc_2015/Meadows.pdf. (Accessed April 2024).

Mekonnen, M.M. and Hoekstra, A.Y. (2012). A global assessment of the water footprint of farm animal products. *Ecosystems*, 15(3), pp.401-415. DOI: https://doi.org/10.1007/s10021-011-9517-8

Meritt W.S., Letcher, R.A., Jakeman, A.J. (2003). 'A review of erosion and sediment transport models.' *Environmental Model Software* 18:761-799. DOI: https://doi.org/10.1016/S1364-8152(03)00078-1

Miller, S. (2022). 'How do you make gin with less water?' Gin Magazine. Available online at: https://gin-mag.com/2022/06/22/how-to-make-gin-with-less-water-sustainability-environment/ (Accessed: January 2024).

Misstear, B.D.R., Brown, L. and Daly, D. (2009). 'A methodology for making initial estimates of groundwater recharge from groundwater vulnerability mapping', *Hydrogeology Journal*, 17(2), pp. 275–285. DOI: https://doi.org/10.1007/s10040-008-0342-x.

Moran, D., MacLeod, M., McVittie, A., Lago, M. and Oglethorpe, D. (2007). 'Dynamics of water use in Scotland.' *Water and Environment Journal*, *21*(4), pp.241-251. DOI: https://doi.org/10.1111/j.1747-6593.2007.00068.x.

Morris, J., Else, M. A., El Chami, D., Daccache, A., Rey, D., and Knox, J. W. (2017). 'Essential irrigation and the economics of strawberries in a temperate climate.' *Agricultural Water Management*, 194, 90-99. DOI: https://doi.org/10.1016/j.agwat.2017.09.004

Morton, R.D., Marston, C.G., O'Neil, A.W., Rowland, C.S. (2021). 'Land Cover Map 2020 (10m Classified Pixels, GB).' NERC EDS Environmental Information Data Centre. DOI: https://doi.org/10.5285/35c7d0e5-1121-4381-9940-75f7673c98f7.

Murphy, E., Curran, T.P., Holden, N.M., O'Brien, D. and Upton, J., (2018) 'Water footprinting of pasture-based farms; beef and sheep', *animal*, 12(5), pp. 1068–1076. DOI: https://doi.org/10.1017/S1751731117002865

NFU Scotland. (2023). 'Impacts of 2022 drought on crops.' Briefing to Scottish Government and SEPA. 4pp.

NFU Scotland. (2024). 'Water resource management policy proposals.' Policy paper. 4pp.

Norbury, M., Phillips, H., Macdonald, N., Brown, D., Boothroyd, R., Wilson, C., Quinn, P. and Shaw, D. (2021). 'Quantifying the hydrological implications of pre-and post-installation willowed engineered log jams in the Pennine Uplands, NW England.' *Journal of Hydrology*, *603*, p.126855. DOI: https://doi.org/10.1016/j.jhydrol.2021.126855

Ó Dochartaigh, B.E.O., Doce, D.D., Rutter, H.K.; MacDonald, A.M. (2015). 'User guide : Aquifer Productivity (Scotland) GIS Datasets. Version 2, revised report.' Nottingham, UK: British Geological Survey. Available online at: http://nora.nerc.ac.uk/id/eprint/509619/. (Accessed February 2024).

Ó Dochartaigh, B.E.O., MacDonald, A.M., Fitzsimons, V., Ward, R. (2015) Scotland's aquifers and groundwater bodies. Nottingham, UK, British Geological Survey, 63pp. Available online at: https://nora.nerc.ac.uk/id/eprint/511413/ (Accessed February 2024).

Parry, S., Mackay, J.D., Chitson, T., Hannaford, J., Magee, E., Tanguy, M., Bell, V.A., Facer-Childs, K., Kay, A., Lane, R. and Moore, R.J. (2024). 'Divergent future drought projections in UK river flows and groundwater levels.' *Hydrology and Earth System Sciences*, *28*(3), pp.417-440. DOI: https://doi.org/10.5194/hess-28-417-2024

Piller. (2024). 'Case study – Piller MRV Technology in the distillation process at Chivas Brothers.' Piller. Available online at: https://www.piller.de/fileadmin/media/pdf-files/product-sheets/PILLER_Case_Study_Chivas_Brothers.pdf (Accessed April 2024).

Pretty, J., Benton, T.G., Bharucha, Z.P., Dicks, L.V., Flora, C.B., Godfray, H.C.J., Goulson, D., Hartley, S., Lampkin, N. and Morris, C. (2018). 'Global assessment of agricultural system redesign for sustainable intensification.' *Nature Sustainability*, 1, 441-446. DOI: https://doi.org/10.1038/s41893-018-0114-0

Quinn, P.F., Hewett, C.J., Wilkinson, M.E. and Adams, R., (2022). 'The role of Runoff Attenuation Features (RAFs) in natural flood management'. *Water*, *14*(23), p.3807. DOI: https://doi.org/10.3390/w14233807

Ritchie, J. and Lewis. J. (eds.). (2003). 'Qualitative Research Practice: A Guide for Social Science Students and Researchers.' Sage Publications, London (336 pages).

Rivington, M., Akoumianaki, I., Coull, M. (2020). '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.' CRW2018_05. Scotland's Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2018_05_report_FINAL%2Blink.pdf (Accessed January 2024).

Rivington, M. and Jabloun, M. (2023). 'Climate Trends and Future Projections in Scotland.' Deliverable D2.1a for the Project D5-2 Climate Change Impacts on Natural Capital. Zenodo. DOI: https://doi.org/10.5281/zenodo.7657945

Rivington, M., Jabloun, M., Matthews, K., Wardell-Johnson, D., Miller, D., (2022). 'Barley Responses to Climate Change. Report of developing capability in the spatial modelling of barley cropping under current and future climates.' RESAS Strategic Research. Available online at: https://www.hutton.ac.uk/sites/default/files/files/RD2-4-1%20Barley%20Responses%20to%20Climate%20Change%20-%20Final%20report%20to%20RESAS%20-%20signed%20off.pdf (Accessed February 2024).

Roberts, M.T., Geris, J., Hallett, P.D. and Wilkinson, M.E. (2023). 'Mitigating floods and attenuating surface runoff with temporary storage areas in headwaters.' *Wiley Interdisciplinary Reviews: Water*, *10*(3), p.e1634. DOI: https://doi.org/10.1002/wat2.1634

Roberts, C. and Maslin, M. (2021). 'How might climate change impact Scotch Whisky production in the next 50-100 years?' University College London report. 21pp. Available online at: https://fosm.de/wp-content/uploads/2021/10/How-might-climate-change-impact-Scotch-whisky-production-in-the-next-50-100-years_v2.pdf (Accessed February 2024).

Rose, D. C., Shortland, F., Hall, J., Hurley, P., Little, R., Nye, C., and Lobley, M. (2023). 'The Impact of COVID-19 on Farmers' Mental Health: A Case Study of the UK.' *Journal of Agromedicine, 28*(3), 346-364. DOI: https://doi.org/10.1080/1059924x.2022.2137616

SAC Consulting. (2023). 'The farm management handbook 2023–2024.' SAC consulting, editor Alastair Beattie, 564pp. Available online at: https://www.fas.scot/downloads/farm-management-handbook-2023-24/ (Accessed April 2024).

SAC Consulting. (2019). 'The Economic Impact of Extreme Weather on Scottish Agriculture.' SAC Consulting. 33pp. Available at: https://www.wwf.org.uk/sites/default/files/2023-09/The-impact-of-extreme-weather-events-on-Scottish-agriculture.pdf (Accessed April 2024).

Salmoral, G., Ababio, B. and Holman, I.P. (2020). 'Drought Impacts , Coping Responses and Adaptation Increase Drought Resilience', *Land*, 9, pp. 23–67. DOI: https://doi.org/10.3390/land9060202

Schestak, I., Styles, D., Black, K. and Williams, A.P. (2022). 'Circular use of feed by-products from alcohol production mitigates water scarcity.' *Sustainable Production and Consumption*, *30*, pp.158-170. DOI: https://doi.org/10.1016/j.spc.2021.11.034.

Scotch Whisky Association. (n.d., a). 'Tours, Trails and Tourism.' Available online at: https://www.scotch-whisky.org.uk/discover/tours-trails-and-tourism/ n (Accessed: January 2024).

Scotch Whisky Association. (n.d., b). 'Scotch Whisky visitor centres become top visitor attraction in Scotland.' Available online at: https://www.scotch-whisky.org.uk/newsroom/scotch-whisky-visitor-centres-become-top-visitor-attraction-in-scotland/ (Accessed: January 2024).

Scotch Whisky Association. (2023a). 'Water Stewardship Framework.' Available online at: https://www.scotch-whisky.org.uk/media/2118/water-stewardship-framework-july-2023.pdf (Accessed January 2024)

Scotch Whisky Association. (2023b). 'Scotch Whisky Association Responsible Water Use.' Available at: https://www.scotch-whisky.org.uk/insights/sustainability/responsible-water-use/ (Accessed: January 2024).

Scottish Government. (2010). 'Results from the Scottish Survey of Agricultural Production Methods.' Scottish Government. Available online at: https://www.gov.scot/publications/results-scottish-survey-agricultural-productionmethods-2010/pages/3/ (Accessed: September 2023).

Scottish Government. (2012). Statistical Publication Agriculture Series: Results from the Scottish survey of agricultural production methods, 2010. Available at: https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2012/10/results-scottish-survey-agricultural-production-methods-2010/documents/statistical-publication-agriculture-series-results-scottish-survey-agricultural-production-methods-2010/statistical-publication-agriculture-series-results-scottish-survey-agricultural-production-methods-2010/govscot%3Adocument/00404867.pdf

Scottish Government. (2016). 'Scottish Survey of Farm Structure and Methods.' Scottish Government. Available online at: https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2016/11/scottish-survey-farm-structure-methods-2016/documents/00509969-pdf/00509969-pdf/govscot%3Adocument/00509969.pdf (Accessed: May 2024).

Scottish Government. (2019). 'Agricultural facts and figures: 2019.' Scottish Government. Available online at: https://www.gov.scot/publications/agriculture-facts-figures-2019/ (Accessed: January 2024).

Scottish Parliament. (2018). 'Brewing and Distilling in Scotland – Economic Facts and Figures.' Available online at: https://digitalpublications.parliament.scot/ResearchBriefings/Report/2018/10/11/Brewing-and-distilling-in-Scotland---economic-facts-and-figures#Introduction (Accessed February 2024)

SEPA. (2013). 'Supporting Guidance (WAT-SG-70) Sector-specific Guidance: Agriculture.' Scottish Environment Protection Agency (SEPA). Available online at: https://www.sepa.org.uk/media/152036/wat-sg-70.pdf (Accessed December 2024).

SEPA. (2018). 'Scotch Whisky Sector Plan.' Scottish Environment Protection Agency (SEPA). Available online at: https://sectors.sepa.org.uk/scotch-whisky-sector-plan/ (Accessed December 2024).

SEPA. (2020). 'Scotland's National Water Scarcity Plan.' Scottish Environment Protection Agency (SEPA) Available online at: https://www.sepa.org.uk/media/510820/scotlands-national-water-scarcity-plan-july-2020.pdf. (Accessed December 2024).

SEPA. (2024). 'Water Situation Report and Archives.' Scottish Environment Protection Agency (SEPA). Available online at: https://www.sepa.org.uk/environment/water/water-scarcity/ (Accessed February 2024).

SEPA. (n.d.). 'An economic analysis of water use in the Scotland river basin district.' 67pp. Scottish Environment Protection Agency (SEPA). Available online at: https://www.sepa.org.uk/media/37271/economic-analysis_water-use_scotland.pdf (Accessed January 2024).

Soulsby, C., Scheliga, B., Neill, A., Comte, J.C. and Tetzlaff, D. (2021). 'A longer-term perspective on soil moisture, groundwater and stream flow response to the 2018 drought in an experimental catchment in the Scottish Highlands.' *Hydrological Processes*, 35(6), p.e14206. DOI: https://doi.org/10.1002/hyp.14206

Teedon, P., Hakeem, N., Helwig, K., Henderson, F. and Martinolli, M. (2020). 'Private water supplies and the local economic impacts in Scotland. CRW2017_11.' Scotland's Centre of Expertise for Waters (CREW). Available online at: https://www.crew.ac.uk/sites/www.crew.ac.uk/files/publication/CRW2017_11_report_Final_2020_05_22.pdf (Accessed December 2023).

UKCEH. (2024). 'eFLaG: Enhanced Future Flows and Groundwater.' UK Centre for Ecology and Hydrology (UKCEH), Available online at: https://www.ceh.ac.uk/our-science/projects/eflag-enhanced-future-flows-and-groundwater (Accessed February 2024).

UK Government. (2021). 'Technical File for Scotch Whisky.' UK Government. Available online at: https://www.gov.uk/protected-food-drink-names/scotch-whisky (Accessed: January 2024).

UK HSA. (2023). 'Health Effects of Climate Change (HECC) in the UK: 2023 report. Chapter 11. The direct and indirect effects of drought on human health in the UK.' UK Health Security Agency (UK HAS). 35pp. Available at: https://assets.publishing.service.gov.uk/media/65705cf4746930000d4888d0/HECC-report-2023-chapter-11-drought.pdf (Accessed January 2024).

UKIA. (n.d.). 'Switching irrigation technologies. Does switching from rainguns to booms, sprinklers or trickle save water, energy and money – fact or fiction?' UK Irrigation Association. 8pp. Available online at: www.ukia.org/3d-flip-book/switching-technologies/ (Accessed April 2024).

UN-Water. (2013). 'What is water security?' United Nations. Available online at: https://www.unwater.org/publications/what-water-security-infographic (Accessed December 2023).

Visser-Quinn, A. et al. (2021). 'Mapping future water scarcity in a water abundant nation: Near-term projections for Scotland', *Climate Risk Management*, 32(March), p. 100302. Available at: DOI: https://doi.org/10.1016/j.crm.2021.100302.

Waajen, A.C. (2019). 'The increased risk of water scarcity in Scotland due to climate change and the influence of land use on water scarcity: issues and solutions.' ClimateXChange University of Edinburgh, 6p. Available online at: https://www.climatexchange.org.uk/media/3680/cxc-water-scarcity-climate-change-and-land-use-options.pdf (Accessed January 2024).

Wilson, P., O Dochartaigh, B., Cooper, M. and Ni Chonchubhair, R. (2023). 'Northern Ireland's Groundwater Environment. Geological Survey of Northern Ireland, Belfast.' Available online at: http://nora.nerc.ac.uk/id/eprint/535562/. (Accessed February 2024).

WWF. (2019). The Economic Impact of Extreme Weather on Scottish Agriculture. Available Online: Microsoft Word – Impact of Extreme Weather Scottish Ag Final.docx (wwf.org.uk). Accessed April 2024).

Yawson, D.O., Adu, M.O., Mulholland, B., Ball, T., Frimpong, K.A., Mohan, S. and White, P.J. (2019). 'Regional variations in potential groundwater recharge from spring barley crop fields in the UK under projected climate change.' *Groundwater for Sustainable Development*, 8, pp.332-345. DOI: https://doi.org/10.1016/j.gsd.2018.12.005

Yazd, S.D., Wheeler, S.A. and Zuo, A. (2020). Understanding the impacts of water scarcity and socio-economic demographics on farmer mental health in the Murray-Darling Basin. *Ecological Economics*, 169, p.106564. DOI: https://doi.org/10.1016/j.ecolecon.2019.106564

Appendix 1 Current water use by the three sectors

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How are abstractions regulated in Scotland?

Surface and groundwater abstractions are regulated by the Controlled Activities Regulations (Regulations) 2005 (CAR) under the Water Environment and Water Services Act (Scotland) 2003 and the subsequent amendments ("CAR 2013" is the Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2013; "CAR 2017" is the Water Environment (Miscellaneous) (Scotland) Regulations 2017; "CAR 2021" is the Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2021). The level of authorisation required is dependent on the effect that the activity will have on the water environment. These fall under 1) General Binding Rules where activities are considered to be at low risk and don't require specific authorisation, 2) Registration for activities that pose low individual risk but may collectively affect the environment, and 3) Licence activities that pose moderate to high risk to the environment. Abstractions greater than or equal to 10m³/day and less than 50m³/day are subject to Registration, while Simple and Complex licence activities are regulated under CAR licences according to abstraction volumes (>50 and >2000m³/day, respectively). Surface water abstractions less than 10m³/day and some other exemptions, for example groundwater abstractions <200m depth below Registration and Licence level abstraction do not require authorisation.

How much water is used by the crop and livestock sector?

Thirteen farm types (Table A1.1) describe the dominant (50% or more) economically valuable activity on the farm holding, covering 6.5 million hectares of Scotland, and 35,000 businesses and 55,000 holdings according to the 2021 Joint Agricultural Census (JAC).

Information from SEPA on licenced abstractions shows that there are:

- 1,205 surface water licences for agricultural irrigation
- 187 groundwater licences for agricultural irrigation

Table A1.1: Thirteen farm types according to the dominant economic activity extracted from JAC. Farms in bold are thought to be the main sectors that use irrigation. Mixed crops may also have potatoes on rotation. Those in italics are likely to use water for housed livestock and granivores; but this will depend on their farming system (intensive or extensive).

Specialist cattle - rearing and fattening
General field cropping (incl potatoes)
Specialist cereals, oilseeds and protein crops
Mixed Crops – Livestock [often feed crops]
Specialist sheep and goats
Graziers [rented land to others for grazing]
Sheep and cattle combined
Specialist dairying
Various grazing livestock
Specialist horticulture and permanent cropping
Specialist granivores (poultry, pigs)
Various granivores combined
Not classified

- 25 surface water licences for agricultural activities other than irrigation (these are likely to be used for livestock watering)
- 9 groundwater licences for agricultural activities other than irrigation
- 145 surface water licences for distilling purposes
- 30 groundwater licences for distilling purposes

Of the identified licences, 1,375 were for surface water sources (85.9%) and 226 were from groundwater sources (14.1%; see Figure 1).

In addition, SEPA registration level abstractor data shows that there are approximately:

- 132 registrations for agricultural irrigation
- 340 registrations for agricultural activities other than agriculture

Whilst a single farm holding may hold more than one abstraction licence at a time (for different sources), the number of abstraction licences covers only a small proportion of 55,000 farms. The rest of the abstractions are likely to be regulated under GBR.

Table A3.1 illustrates the percentage of abstractions by the agricultural and distilling sectors for years 2017 and 2018. For these two years, abstraction return data is available on all abstraction types, including drinking water. Increased abstraction for agricultural irrigation can be seen in 2018 (drought year), as compared to 2017 (average year). However, overall, abstractions by agricultural and distilleries sectors are comparable with drinking water abstractions. 'Other' uses, including hydropower and some 'unknown' purposes are responsible for more than half of abstractions by volume.

Most of the crop irrigation in Scotland occurs along east coast areas such as East Lothian, the Borders, Angus, and Fife (SEPA, 2013), mainly to support potato growing, soft fruits, and vegetable production (Scottish Government, 2010). Other crops, such as spring barley, are mainly dependent on rainfall and rely on soil moisture for crop growth. For example, Cammarano *et. al.,* (2019) found that rainfall is more important than temperature regarding spring barley yield. Rainfall across Scotland during the growing months of April to August ranges from 180 mm to over 400mm (Cammarano *et. al.,* 2019). In Scotland, barley is primarily grown for animal feed and for spirit distilling.

For irrigated crops, the main source of irrigation is on-farm groundwater (48.3%), followed by mains water supply (26.2%), off-farm surface water – water sourced outside the farm boundary – (23%), on-farm surface water sources (19.4%) and other sources (10.5%) (Scottish Government, 2016). Water is typically applied using sprinkler irrigation (57.2%) surface irrigation – flooding of the field surface or furrows in the soil – (30.5%) and drop irrigation (17.8%) (Scottish Government, 2016). Irrigation needs are highly dependent on agroclimatic zone, and soil moisture. For example, high soil moisture and wetter agroclimatic zones would need around 45 mm per year of irrigation to grow potatoes, but a drier agroclimatic zone with low soil moisture would need up to 195 mm per year (Knox, Weatherhead and Ioris, 2007). With the latest available figures for irrigation methods from 2016, there is a need for updated annual surveys to understand how irrigation requirements differ year on year.

Sixty percent of land area in Scotland is used for livestock farming (Visser-Quinn *et. al.,* 2021). In 2019, Scotland produced over 1,371 million litres of milk, 588,000 beef cattle, and 2,411,000 sheep for market, generating an income of £1,153M from livestock, and £511M from livestock products (Scottish Government, 2019). To continue to produce such quantities, the Scottish livestock industry is dependent on water (Köseoğlu, 2017), which is abstracted for use in both livestock drinking requirements and for cleaning purposes (Moran *et. al.,* 2007). In the UK, where many livestock are farmed outdoors for most of the year, past droughts have impacted feed availability and grass productivity, causing problems for livestock farmers (Salmoral, Ababio and Holman, 2020).

There are limited studies, information or data on livestock water use in Scotland. Global figures suggest that the average water footprint for animals (live weight) across various production systems was 4,325 m^3/ton for chicken meat, 5.988 for pig meat, 10,412 m^3/ton for sheep meat, and 15,415 m^3/ton for beef (Mekonnen and Hoekstra, 2012). However, the majority of this water is needed for growth of animal feed (green water), with only an average of 1.1% of these amounts are required for drinking water (blue water) (Mekonnen and Hoekstra, 2012). Water footprints are sensitive to different livestock production systems, for example the systems in Scotland will be different to systems in the USA. The study of pasture-based farms in Ireland by Murphy *et. al.,* (2018) developed carcass weight average water footprints for beef (8391 l/kg or 8,526 m^3/ton) and sheep (7,672 l/kg or 7,795 m^3/ton), which may be more representative of Scottish systems.

Chatterton *et. al.,* (2010) developed a national average water footprint for English beef (17,657 m^3/ton) and lamb (57,779 m^3/ton) production, also using carcass weight. The significant difference in the water footprint for lamb production compared to Mekonnen and Hoekstra (201) and Murphy *et. al.,* (2018) is due to upland hill systems having lower grass yields and thus resulting in a greater green water footprint, however, green water accounting in upland areas, where rainfall is typically higher, is disputed (Chatterton *et. al.,* 2010), as without upland grazing natural vegetation growth would intercept rainfall, which is no different to being intercepted by upland grasslands.

Water use in Scottish agriculture is somewhat difficult to quantify, leading to the need to make interpretations from other regions, which is problematic due to difference in production systems and water use definitions. In the past, there have been no regulations or requirements to record water use in Scotland (Knox, Weatherhead and Ioris, 2007; SEPA, 2013), leading to a general lack of data, as demonstrated by the lack of livestock water footprints in Scotland. Future research is required to increase understanding of water use within both livestock and crop sectors.

How much water is currently needed by the distilling sector?

The Scotch Whisky Association state there were 145 malt and grain whisky distilleries in 2023. Many of these distilleries produce both whisky and other distilled spirits. There are approximately 90 gin distilleries.

In Scotch whisky production water is abstracted for several purposes. To be labelled Scotch the water used to create the mash and to dilute the resulting alcohol must be Scottish (UK Government, 2021). Water is needed for cooling processes during production (Creaney *et. al.,* 2021; Carmen and Waylen, 2023). When used for cooling, water is often abstracted from rivers and then returned to the water source (SEPA, 2018).

In 2012, the Scotch whisky industry used a total of 52 million cubic metres of water (Scotch Whisky Association 2012, in Meadows and Strachan, 2015). Between distilleries, there is variation in the amount of water used in the production of whisky, likely due to differences in processes and volumes of spirit produced. One analysis of water needed for whisky production in Scotland shows that to produce 1 litre of pure alcohol, roughly 114 litres of water were needed (Schestak *et. al.,* 2022). Of these, 66 litres were for cooling, 27 litres for boiling, 19 litres for mashing, and 2 litres for cleaning (Schestak *et. al.,* 2022). Water for cooling is considered a considerable problem within the sector, as water temperatures are predicted to increase in summers. As they do, increased amounts of water are needed to adequately cool the production processes, leading to greater abstraction amounts. This runs the risk of conflicting with limits on abstraction during summers, disrupting production. The Scotch Whisky Association Water Stewardship Framework acknowledges that changes to water, due to climate change, in Scotland will impact the industry, communities, and environment. To mitigate impacts, the framework sets out objectives for those in the Scotch industry to help organisations aim for responsible consumption, engagement with stakeholders, and advocacy. Within the framework they set out actions that should be taken by members to meet the above objectives – for example, a water use goal of 12.5 – 25 litres per litre of pure alcohol by 2025 (Scotch Whisky Association, 2023b).

Water is not only used in the distilling of whisky itself, but also in the tourism that often goes alongside it, where water is required for both drinking and cleaning. In 2022 alone whisky tourists spent £85 million in Scottish distilleries (Scotch Whisky Association n.d.a). Where there are distillery tours there are often visitor centres, over 70 in distilleries across Scotland (Scotch Whisky Association n.d.b) and with these come bars and sometimes accommodation.

Available data suggests that most whisky abstractions take place in the Highlands region. The river Spey alone is home to the greatest concentration of Scottish distilleries in the nation and is historically a drought hotspot (Visser-Quinn *et. al.,* 2021). Some distilleries are already feeling the pressure of water scarcity, with increasing concerns about the impact drier weather will have on abstraction licences (ITV News, 2022).

The UK is the largest gin producer in Europe, and in recent years gin consumption in the UK and Ireland have also increased, creating a growing market for this production (Angleitner *et. al.,* 2021). In Scotland, around 20 whisky distilleries are now also producing gin (Madsen, 2022). As a distilled spirit, gin production faces the same water scarcity issues as whisky. To produce gin, water is needed during fermentation, cooling, and dilution – with cooling being responsible for the bulk of the water use (Miller, 2022). This is worth considering when looking at abstraction in the spirits sector across Scotland.

Appendix 2 What climate changes can we expect to see in the next 5–15 years and up to 2050?

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Rivington and Jabloun (2023) used observed baseline data (HadUK-Grid dataset[2]) produced using a spatial interpolation of data between UK Meteorological Office observation stations, and future UKCP18 climate projections RCP8.5 (both datasets at 1 km resolution) to investigate recent (i.e., 1990–2019) and future (2020–2049) climate changes compared to the 1960–1989 baseline period.

The observed trends in precipitation, maximum and minimum temperature were derived by comparing data from 1990–2019 with a 1960–1989 baseline period, which can be summarised as:

Precipitation:

- There has been an overall increase in precipitation, with the area of Scotland experiencing higher precipitation being larger than that of decreases (Figure A2.1).
- There is a wide variation in spatial and temporal change.
    - o In the west precipitation increased in December to May, but either remained similar or decreased in July, August, and October.
    - o Eastern Scotland became drier in January, March, May, August, September and December, but wetter in February, June, July, October and November.
- The largest increases in precipitation occurred in February.
- There has been mixed response in terms of variability in temporal and spatial patterns of change in precipitation.
    - o January, April, July, and November (and to a lesser extent August) have seen a decrease in variability in the west.

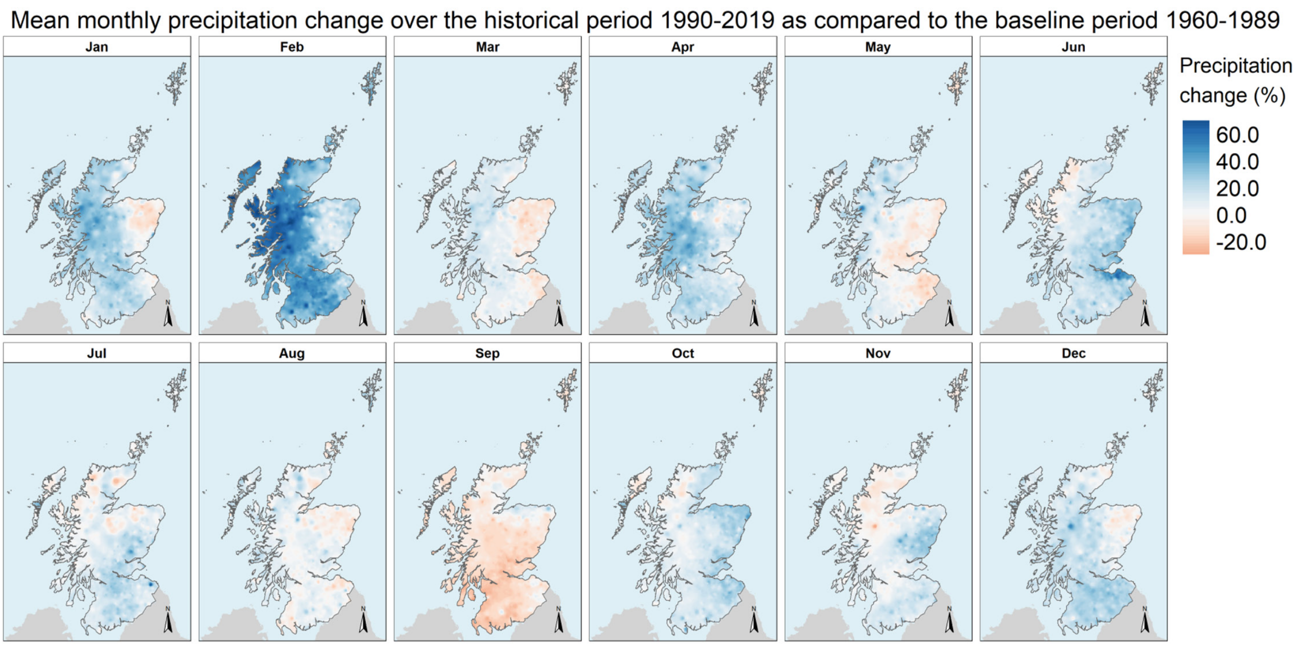


Figure A2.1: Relative change (%) in mean monthly precipitation between the recent period (1990 – 2019) and baseline period (1960 – 1989).

[2]HadUK-Grid - Met Office

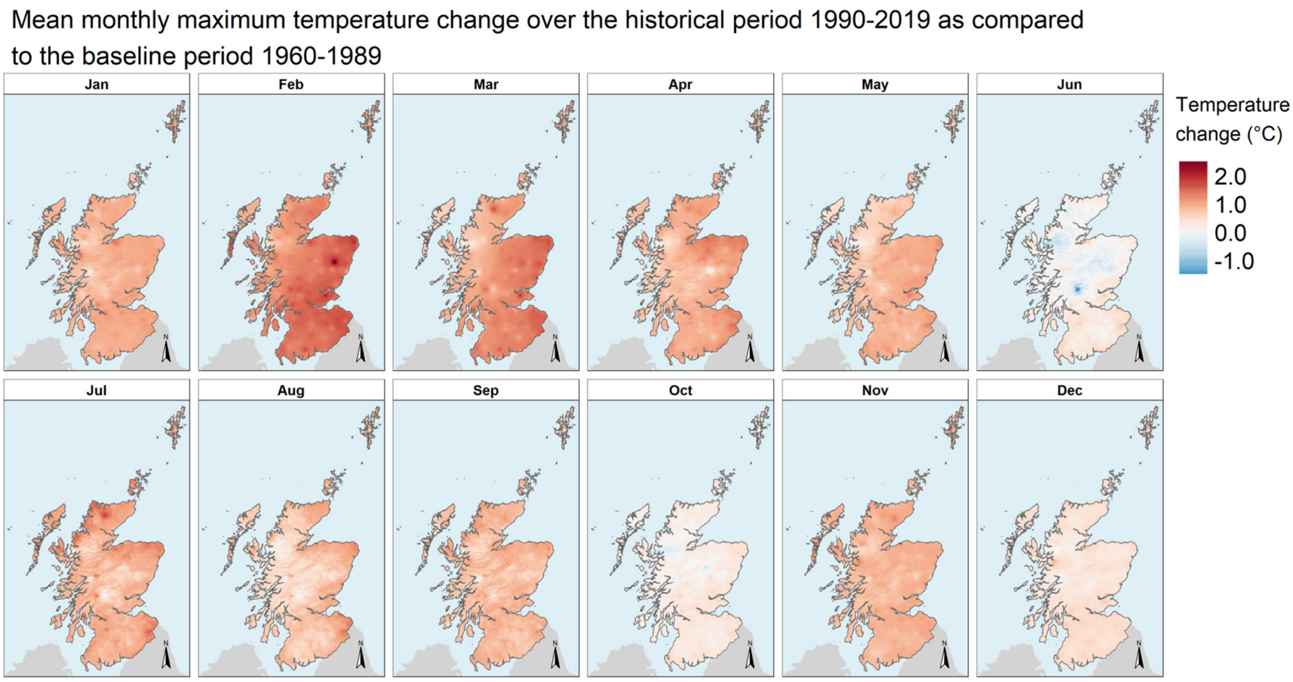


Figure A2.2: Change in mean monthly maximum temperature change between the recent period (1990 – 2019) and the baseline period (1960 – 1989).

Temperature:

- For all months there has been an overall increase in temperature, except for the maximum in June (Figure A2.2) and to a lesser extent October and December for the minimum temperature (Figure A2.3).
- February and March show the largest amount of warming, up to 2°C, whilst other months show an approximate average increase of 1°C.
- The rise in temperature is relatively uniform across the country, and does not reflect the topographical influence, though for some locations there has been little or no change from the 1960 – 1989 baseline period.
- There has been a mixed response in terms of variability of how much change there has been and where this has occurred.
    - January, February, and August have seen an almost nationwide shift towards reduced variability (standard deviation), whilst March, April (except the Lochaber and northern Argyll areas), September, October and November have seen a widespread increase.
- All months, with the exception of June and to a lesser extent April and August, show a general national trend of a positive increase (warming) in diurnal temperature range.

Future Projections

- Data from the UKCP18 climate projections (12 individual model simulations referred to as Ensemble Members (EMs)) for 2020–2049 were compared with the observed 1960–1989 baseline to identify potential future changes. The 12 projections are based on the high emissions scenario (RCP8.5) but consist of a range of possible climate change from 1°C increase in temperature and an increase in precipitation total, to 3.5°C increase and a reduction in precipitation. Figure A2.4 shows the agreement in either having an increase or decrease in monthly precipitation for all 12 projections for the 2020 – 2049 period, while Figures A2.5 and A2.6 give an example of monthly changes in maximum and minimum temperature based on the EM01 projected climate for 2020–2049.

Precipitation:

- Projections for the period 2020 to 2049 indicate Scotland's climate to be wetter in December, January (both c.10%), February (45 – 55%) and April (25%) but less so in March (c. 5%).
    - These projected changes align with the observed changes already seen.
- For the 2020 to 2049 period, August, September, and October are projected to become drier.

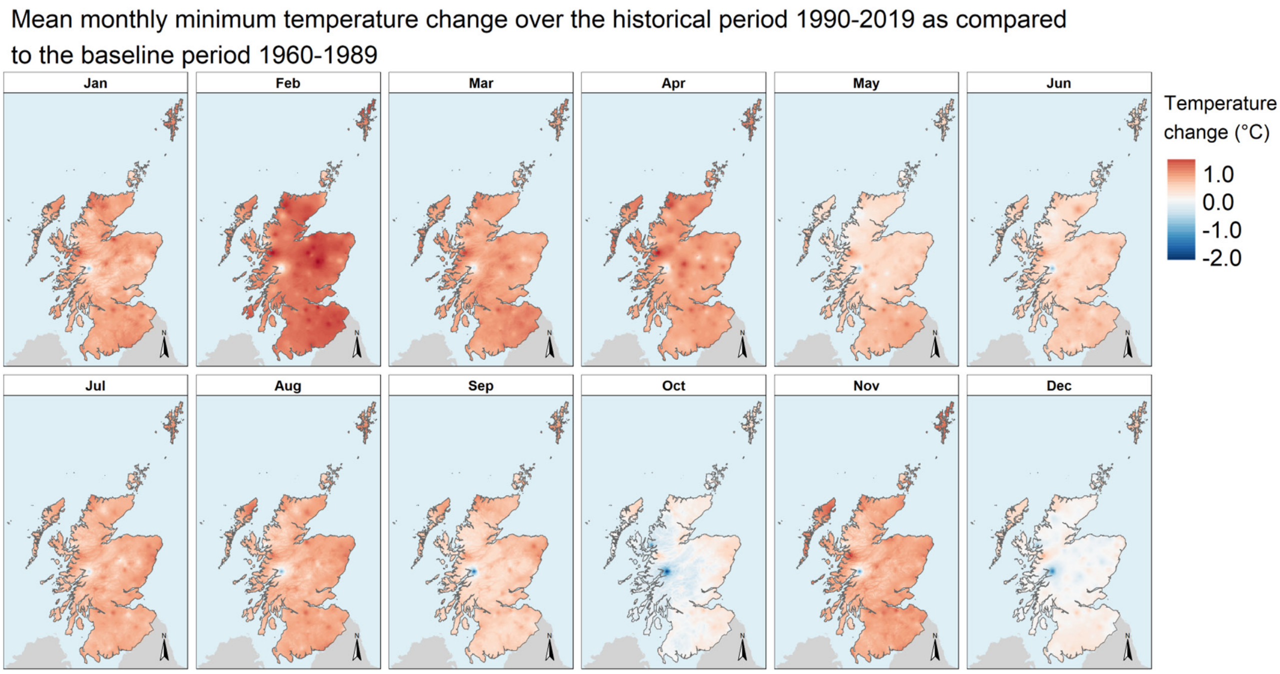


Figure A2.3: Change in mean monthly minimum temperature change between the baseline period (1960 – 1989) and recent period (1990 – 2019).

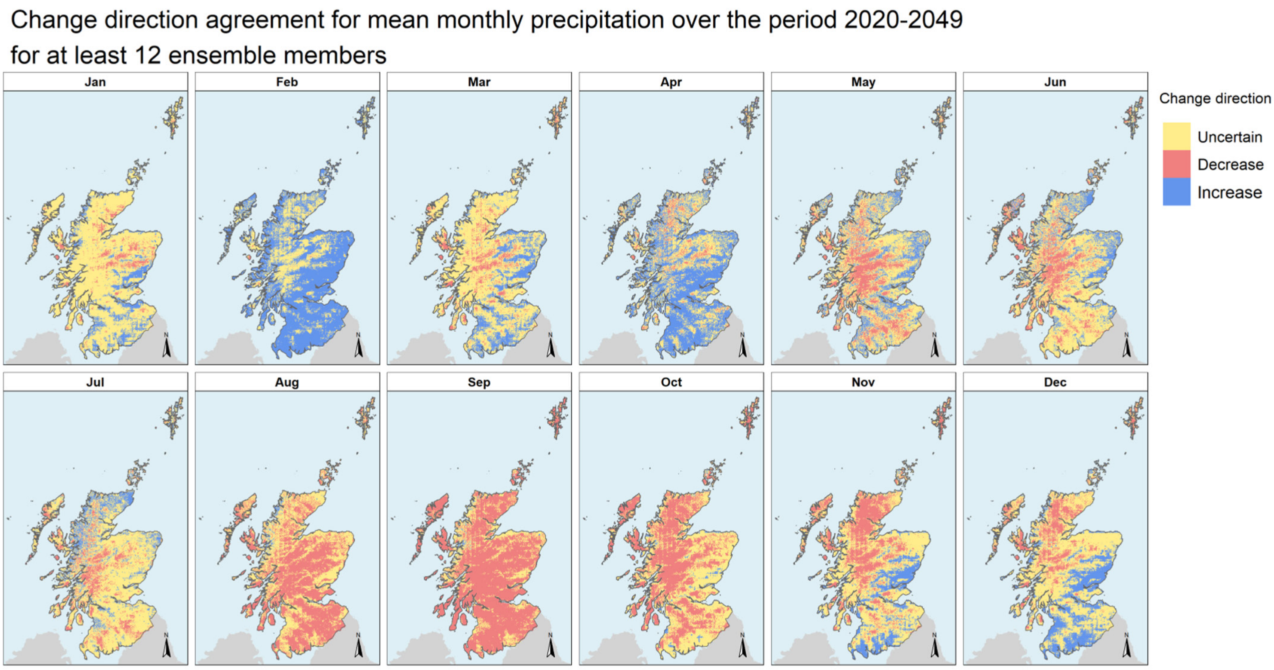


Figure A2.4: Agreement map for all 12 projections on the direction of change in mean monthly precipitation for the 2020 – 2049 period.

- There is a high level of agreement between projections that February and April precipitation will increase, whilst August, September and October will decrease.
- There is large spatial variation in changes to the monthly mean precipitation between projections: eastern areas may become wetter in some months (February, April, May, November, and December); upland areas are likely to decrease in May, August, September and October, and November in the north.

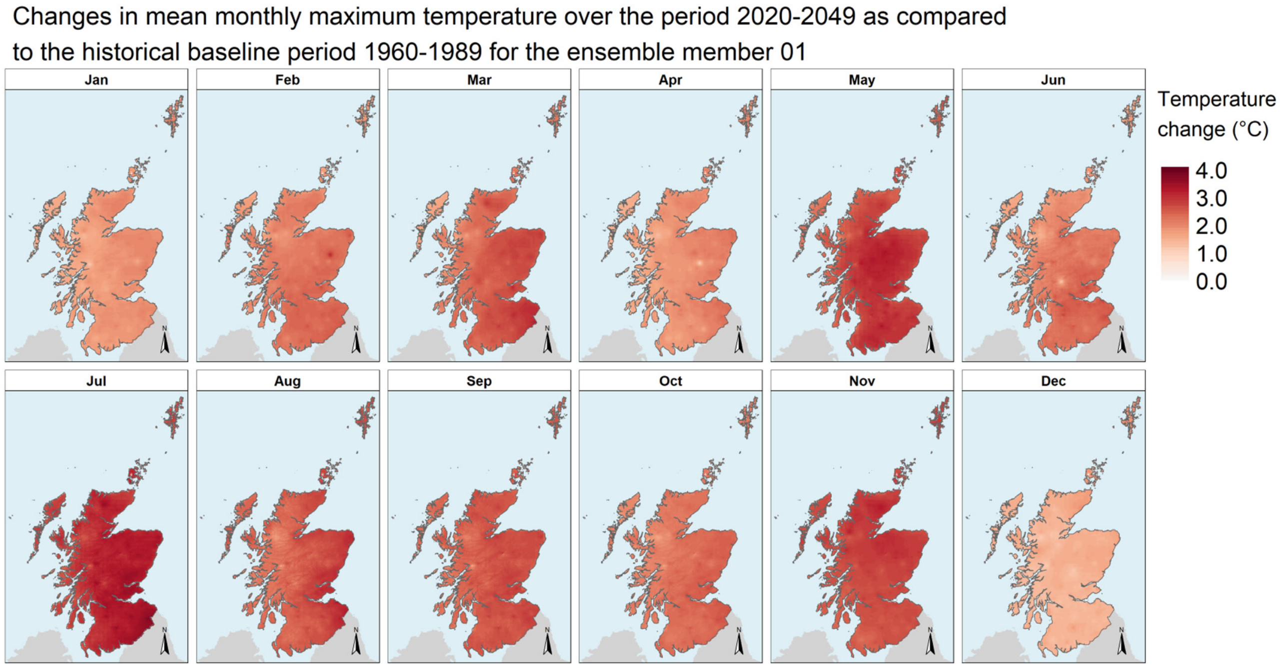


Figure A2.5: Ensemble Member 01 projection of change in mean monthly maximum temperature (°C) for the 2020 – 2049 period compared to the 1960 – 1989 baseline period.

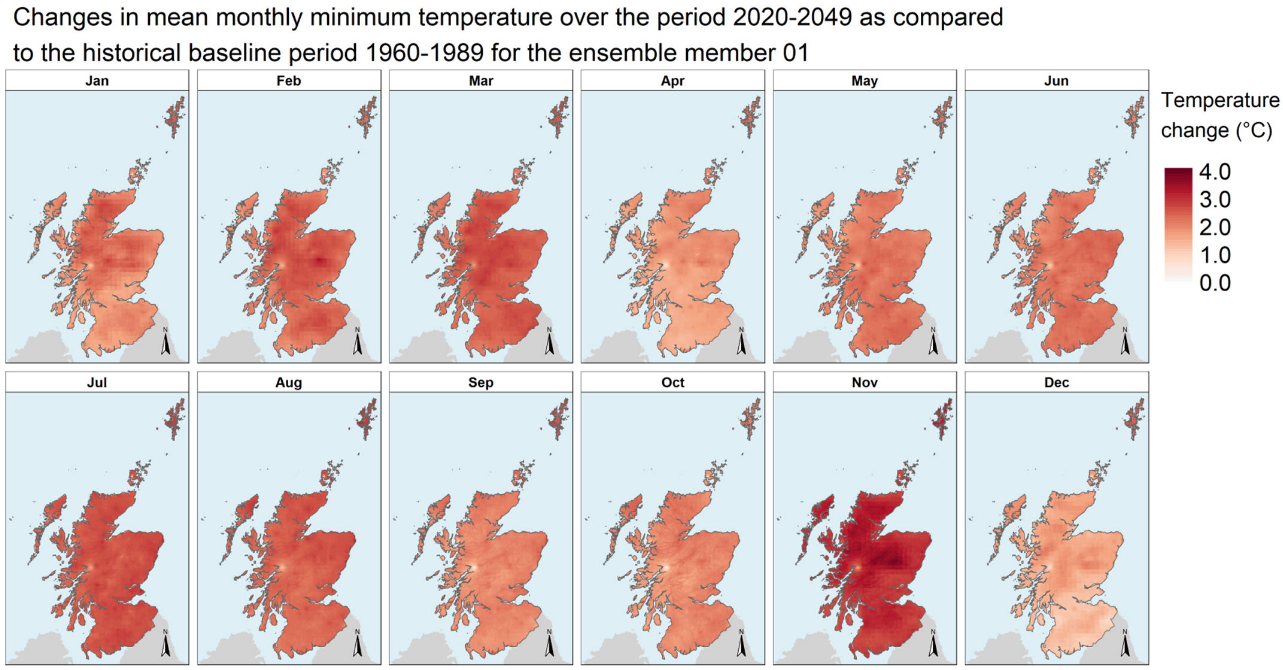


Figure A2.6: Ensemble Member 01 projection of change in mean monthly minimum temperature (°C) for the 2020 – 2049 period compared to the 1960 – 1989 baseline period.

Temperature:

- The observed warming trends in maximum and minimum temperature are projected to continue through the 2020 – 2049 period. There is high agreement between all 12 projections on there being continued warming.
- There is a greater amount of warming between May and November (up to 4°C per month between 2020 – 2049), but also with substantial warming in the winter (variable by projection, approximately 2-3°C).
- The spatial distribution of change is relatively uniform across Scotland, e.g. does not reflect topographical differences.

Future temporal and spatial change in meteorological drought indicators

Observed and future water availability can be assessed using a Climatic Water Balance indicator (CWB), defined as the difference between precipitation input (P) and reference

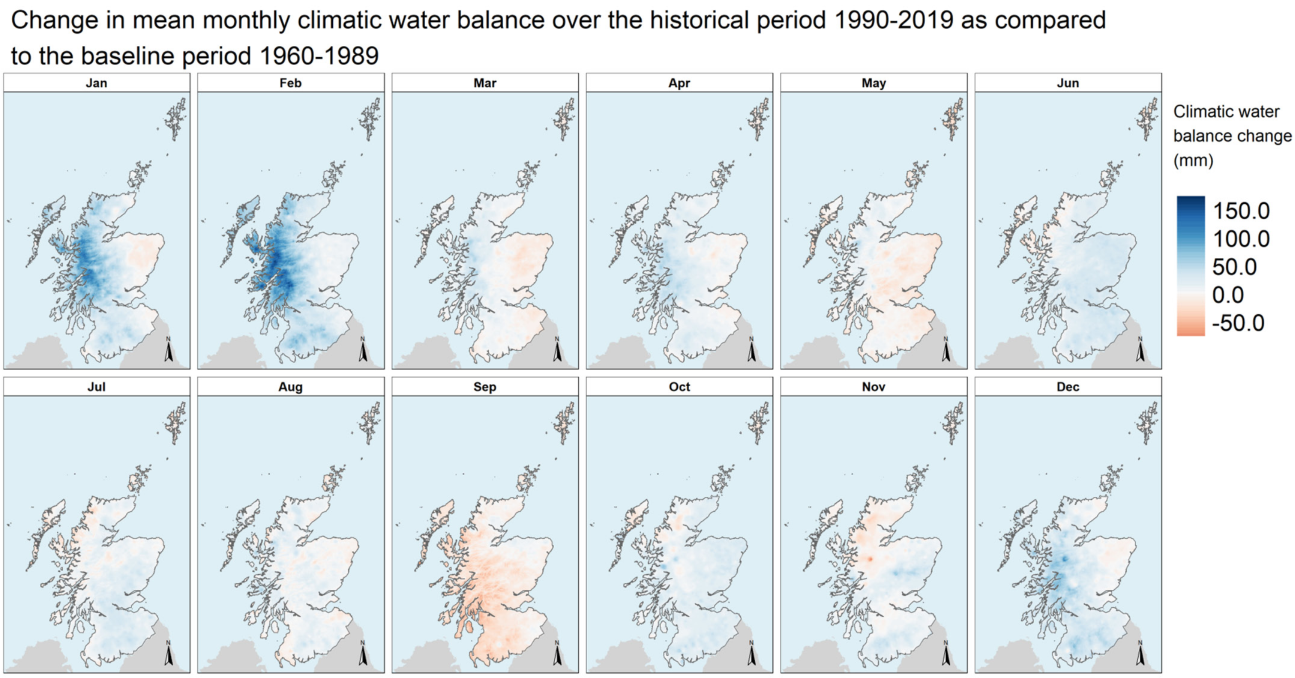


Figure A2.7: Change in the Climatic Water Balance per month between the 1960 – 1989 baseline and 1990 – 2019 recent period.

evapotranspiration (ETo) output, which is a metric of the combined impacts of changes in temperature and precipitation on water availability and its limitation that can lead to the occurrence of meteorological drought and subsequent water shortages.

CWB was calculated for the whole of Scotland on a monthly basis by Rivington and Jabloun (2023) using 1 km interpolated gridded observed climatic data and UKCP18 climate projection daily climatic data (for x 12 Ensemble Members of a Regional Climate Model for the 'high emissions' scenario (RCP8.5)) for each year of the observed (1960 – 1989 and 1990 – 2019) and projected future periods (2020 – 2049) (see example in Figure A2.7). Then averages were calculated for each period and the two CWB classes were determined (mean CWB <0, deficit and mean CWB ≥ 0, surplus). The calculated direction of change in CWB between the different time periods and the baseline period (1960 – 1989) indicate potential differences in water availability (Figure A2.8). Below a summary is given of these trends based on the findings of Rivington and Jabloun (2023).

Observed trends:

- There has been an observed change in CWB compared to the baseline period of 1960 – 1989, which is variable both spatially and temporally:
    - West coastal areas have become wetter (increased surplus water) between December to April.
    - Eastern Scotland has experienced a decrease in water availability between March to May, as has the whole of Scotland in September.
    - June to August have experienced an increase in CWB (precipitation is greater than evapotranspiration) but the surplus is low (close to 0 mm) and variable, with deficits in the East.

Projected changes:

- Projections show that there may be a shift in where and when parts of Scotland have a surplus or deficit of water.
- A key finding is that some upland areas of central Scotland are projected to shift from water surplus to deficit (Figure A2.8).
    - Most notably this is seen in May for the central Highlands and in August in the eastern and southern upland areas plus southern Argyll, Islay and Jura and parts of the Outer Hebrides.
    - Large parts of eastern Scotland in September are projected to see a shift to CWB deficit.

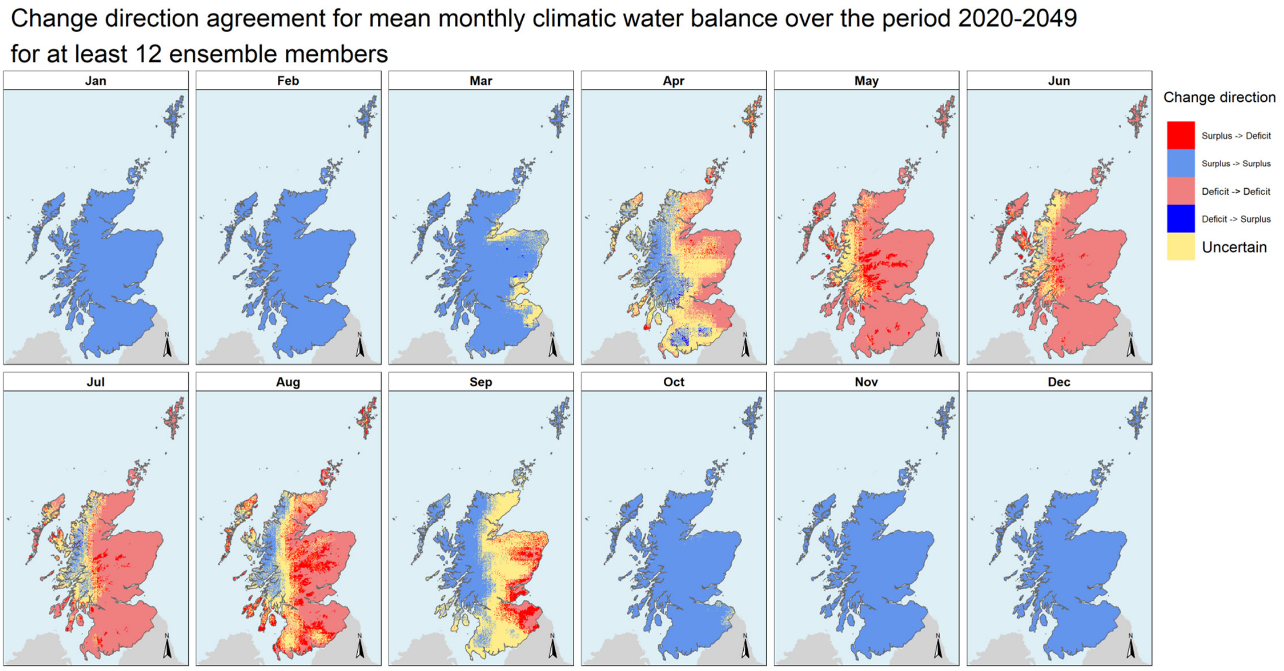


Figure A2.8: Agreement maps for the change direction (increase: blue/decrease: red) of the Climatic Water Balance for the period 2020 – 2049 for all 12 climate projections (ensemble members) relative to the baseline period 1960-1989. Yellow areas indicate no agreement between projections (Rivington and Jabloun, 2023).

- For the 2020 – 2049 period, there is good agreement between the 12 projections that October through to March Scotland will remain in CWB surplus (precipitation is greater than evapotranspiration), but that May to August in Eastern Scotland will remain in CWB deficit.

Climatic Water Balance in relation to cultivated land

The direction of change in CWB for individual land cover classes, derived from UK-CEH's Land Cover Map (LCM) for 2020 (Morton *et. al.,* 2021), has been previously used to assess the exposure of different land uses to changes in observed and future climate (Gagkas *et. al.,* 2023). Here we present results related to the areal extent of cultivated land mapped by LCM, i.e., Arable land and Improved grasslands (Figure A2.9), occurring within areas of observed and projected climatic water deficits or surpluses. For this analysis, we selected all 1km grid cells from the climatic layers for the recent (1990 – 2019) and future periods (2020 – 2049) that contained at least one hectare of LCM Arable land or Improved grasslands. This analysis was also extended to include both the CWB direction of change and CWB ratios, defined as the ratio of P to ETo, with:

- CWB ratios >2 indicating a Strong Surplus.
- CWB ratios <2 indicating a Strong Deficit.

It needs to be noted that the total areas under water surplus or deficit are the same based on either CWB direction of change or ratios; the latter is included here to also provide an assessment of the magnitude of either water surpluses or deficits. It is not feasible for this analysis to present results for all 12 Ensemble Members (EM); hence we selected three (3) EMs:

- EM04 representing a climatic scenario with precipitation (mean annual total) similar to the baseline period, but 2.2°C warmer.
- EM05 represents a scenario that is c.3% drier than the historical baseline (mean annual total precipitation is less, but with spatial variation) and 2.1°C warmer.
- EM15 is a scenario with a higher mean annual total precipitation, hence c.9% wetter and 1.1°C warmer (Note: Rivington and Jabloun (2023) indicate that temperatures have already increased more than this from the baseline period).

Figures A2.10 and A2.11 present national maps of CWB ratios for the recent (1990 – 2019) and future dry scenario (EM05 2020 – 2049) for April and September, the months when the transition from water surpluses to deficits and the recovery from water stress is occurring, respectively.

Based on this analysis, we found that, at a national level, observed shifts mainly from water surpluses to water deficits in late summer and early autumn are the main drivers of the degree of exposure of most land cover types to climatic stress, depending on their spatial distribution in relation to west vs east geographical gradient. For cultivated land in particular, Arable land, which is mostly located in the eastern part of Scotland, and to a lesser extent Improved grasslands were found to be the most exposed habitat types to climatic water stress (Figure A2.9). Almost all Arable land in the recent period (1990 – 2019) was found to be in constant climatic water deficit from April to August, whilst around 35% of Arable land is also in water deficit in March (Figure A2.12). Future projections give a wetter prediction for March and similar continuous water deficits for the April to August period, however 60% (based on EM04) to 90% (based on EM05) of Arable land is projected to be under water deficit in September as well. The greater area of Arable land being under strong water deficit is given for the recent period and EM04 future projection, but overall EM05 future projection (dry scenario) gives the greatest area in continuous water deficit (both moderate and strong) (Figure A2.13).

For Improved grasslands in the recent period (1990 – 2019), around 85% (in September) to 100% of the area was found to be in water surplus from September to March, around 80% of Improved grasslands went into water deficit in April, and then almost 100% of the area stayed in deficit between May and July (Figure A2.14). Recovery from deficits starts in August when water deficits drop to ~ 72% of the Improved grasslands area. Looking at the future climate scenarios, 90% to 100% of the area of Improved grasslands is projected to be under water surpluses from October to March, (Figure A2.14). The dry future scenario (EM05) gives a smaller proportion of Improved grasslands being at strong water deficits compared to the other future projections, however EM05 gives the greater area overall of Improved grasslands being under both moderate and strong deficits (Figure A2.15).

Overall, the range of climatic future projections investigated here indicate wetter spring conditions, especially in March, compared to the recent period of 1990 – 2019, which may prolong water saturation in cultivated topsoils and adversely affect their trafficability. In addition, a great proportion of Arable land and Improved grasslands, especially those located on the eastern side of Scotland, are projected to be under water deficit/stress in September, potentially increasing the need for irrigation of certain crops.

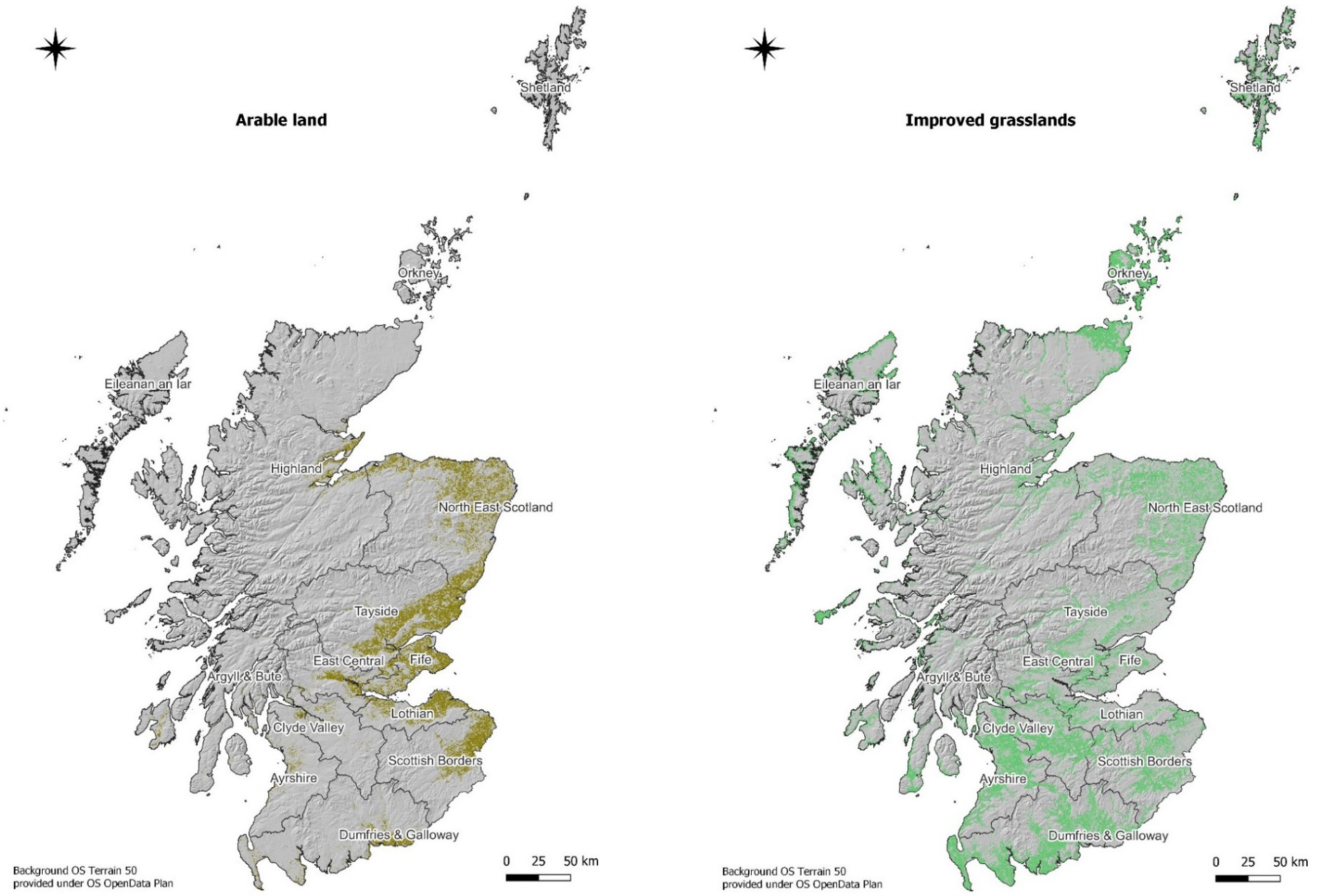


Figure A2.9: Areas of Arable land and Improved grasslands based on the CEH Land Cover Map for 2020, superimposed by the boundaries of Scotland's Agricultural Regions.

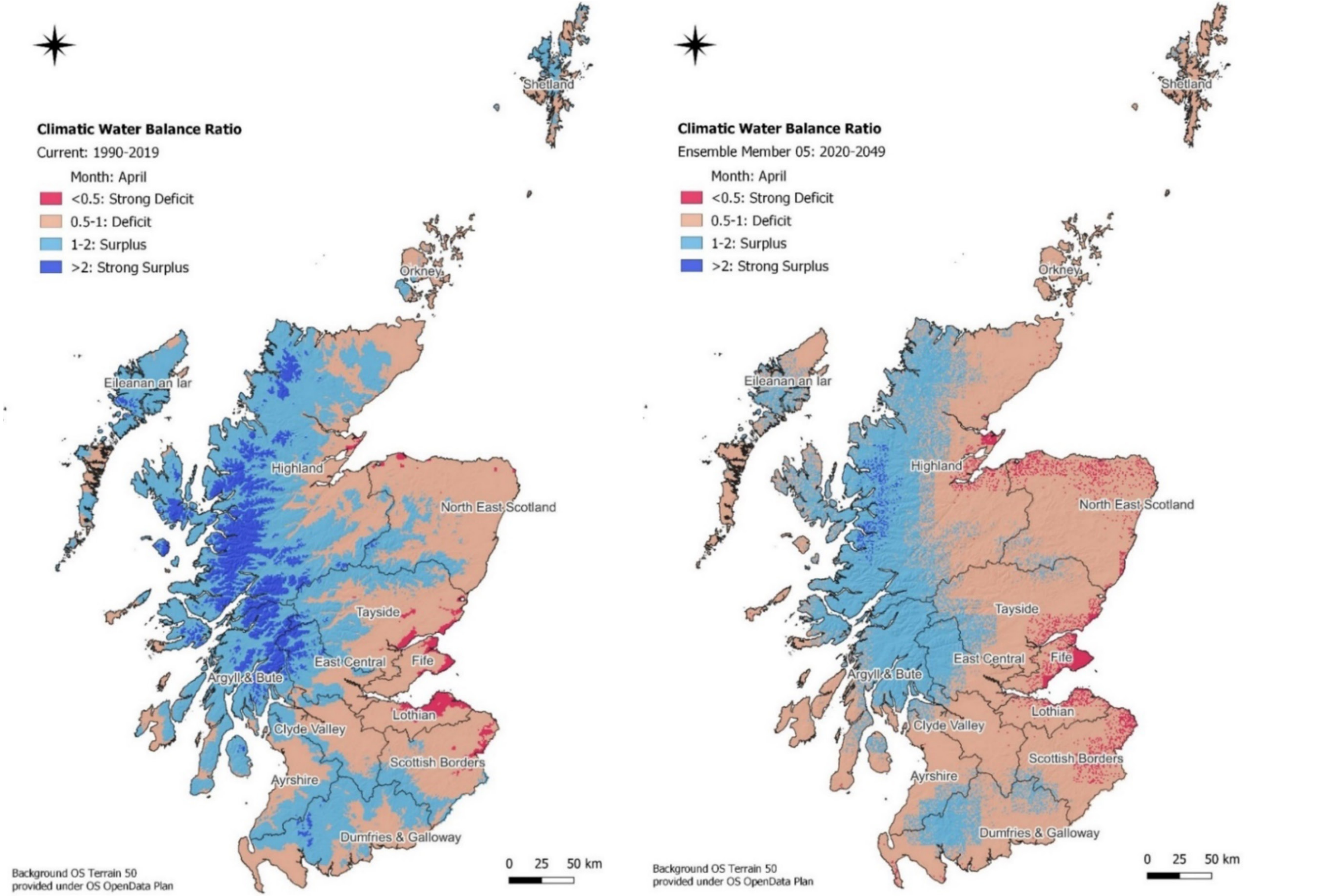


Figure A2.10: Maps of Climatic Water Balance ratio classes for April based on observed climate for the recent 1990 – 2019 period and projected future climate based on EM05 (Dry scenario), superimposed by the boundaries of Scotland's Agricultural Regions.

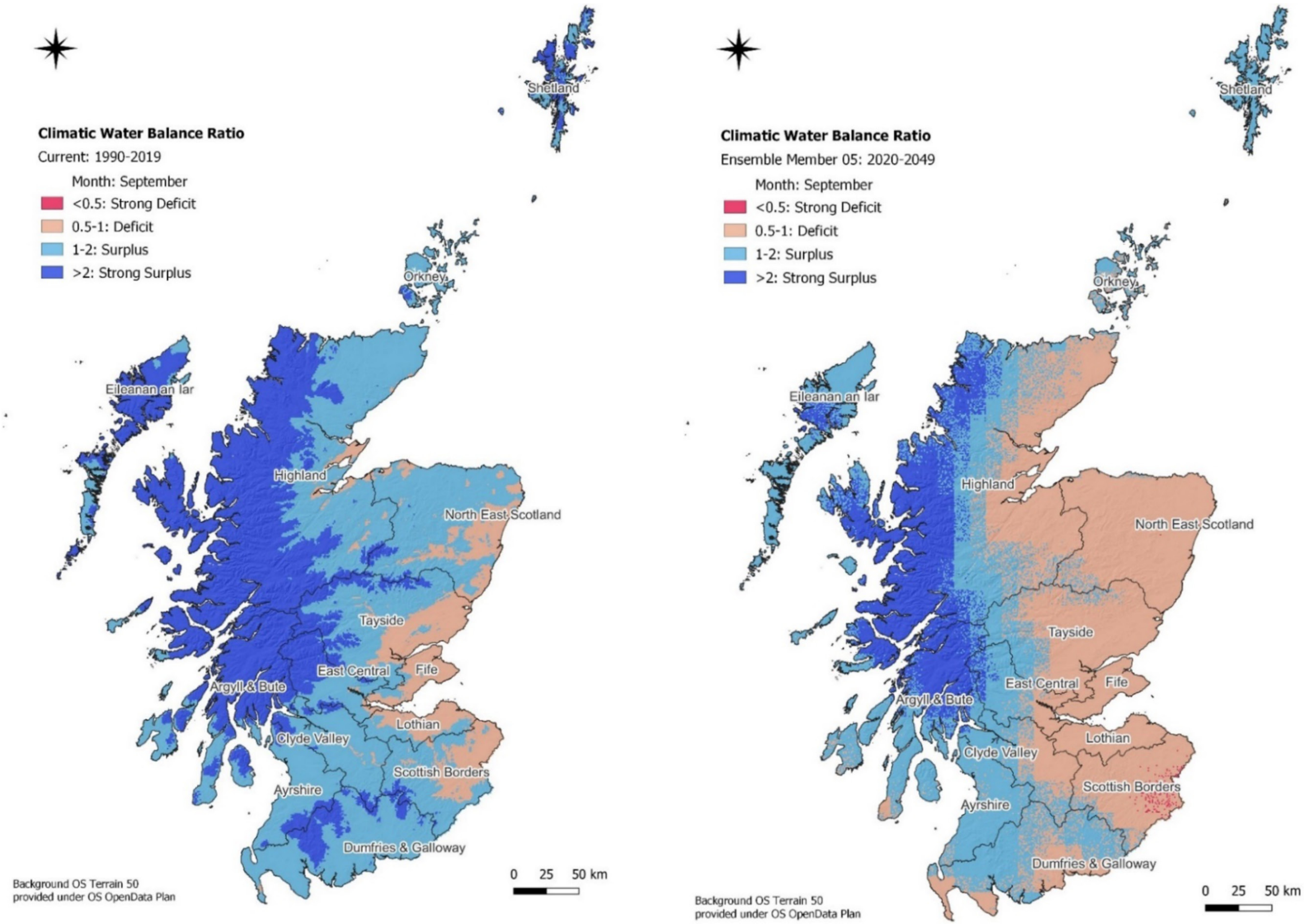


Figure A2.11: Maps of Climatic Water Balance ratio classes for September based on observed climate for the recent 1990 – 2019 period and projected future climate based on EM05 (Dry scenario), superimposed by the boundaries of Scotland's Agricultural Regions.

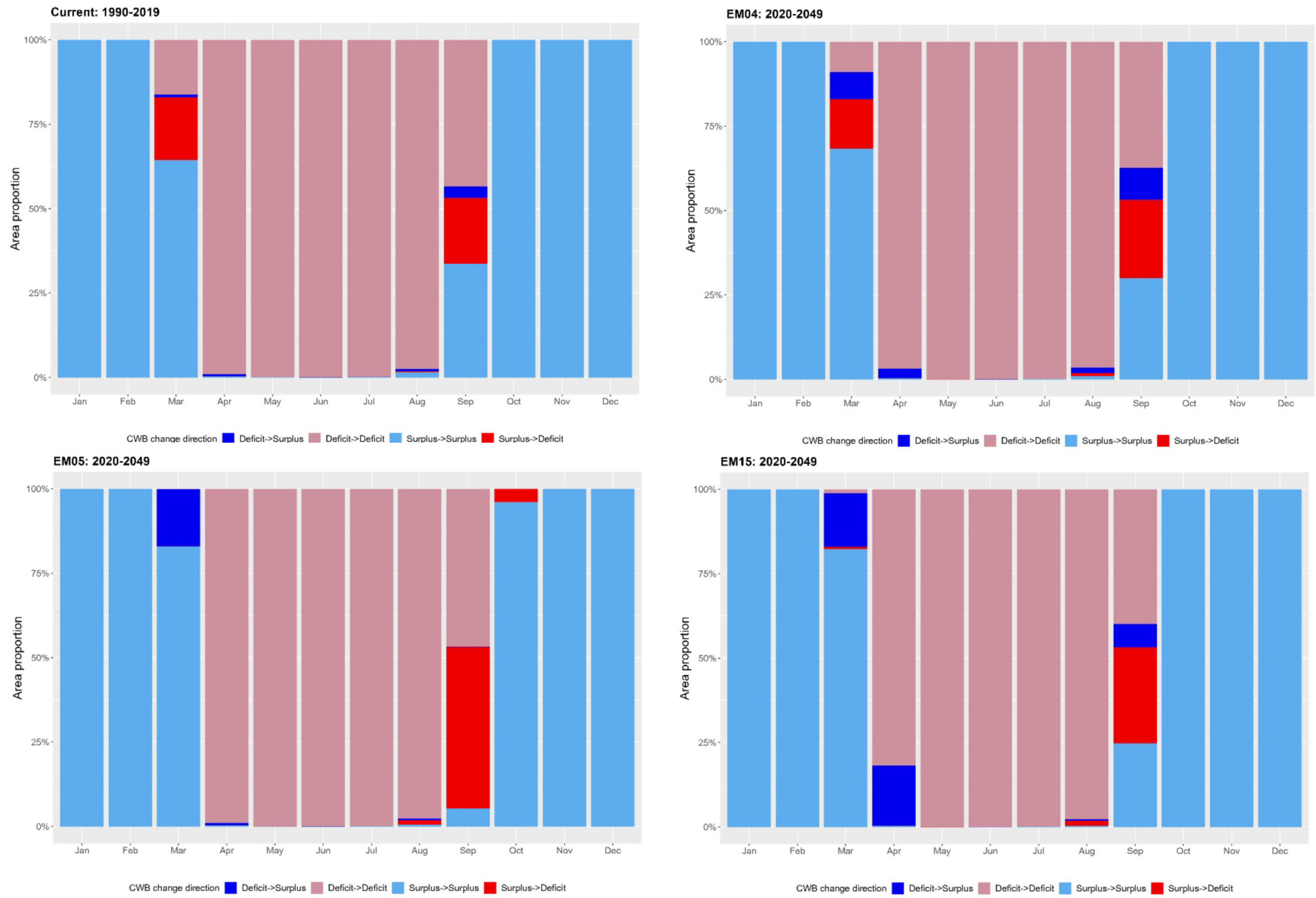


Figure A2.12: Area proportions for the monthly change direction in Climatic Water Balance for Arable land based on UKCEH LCM 2020 for the 1990 – 2019 period and for the 2020 – 2049 period for Ensemble Member (EM) 04, 05 and 15, relative to the baseline period 1960 – 1989.

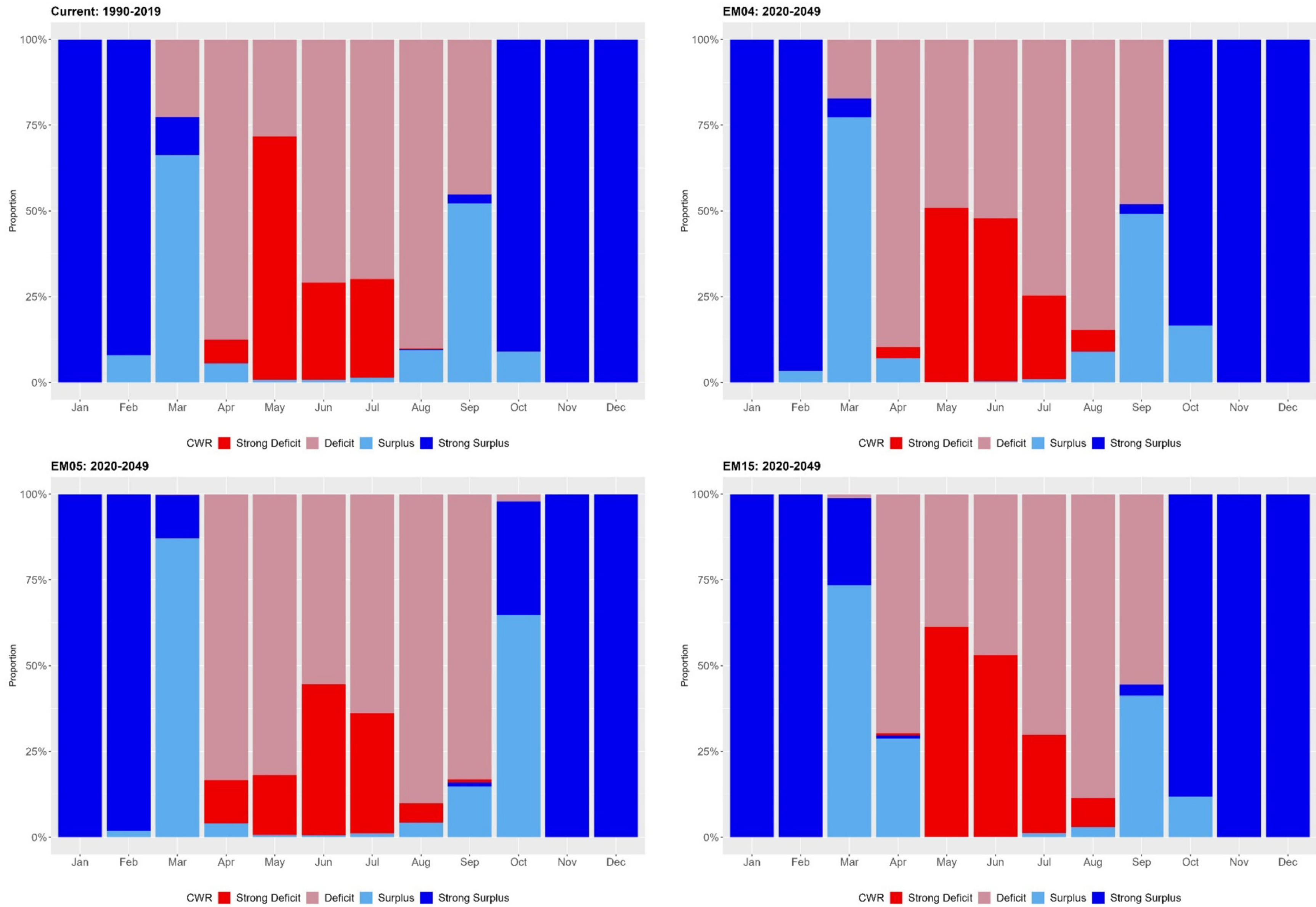


Figure A2.13: Area proportions for the monthly Climatic Water Balance Ratio classes for Arable land based on UKCEH LCM 2020 for the 1990 – 2019 period and for the 2020 – 2049 period for Ensemble Member (EM) 04, 05 and 15, relative to the baseline period 1960 – 1989.

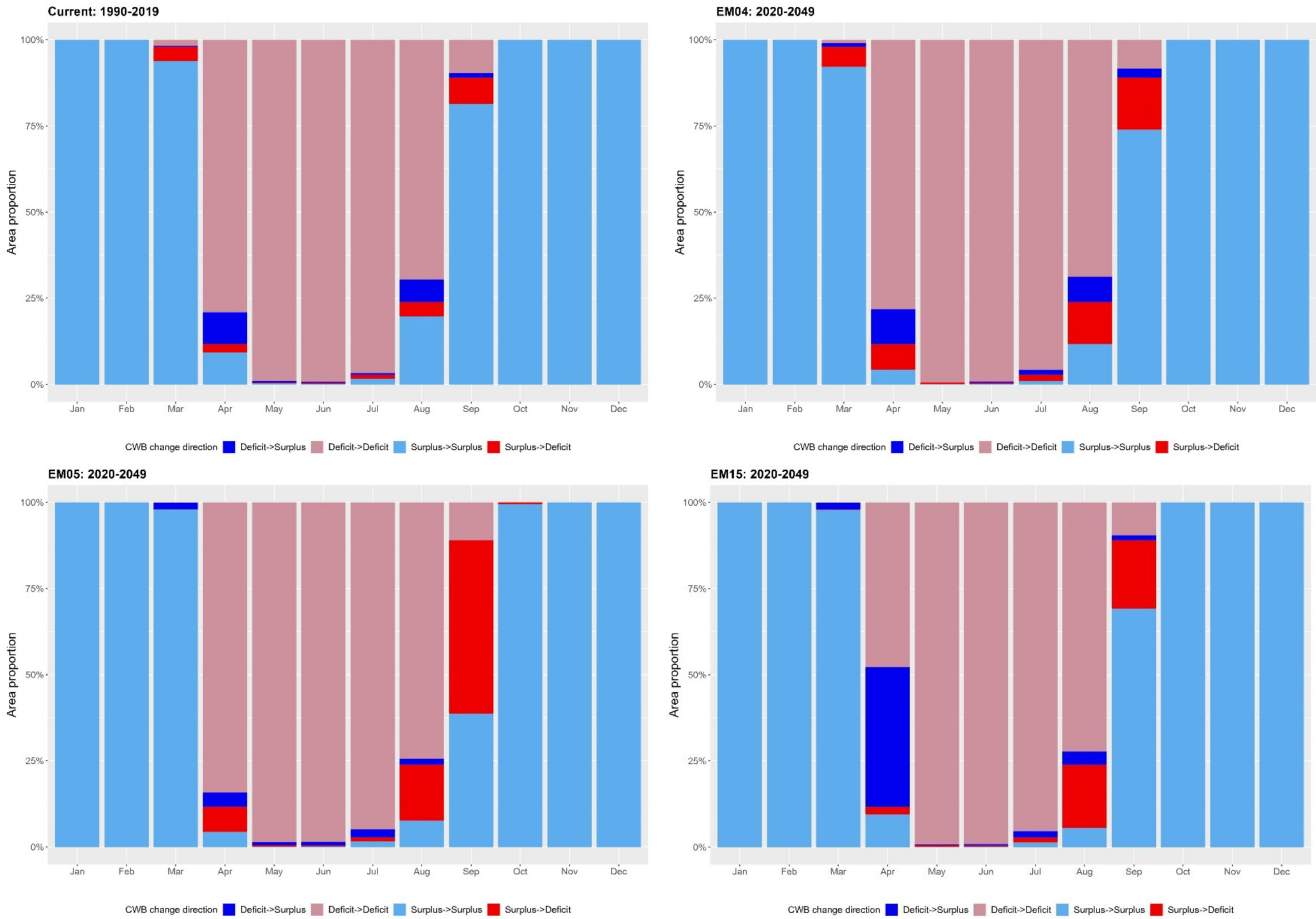


Figure A2.14: Area proportions for the monthly change direction in Climatic Water Balance for Improved Grasslands based on UKCEH LCM 2020 for the 1990 – 2019 period and for the 2020 – 2049 period for Ensemble Member (EM) 04, 05 and 15, relative to the baseline period 1960 – 1989.

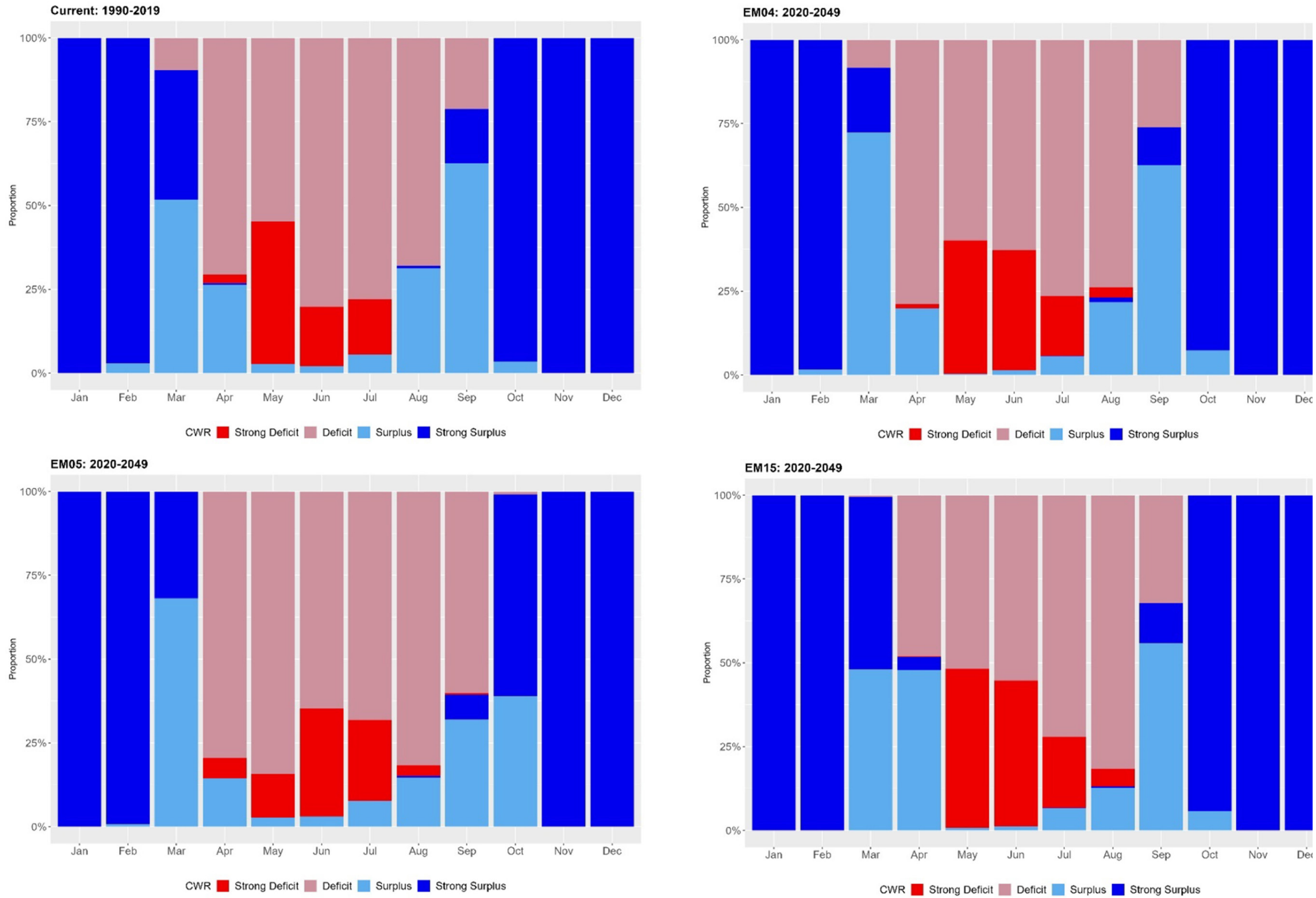


Figure A2.15: Area proportions for the monthly Climatic Water Balance Ratio classes for Improved Grasslands based on UKCEH LCM 2020 for the 1990 – 2019 period and the 2020 – 2049 period for Ensemble Member (EM) 04, 05 and 15, relative to the baseline period 1960 – 1989.

Climatic Water Balance in relation to water abstractions

Meteorological drought conditions at the locations of licenced agricultural and distillery abstractions provided by SEPA were investigated by overlaying the abstraction locations with the CWB direction of change and CWB ratio layers for the recent period (1990 – 2019) and the projected future climate period (EM04, EM05 and EM15 for 2020 – 2049). Figure A2.16 shows the spatial distribution of the 1,505 agricultural abstractions used for either irrigation or uses other than irrigation, and the 217 distillery abstractions included in this analysis.

As expected, due to their geographical co-occurrence, meteorological conditions and trends for the recent and future climate periods in the locations of agricultural abstractions were similar to those described in the area of Arable land. However, overall, a greater proportion of agricultural abstractions was under climatic deficits in April and September compared to the respective proportions of Arable land. Almost all agricultural abstractions were in continuous water stress during the April to August period based on observed CWB for the recent period (1990 – 2019) and future climate for 2020 – 2049 based on the EM04 and EM05 projections, while conditions were wetter based on the EM15 projection in April with 206 agricultural abstractions (~14%) being in water surplus (Figure A2.17). Around 74% of all agricultural abstractions were in water deficit in September as well based on the EM04 (similar) and EM15 (wetter) future projections, but this increased to 83% of agricultural abstractions based on observed climate for the recent period and to 98% based on the EM05 (drier) future projection. Conversely, almost all of agricultural abstractions were under water surplus in March based on the EM05 and EM15 future projections, decreasing to 74% for the EM04 future projection and just 50% for the recent period based on the observed data. Overall, as in the case of Arable land, a greater proportion of agricultural abstractions was under strong deficits for the recent period compared to the selected future projections, but a greater proportion was under water stress (both moderate and strong deficit) based on the EM05 future projection (Figure A2.18).

Recent and projected future climatic conditions in the locations of the distillery abstractions were overall found to be wetter in March and September than in the locations of the agricultural abstractions, reflecting the wider geographical spread of distillery abstractions compared to the agricultural ones (Figure A2.19). Based on observed data for the recent 1990-2019 period, 20% and 88% of distillery abstractions were in water deficit in March and August, respectively, while almost all distillery abstractions were in continuous water stress between April to July. These figures were very similar based on the EM04 projected climate scenario. On the other hand, almost all distillery abstractions were in water surplus in March based on the EM05 and EM15 projections (dry and wet climate scenario, respectively), while 95% and 79% of all distillery abstractions were in water deficit in August based on the EM05 and EM15 projected scenarios, respectively. Only around 20% of distillery abstractions were in water deficit in September based on the observed data for the recent period of 1990 – 2019 and EM04 projected climate for 2020 – 2049, rising to ~40% based on the EM15 projected climate scenario; however, 85% of distillery abstractions were still under water stress (deficit) when CWB based on the EM05 (i.e., dry) future scenario was used. As in the case of agricultural abstractions, a greater proportion of distillery abstractions was in continuous water deficit (both moderate and strong) based on the EM05 future climate projection (Figure A2.20). It is important to consider that the material presented here is for mean CWB conditions, however, there is likely to be large annual and within season variability. Hence the scale of water surplus and deficit and spatial variation, will vary with extreme conditions.

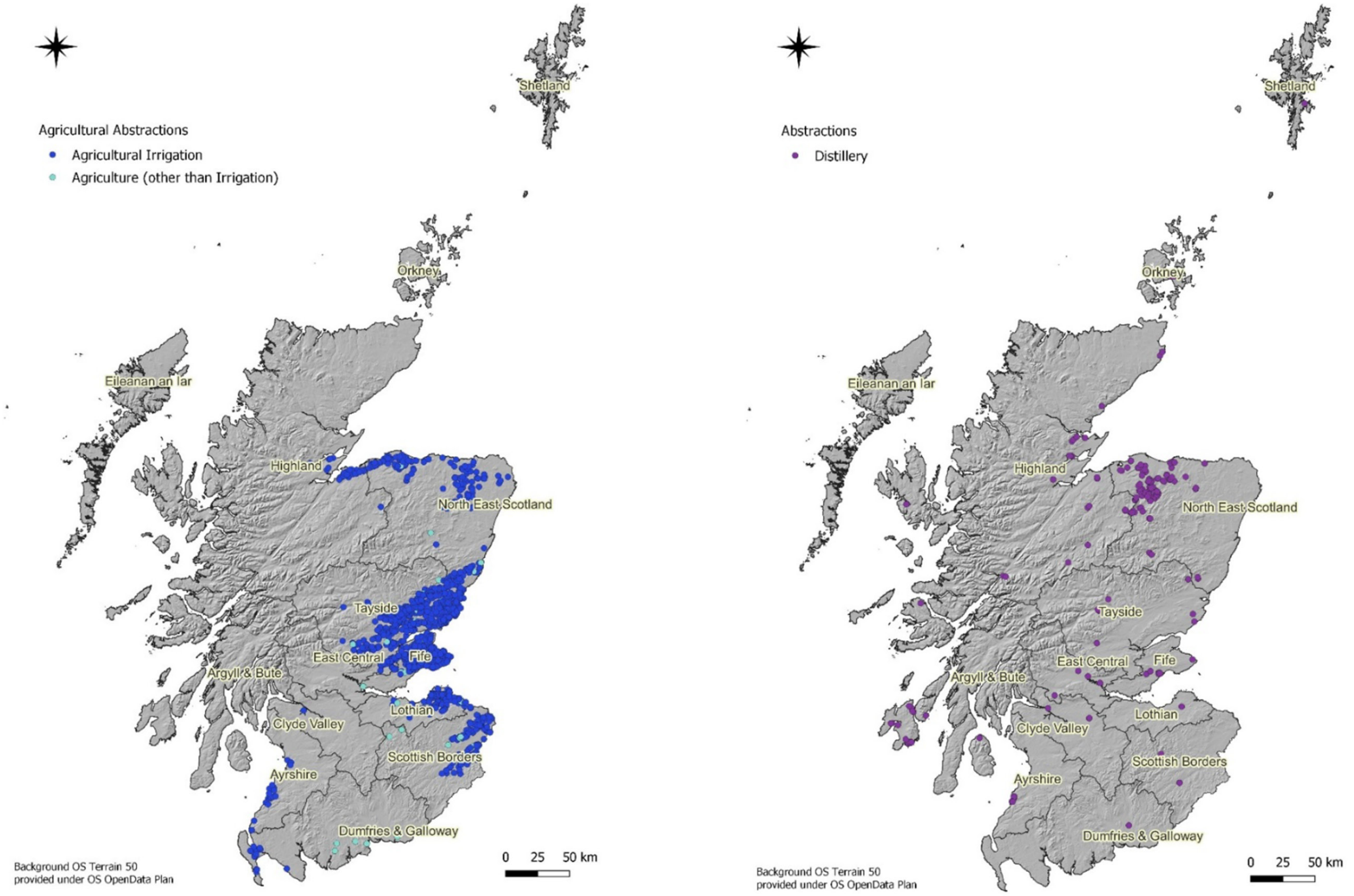


Figure A2.16: Locations of licenced agricultural and distillery abstractions, superimposed by the boundaries of Scotland's Agricultural Regions.

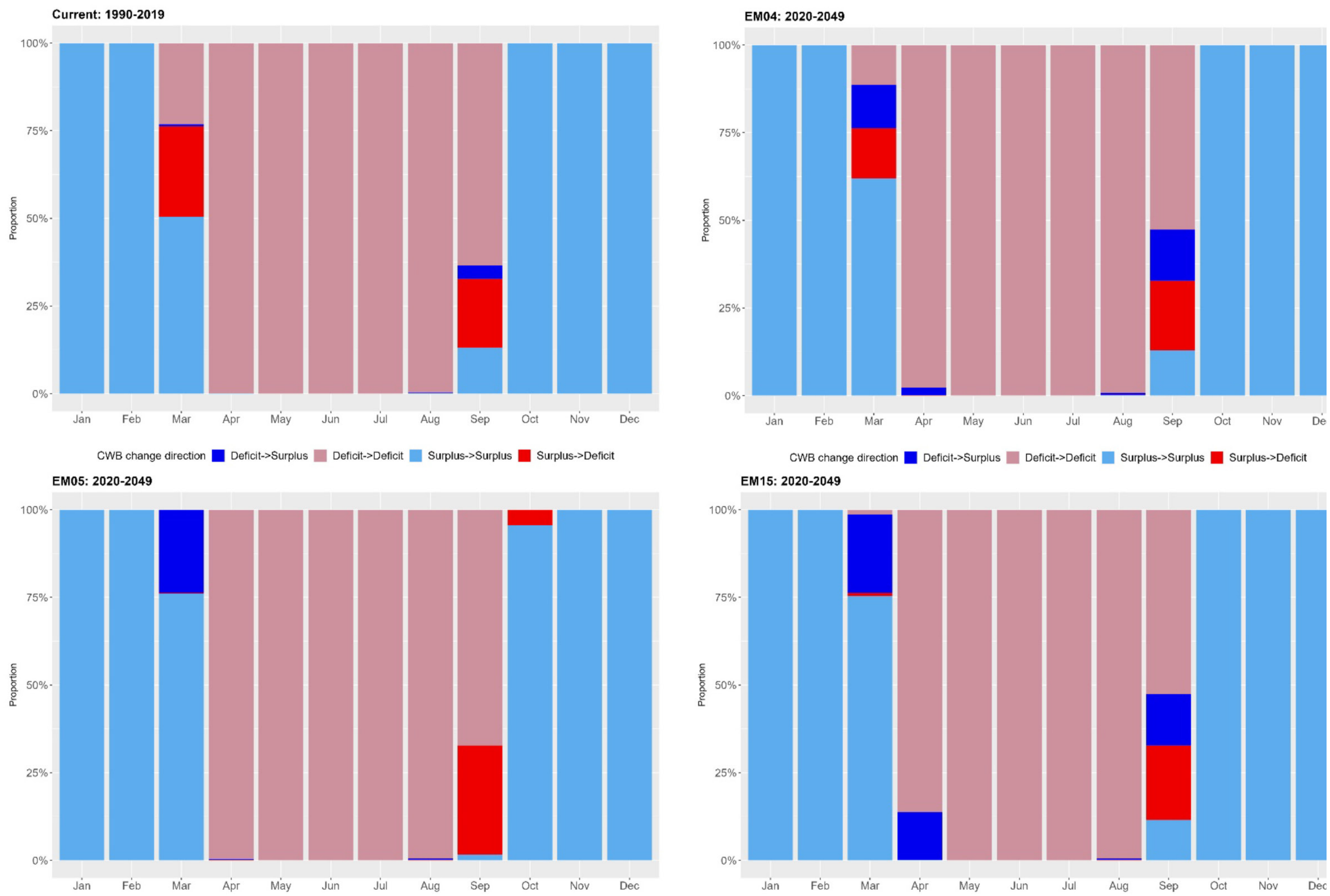


Figure A2.17: Proportions of counts of SEPA's licenced agricultural abstractions for the monthly change direction in Climatic Water Balance for the 1990 –2019 period and the 2020 – 2049 period for Ensemble Members (EM) 04, 05 and 15, relative to the baseline period 1960-1989.

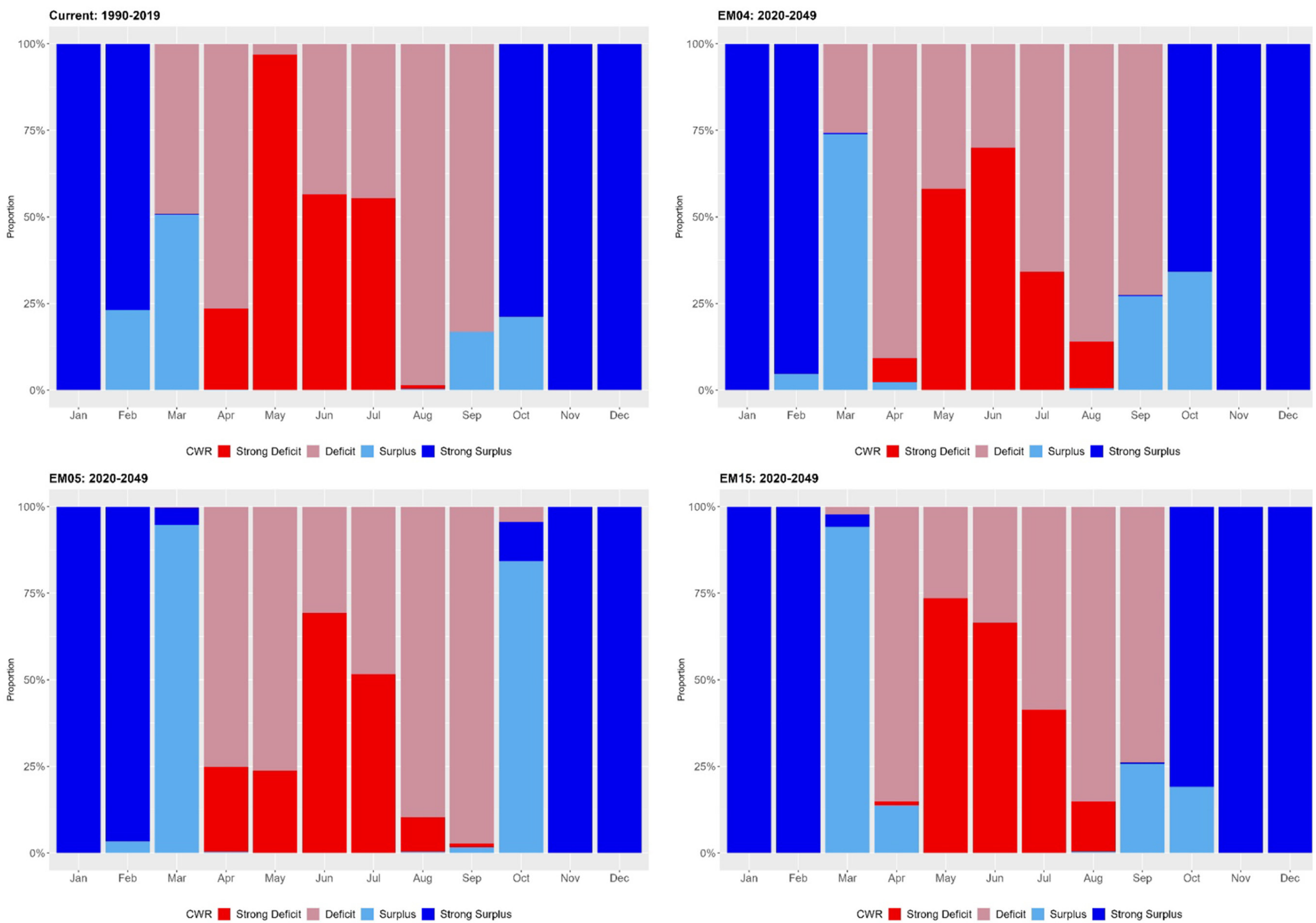


Figure A2.18 : Proportions of counts of SEPA's licenced agricultural abstractions for the monthly Climatic Water Balance Ratio classes based for the 1990 – 2019 period and the 2020 – 2049 period for Ensemble Members (EM) 04, 05 and 15, relative to the baseline period 1960-1989.

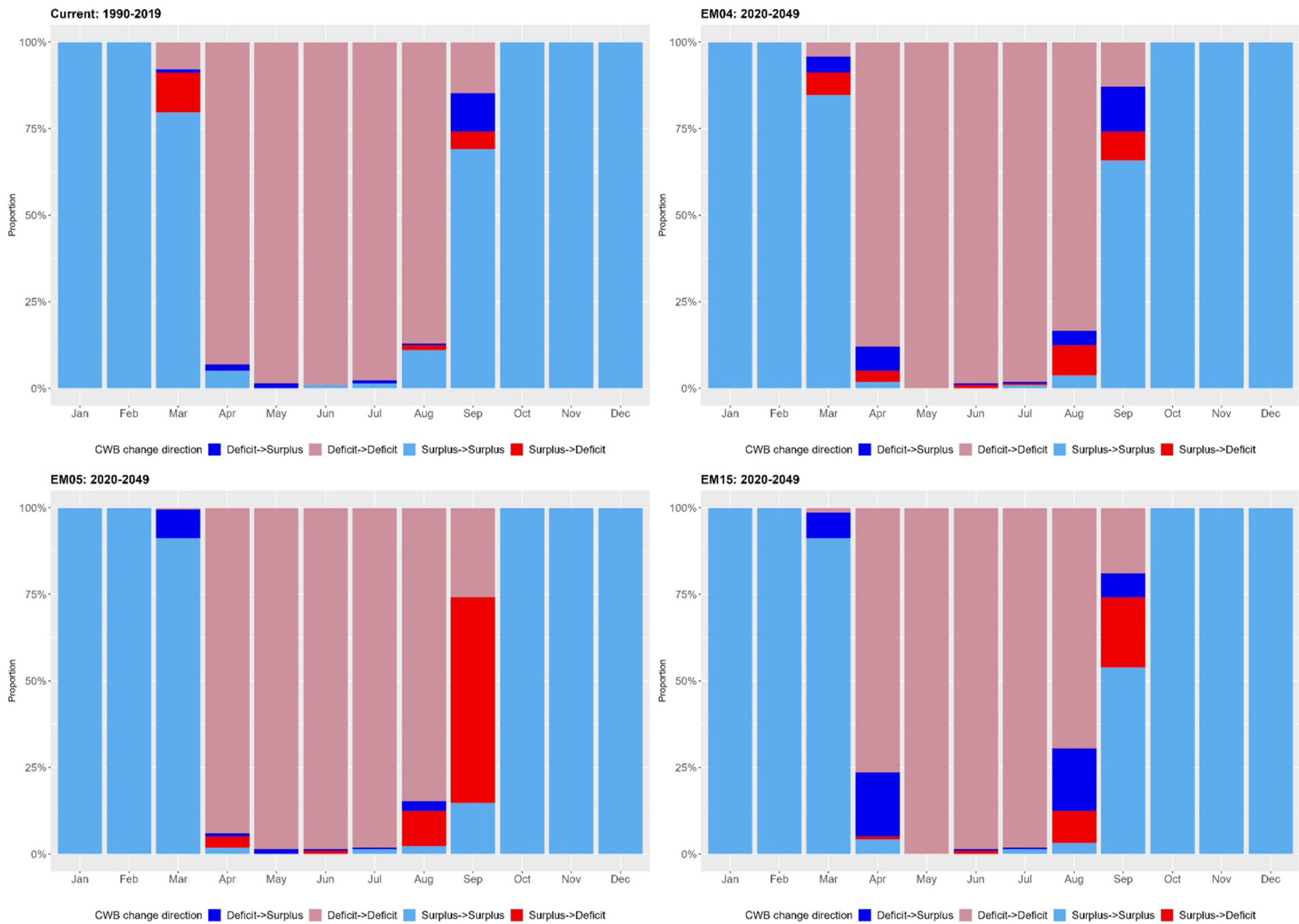


Figure A2.19 : Proportions of counts of SEPA's licenced distillery abstractions for the monthly change direction classes in Climatic Water Balance for the 1990 – 2019 period and the 2020 – 2049 period for Ensemble Members (EM) 04, 05 and 15, relative to the baseline period 1960 – 1989

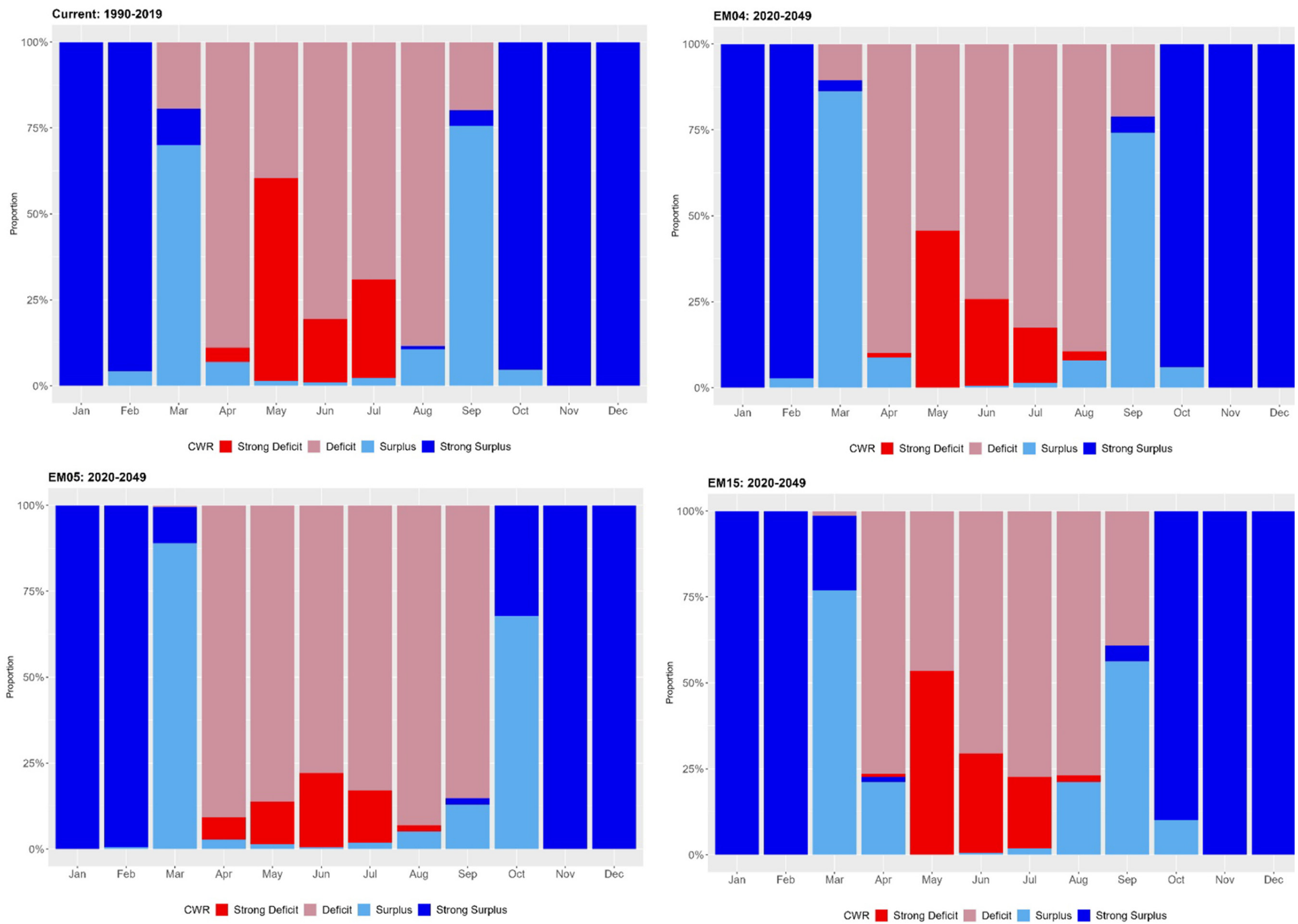


Figure A2.20: Proportions of counts of SEPA's licenced distillery abstractions for the monthly Climatic Water Balance Ratio Classes based for the 1990-2019 period and the 2020-2049 period for Ensemble Members (EM) 04, 05 and 15, relative to the baseline period 1960-1989.

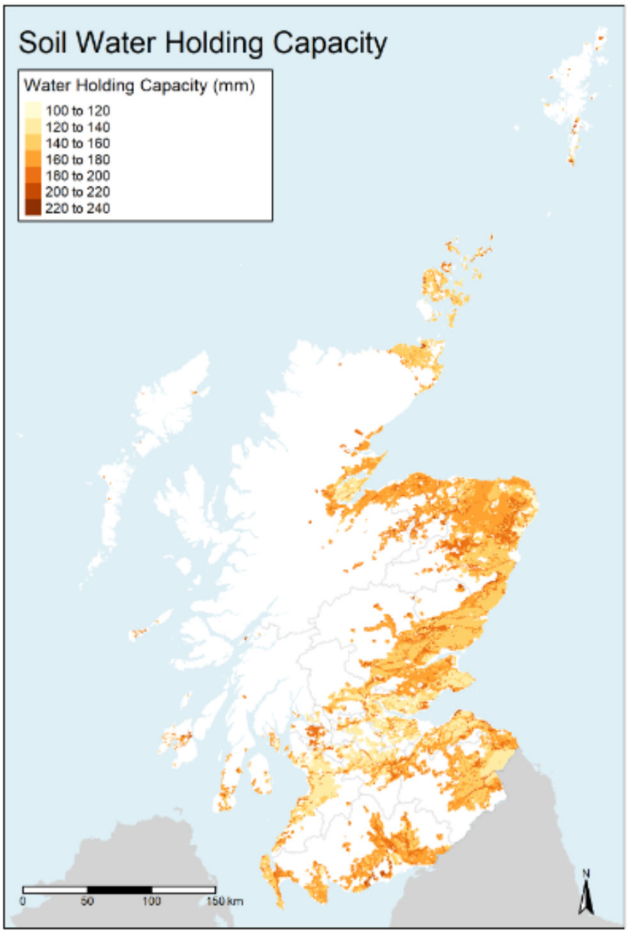
Water stress impacts on crop yield: the case of barley

Rivington *et. al.* (2022) used a crop simulation model and spatial weather, soil, and land use data to estimate barley growth across Scotland for multiple years under current climate (based on observed climate from the UK Met Office for the period 1994 to 2015) and the 12 future projected climates described previously in this report (UKCP18 projections for RCP8.5) for the future periods of 2020 – 2049 and 2050 – 2079. The study area of this analysis was the 1 km climatic grids covering areas where barley is currently being grown extended to adjacent areas (1 km buffer) in which barley could hypothetically be grown, specifically allowing for climate change.

A key element in the development of the crop simulation platform was the estimation of the soil's water holding capacity (SWHC), which was calculated as the difference between two main crop-related soil hydraulic properties, the drain upper limit (DUL) and the lower limit (LL). Patterns of WHC were spatially variable (Figure A2.21) and varied between 104 to 222 mm with a median value of 159 mm. Around 6% of the total barley cropped area was classified as having Low SWHC (less than 134 mm: 10th percentile) indicating locations that may be more vulnerable to future dry conditions), 90% of the barley cropped area was classified as having Average SWHC (between 134 mm and 184 mm (90th percentile)) and the remaining 4% was classified as having High SWHC (more than 184 mm).

In addition, a Water Stress Indicator (WSI) was calculated as 1- Yw/Yp where Yw is water limited yield and Yp is potential yield where water is not limiting, and yield is mainly driven by solar radiation. A WSI value of 0 represents no water stress and 1 is high water stress leading to crop failure. Values in the mid-range imply stress can occur that reduces yields. It was found that the timing of when water stress occurs in relation to the crop growth stage during a growing season is critical, e.g. low water availability between crop emergence and flowering will likely have more of a yield impact than if between flowering and harvest.

The modelling utilised the climatic water balance layers described previously as indicator of water



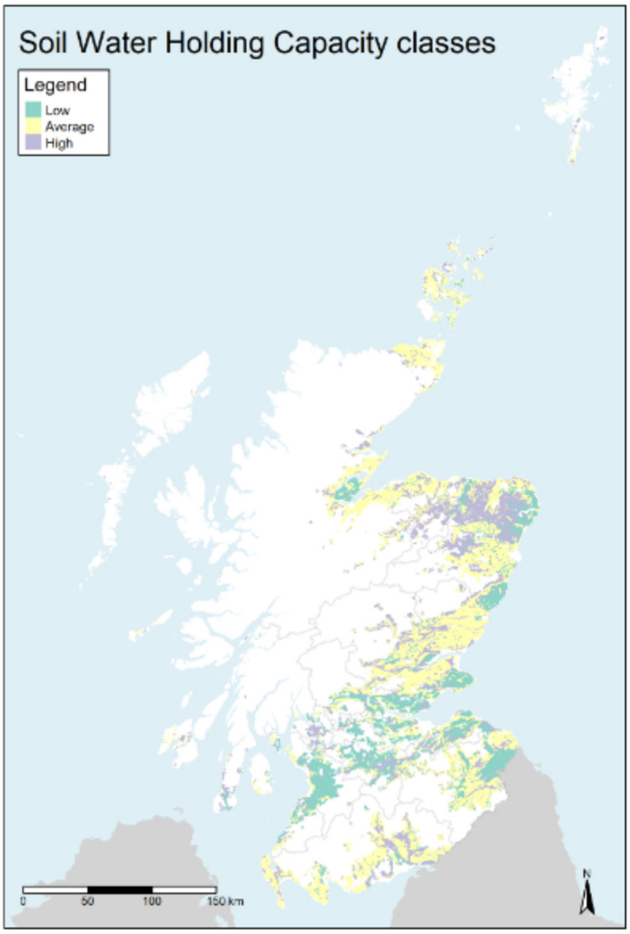


Figure A2.21: Spatial distribution of the soil water holding capacity (WHC) (left map) and the different WHC classes (right, see text for explanation) (Rivington *et. al.*, 2022).

shortage and found that on average the barley reproductive phase will likely suffer from water shortage for most of the future climate members. The soil capacity to hold water will determine how barley yield is affected as soils with high water holding capacity will benefit from water surplus during the vegetative phase and the surplus can be used during the grain development.

Overall, the key findings of this work were:

- With the high emissions scenario used (RCP8.5), climate change is likely to have both positive and negative impacts on barley growth and annual yields, but with an overall decrease in yields by the 2040s, which continues to worsen by the 2070s.
  - It should be noted that there is little difference in estimated climate change between the low and high scenarios until c. 2040 – 2050, after which they start to diverge.
- Under the twelve climate projections used (which leads to temperature increases ranging from 1 to 3.5°C and 7% increase to 14% decrease in growing season precipitation), barley yields are likely to decrease in many parts of Scotland.
  - This will likely be due to additional water stress, especially if water is limited in the spring to early summer periods.
  - Future higher temperatures and potentially reduced precipitation are likely to lead to an increased water deficit, where evapotranspiration loss of water to the atmosphere is greater than the precipitation input to soils.
  - Areas with better soil water holding capacity appear to be more resilient and could potentially experience increases in yield when favourable climatic conditions permit.
- There is good agreement between the climate projections as to where these changes in yield may occur.
- There is likely to be increased annual variability, with some years potentially experiencing good yields when conditions are favourable.
- The spatial extent and temporal frequency of yield decreases is likely to cause substantial challenges to the barley supply chain and end users.
- Earlier sowing appears to be a viable adaptation option.

Appendix 3 Future drought profiling

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Summary

Scotland's land and water resources are increasingly vulnerable to periods of drought, impacting water users and the water environment. Abstractions by sectors with high water demands are forecasted to exacerbate the direct climate change impacts by amplifying both frequency and duration of drought events (Visser-Quinn *et. al.,* 2021). This study addresses the limitations of earlier assessment (Visser-Quinn *et. al.,* 2021) by using detailed abstraction return values for all sectors including agricultural and distillery sectors obtained from SEPA and public supply from SW to allow a more accurate assessment of the current state of Scotland's water resources and their vulnerability to climate extremes. The overarching aim of this work was to determine how abstractions by these different water sectors may exacerbate the climate change impacts on droughts in Scotland in the near-future up to 2050s. Future abstractions scenarios using historical abstractions under future climate change were developed to demonstrate a more realistic assessment of future drought impacts in Scotland. These scenarios include no increase in abstraction (using the baseline annual time series repeated until 2050) and increasing abstractions by 5%, 10%, 15%, 20%, and a worst-case scenario of 25%. We used the daily time series data of total aggregated abstraction for the baseline period (2007 – 2018) to project future abstractions for the period 2019 – 2050. We found an increase in mean, minimum and maximum frequency and drought duration between the baseline (2007 – 2018) and future periods (2019 – 2050). Mean drought frequency increased from 0.33 to 0.65, while average drought duration increased from 31 to 51 days across the 23 study catchments. Up to 25% increase in historical abstractions did not impact significantly future water availability across catchments in Scotland. Therefore, the observed increase in future drought duration and frequency can be primarily attributed to the hydrological model projections of decreased future flows.

Introduction

Scotland's land and water resources are increasingly vulnerable to periods of drought, impacting water users and the water environment. Abstractions by sectors with high water demands are forecasted to exacerbate the direct climate change impacts by amplifying both frequency and duration of drought events (Visser-Quinn *et. al.,* 2021). In 2022, large parts of Scotland experienced moderate to significant drought conditions, resulting in SEPA restricting water abstractions for license holders in many areas. Previous studies have assessed the potential future water scarcity in Scotland (Visser-Quinn *et. al.,* 2021). However, these analyses were limited by the lack of available data on actual abstractions.

In Visser-Quinn *et. al.,* 2021, abstractor data returns were not used and assumed that all licensees abstract the full daily licensed volume, i.e. maximum abstraction occurs at all times. The study focused on non-public surface water supply abstractions for four different sectors in Scotland, however, raw water abstractions by Scottish Water for public water supply was not accounted for.

We overcome these data limitations by using detailed abstraction return values for all sectors including agricultural, distillery sectors obtained from SEPA and public water supply from SW. This allows a more accurate assessment of the current state of Scotland's water resources and their vulnerability to climate extremes. The overarching aim of this work is to determine how abstractions by these different water sectors may exacerbate the climate change impacts on droughts in Scotland in the near-future up to 2050s.

The objectives of this study are:

1. Forming a detailed licensed actual abstraction database comprising of sectoral abstractions from SEPA and public water supply abstractions from Scottish Water.
2. Designing a drought profiling framework and using the abstraction database in combination with historical and future flow projections (Hannaford *et. al.,* 2022).

We aim to use raw abstraction daily licensed data in the historical period and define future plausible abstractions scenarios under future climate change to demonstrate an improved assessment of future drought impacts in Scotland.

Data and methods

Hydroclimatic data – eFLaG

Enhanced future FLows and Groundwater' (eFLaG) (Hannaford *et. al.,* 2022) is a dataset of nationally consistent hydrological projections for the UK, based on the latest UK Climate Projections (UKCP18). The hydrological projections are derived from a range of hydrological models (Grid-to-Grid, PDM, GR4J and GR6J), to provide information on hydrological model uncertainty. The data consists of a 12-member ensemble of transient projections from high emissions scenario (RCP8.5) of present and future (up to 2080) daily river flows, produced using bias corrected data from the UKCP18 Regional (12 km) climate ensemble. Among these 12 ensemble members for emission scenario RCM 8.5, we use ensemble member 05 that is indicative of dry scenario. These flow projections are available for 200 river catchments across UK. This dataset has been developed with drought, low river flow and low groundwater level applications as the primary focus.

In this study, we use G2G model simulated flows. G2G is not calibrated to individual catchments, hence simulates natural flows, whereas the lumped models like PDM, GR6J are calibrated to the observations, meaning simulated flows are not natural, as they implicitly include artificial impacts, including water abstractions. Since our drought profiling method (explained below) involves subtracting abstracted volume of water from the river flow volume to obtain the volume of water available at each catchment outlet, we believe using an uncalibrated model like G2G would lead to lesser bias.

Flow observations and projections

Daily modelled flow observations (driven by observed climate) and projections (driven by RCM) from G2G model were extracted for a historical period (1990 – 2018), and the near-future (2018 – 2050).

Abstraction database formation

We have collated the raw abstraction data from SEPA that comprises of daily licensed sectoral abstraction data for years from 2007 – 2022 (please note 2008 – 2018 is a complete dataset, 2019 was lost because of the cyber-attack and 2020 – 2021 is a partial dataset for prioritised catchment. Catchment level daily abstractions for public water supply for the year 2017 – 2022 were made available by Scottish Water. We have imported all the abstraction datasets in R platform and performed several data processing steps including data cleaning owing to missing location coordinates, missing water body information and negative abstraction values due to several reasons. We then aggregated SEPA raw daily abstraction data at catchment level to bind it with the Scottish Water daily catchment level abstraction data to form a comprehensive abstraction database. Abstraction activity is classified by sector by SEPA as follows:

1. Agricultural irrigation (fixed + mobile)
2. Agricultural non-irrigation
3. Hydropower
4. Distillery
5. Golf Course
6. Fish Production
7. Industrial commercial Process Water (excluding distilleries)
8. Industrial commercial evaporative cooling (excluding distilleries)
9. Mining quarrying
10. Pumping test
11. Navigation
12. Unknown

The database consists of both surface and groundwater abstractions. Whilst we have used both sources of abstraction data for this work, we have split the database into surface and groundwater abstraction using SEPA guidelines based on raw abstraction location description using keywords "groundwater", "BH", "borehole", "GdW", "Spring" to identify a groundwater source. Groundwater abstractions were then shared with BGS for the groundwater assessment presented in Appendix 4.

Abstraction database overall summary

Excluding the period prior to 2011, when abstraction returns were not mandatory, the database shows an increase in the number of abstractions returns up to a maximum of 1,227 unique abstraction licences (excluding Scottish Water licences) (Figure A3.1). Unfortunately, it is not possible to extract any additional insights on the evolution of abstraction after 2018 due to a data loss by SEPA because of a cyber-attack that affected their databases.

Regarding the different sectors of interest in this report, irrigation licences have increased over the period of study, and they accounted for nearly half of all the licences for purposes different than drinking water supply. In contrast, licences for agricultural purposes other than irrigation are quite anecdotal, and saw a decrease up to 2018. This is probably due to many of these purposes preferring to get their supply directly from the drinking water network to avoid treatment costs (especially for livestock). The number of individual licences for distilleries also saw a steady increase between 2011 and 2018.

With regard to abstracted volumes, Figure A3.2 and Table A3.1 show that the sectors considered in this study represent a minimal portion of all the water abstracted in Scotland (at the national level). Between 2013 and 2018 total abstractions for agricultural irrigation averaged 240 hm^3 (1 hm^3 = 1,000,000 m^3), with a sharp increase in 2022 despite data for that year being only for prioritised catchments. Total abstractions for distilleries show a reduction of nearly 50% between 2015 and 2018 in comparison to the period between 2009 and 2013, with an outlier value in 2014 that may require further investigation. For comparison, licenced abstractions for drinking water supply were of approximately 700 hm^3 in 2018 and 2022. In any case, all these consumptive abstractions are a minimal fraction of all the abstractions under the category 'Other', which includes uses like hydropower, navigation, or fisheries (of non-consumptive nature) as well as many licences classified as 'unknown'.

Future abstractions

We used the daily time series data of total aggregated abstraction for the baseline period (2007 – 2018) to project future abstractions for the period 2019 – 2050. Initially, we computed the average time series of total aggregated abstractions during the baseline. Subsequently, we applied percentage increases to this average time series, representing various scenarios. These scenarios include no increase in abstraction (using the same annual time series repeated until 2050) and increasing abstractions by 5%, 10%, 15%, 20%, and a worst-case scenario of 25%.

Data availability

Raw abstraction data locations provided by SEPA, when matched to the corresponding catchments

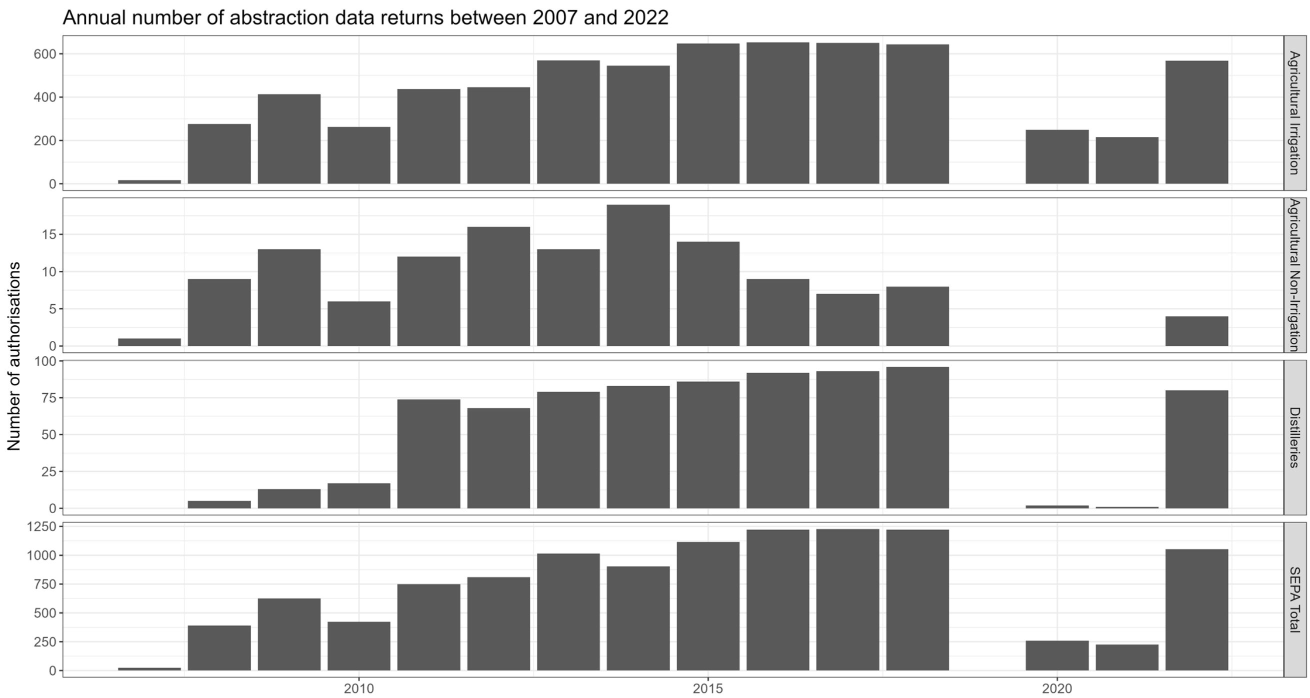

Figure A3.1: Number of unique abstractions data returns submitted annually to SEPA (excluding Scottish Water) in the period 2007-2022.

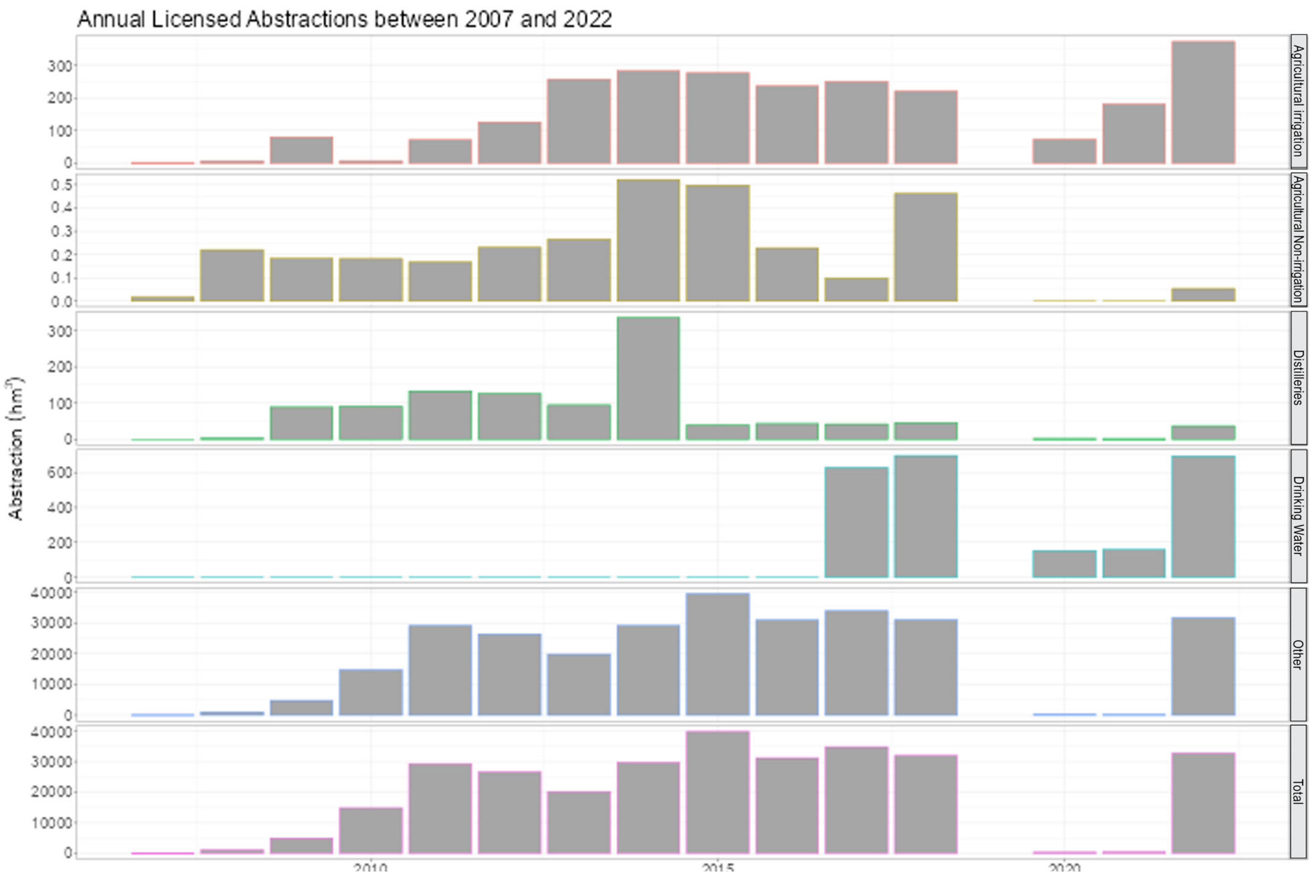

Figure A3.2: Total reported abstracted volumes submitted annually to SEPA (excluding Scottish Water) in the period 2007 – 2022.

Table A3.1: % of abstractions by volume by abstraction type for years 2017 and 2018 across Scotland.

Year	Agricultural Irrigation	Agricultural Non-Irrigation	Distilleries	Drinking Water	Other
2017	11.0	0.0	5.1	20.8	63
2018	15.7	0.1	5.4	20.4	58.4

from SEPA catchment boundary layer, resulted in 85 catchments across Scotland with available data. These catchments were then reduced to 23 based on the availability of both daily time series of flow projections from eFLaG and past daily time series of abstraction data. In Figure A3.3 catchments marked in yellow are the catchments for which the daily time series of abstraction data are available, catchments marked in pink are the catchments for which both daily time series of abstraction data and eFLaG projections are available and were included in this study. eFLaG flow datasets are available based on NRFA station numbers (marked in red). We only used eFlaG flow data for the most downstream NRFA gauge station in each catchment. This is because, although we had received raw abstraction data for multiple locations within the water bodies from SEPA, SW's abstraction data were integrated at the catchment scale.

Hence, only a catchment-aggregated comparison between volume of total abstraction (SEPA+SW) and eFlaG flows at the most downstream gauge station (as a representation of total catchment water availability) was possible.

Drought profiling framework

We designed a drought profiling framework (shown in Figure A3.4), adapted from Visser-Quinn *et. al.* (2021). We determine the available volume, per catchment, per day (*Vav*), for the scenarios mentioned in (Table A3.2). All scenarios focus both on climate change projections and the total aggregated abstractions, meaning the impact of climate change, and the abstractions are not considered in isolation therefore not allowing the respective impact to be determined. We have used this framework to extract the droughts in the baseline period twice, once using G2G model simulated flows driven by observations and then from G2G model simulated flows driven by RCM. A long-term Q95 threshold (*Vt*), a measure of the flow equalled or exceeded 95% of the time, was therefore, determined twice for the time 1990–2018, first from the G2G model simulated flows driven by observations and then from G2G model simulated flows driven by RCM. From the G2G model simulations, a five-day average flow was then determined (enabling pooling of droughts where the inter-event period is less than five-days). Flows (*V*) for each catchment was then converted to daily flow volumes (m^3) to enable subtraction of abstraction volumes (*Vactual*) in cubic metres, to obtain the volume of water available after abstraction (*Vav*). Flow deficit was then calculated, if the available volume of water following abstraction was less than the Q95 threshold. As per Scotland's environmental standards (Hayes *et. al.,* 2017), low flow events were defined as periods where the volume of water available, following actual abstraction, fell below the long-term Q95 threshold. Here, we considered each continuous period of flow deficit as a distinct event. Following the drought definition from Visser-Quinn *et. al.* (2021) we define drought as a low-flow event where event duration ≥ 30-days. Finally, based on this criterion, we extracted the drought events and determined the summary metrics such as drought frequency and durations for all the scenarios (Table A3.2) across all 23 catchments (Figure A3.3). Drought frequency was defined as a count of the total number of drought events divided by the 12-year time series (historical, 2007 – 2018), and 32-year time series in the (future, 2018 – 2049), whilst Duration is a measure of the average event duration.

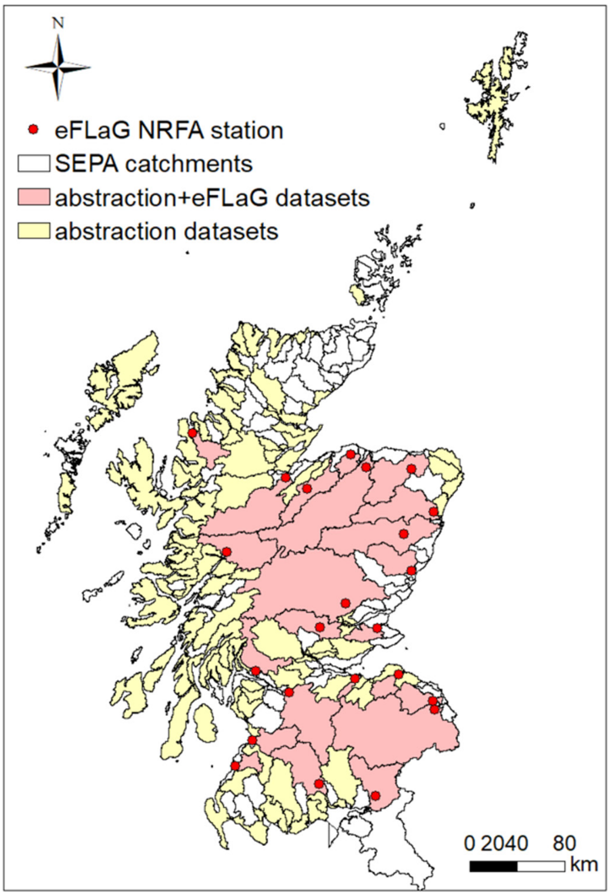

Figure A3.3 Catchments with the availability of daily time series of abstraction data (in yellow), availability of both daily time series of abstraction data and eFlaG daily flow projections (in red), overlaid on SEPA catchment boundary (in white). Red dots are the NFRA flow stations.

Table A3.2: Scenarios analysed within the drought profiling framework to extract the drought frequency and average drought duration.
Scenario 1: Baseline: G2G model runs driven by observation + total aggregated abstractions (2007-2018)
Scenario 2: Baseline: G2G model runs driven by RCM + total aggregated abstractions (2007-2018)
Scenario 3: Future: G2G model runs driven by RCM + (0, 5, 10, 15, 20, 25) % total historical aggregated abstractions (2019-2050)

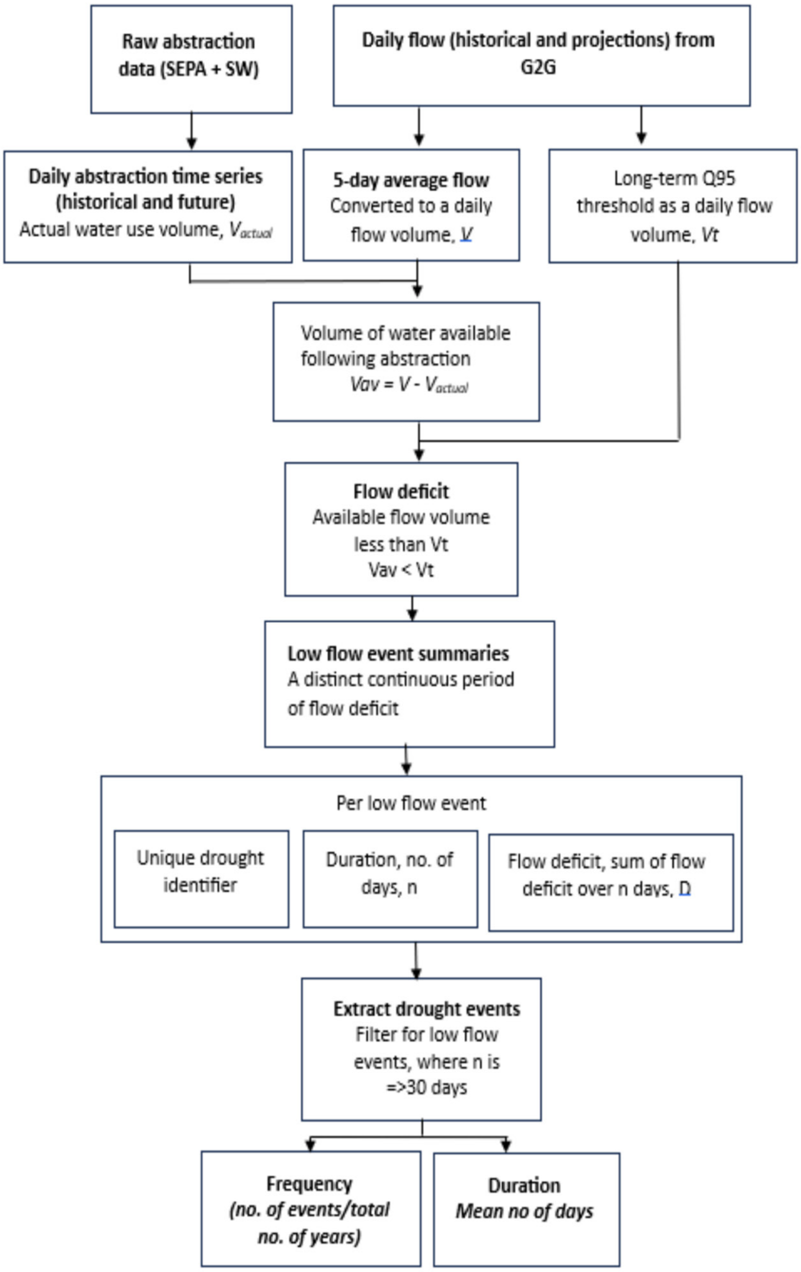

Figure A3.4: Drought profiling framework applied per 23 catchments across Scotland to obtain drought frequency and drought duration.

Results

Comparison of drought frequency and duration – Baseline period using RCM and observations

In Figure A.3.6a drought frequency is extracted for the historical period based on G2G modelled flows driven by observed climate whereas Figure A3.6b is based on G2G modelled flows driven by high emission future scenario RCM. We observe a difference between number of drought events per year in Figures A3.6a and A3.6b which can be attributed to the G2G modelling bias (Figure A3.5) related to the different sources of climatic input (observations vs RCM). The bias in the historical flow projections extends from a negative bias of -12.9% at River Ewe to the maximum positive bias of 73.7% at river Lochy. We observe maximum drought frequency of two (2 drought events in 1 year) at River Clyde when simulated by observations, compared to 1.92 (1.92 drought events in 1 year) at River Ness when simulated by RCM. In case of average drought durations, we see maximum average drought durations of 106 days (River Ness) with a mean of 42 days when simulated using observations whereas maximum duration of 81 days (River Ness) with a mean of 31 days when simulated using RCM. Minimum average drought duration of 0 days is observed in both cases at river Esk, Nith, Water of Girvan, River Ayr.

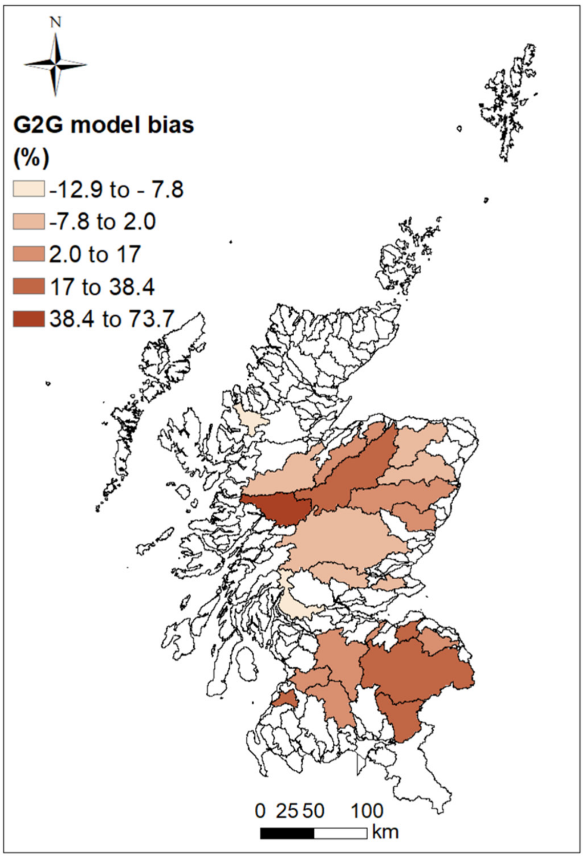

Figure A3.5: Percentage bias in G2G model simulations driven by RCM computed against G2G model simulations using observations. Catchments in white were not included in the analysis due to lack of data.

On average, the tendency of G2G model driven by RCM was to overestimate the flows (average bias of +10%), leading to fewer drought events and shorter durations, as depicted by the mean drought duration values in both cases. The observed biases should, therefore, be borne in mind when interpreting the results.

Comparison of drought frequency and duration – Baseline period using RCM and future period

An increase in both frequency of drought events and average drought duration (shown in Figure A3.6c and A3.7c respectively) is observed for all cases: mean, minimum and maximum; in the future (2019–2050) with no increase in the baseline abstraction scenario as compared to the frequency of drought events and average drought duration in the baseline period (2007–2018) (Figure A3.6b and A3.7b). We observed an increase in mean drought frequency from 0.33 to 0.65 across catchments in the baseline and the future, respectively. We observe a maximum frequency of 1.92 and 2.31 in the baseline and future period respectively at catchment River Ness. We observe a minimum frequency of 0 events/year in the baseline period at many catchments i.e. no drought events at river Esk, Nith, Water of Girvan, River Ayr, River Don, and Findhorn whereas 0.03 minimum number of events/year is observed in the future period at Water of Girvan, therefore resulting in increased number of drought hotspots in the future. In the future scenario with an increase of 25% baseline abstractions (shown in figure A3.6e), we see a further increase in the maximum frequency of up to 2.44 with an increase in mean frequency of upto 0.7. However, we observe no change in the minimum frequency (0.03 at Water of Girvan) from that of future scenario with no increase in abstraction.

We observed an increase in average drought durations from 31 to 51 days across catchments in the baseline and future respectively. Maximum average drought duration is observed at River Ness in both baseline and future period of 81 days and 86 days respectively. Similar to the drought frequency, minimum average drought duration of 0 days was observed in the baseline period at river Esk, Nith, Water of Girvan, River Ayr, River Don, and Findhorn whereas a minimum average drought duration of 31 days is observed in the future period at Water of Girvan, suggesting an increase in the drought events in the future. In the future scenario with an increase in baseline abstractions by 25% (figure A3.7e), we see a further increase in the maximum drought durations of up to 95 days with an increase in mean drought duration of up to 53 days.

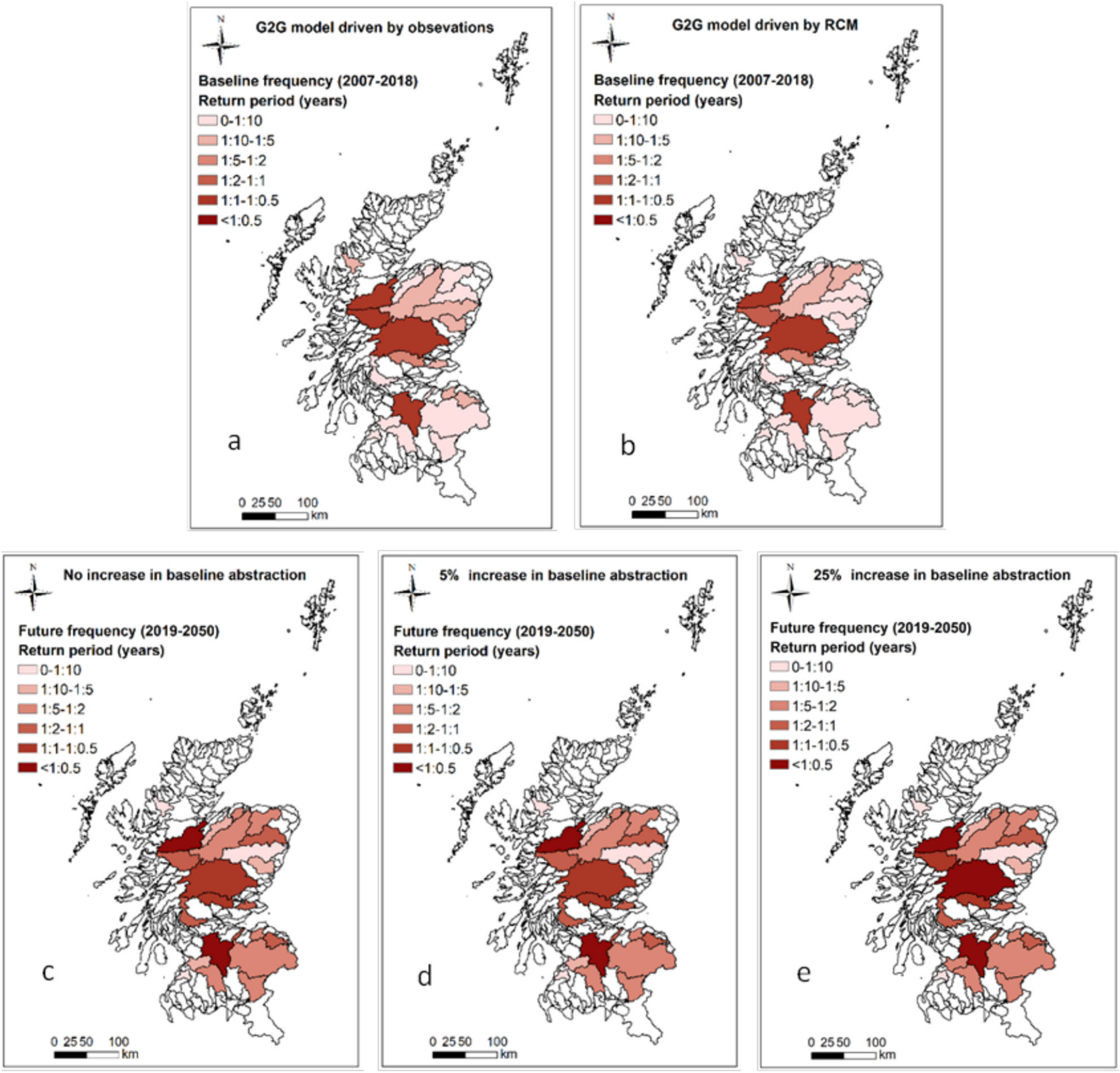

Figure A3.6: Drought frequency extracted from the drought profiling framework for the (a) historical period (2007 – 2018) driven by G2G model simulated flows using observations and baseline abstractions (b) historical period (2007 – 2018) driven by G2G model simulated flows using RCM and baseline abstractions (c) future (2019 – 2050) using G2G projected flows and baseline abstractions. (d) future (2019 – 2050) using G2G projected flows and 5% increase in baseline abstractions. (e) future (2019 – 2050) using G2G projected flows and 25% increase in baseline abstractions. Catchments in white were not included in the analysis due to lack of data.

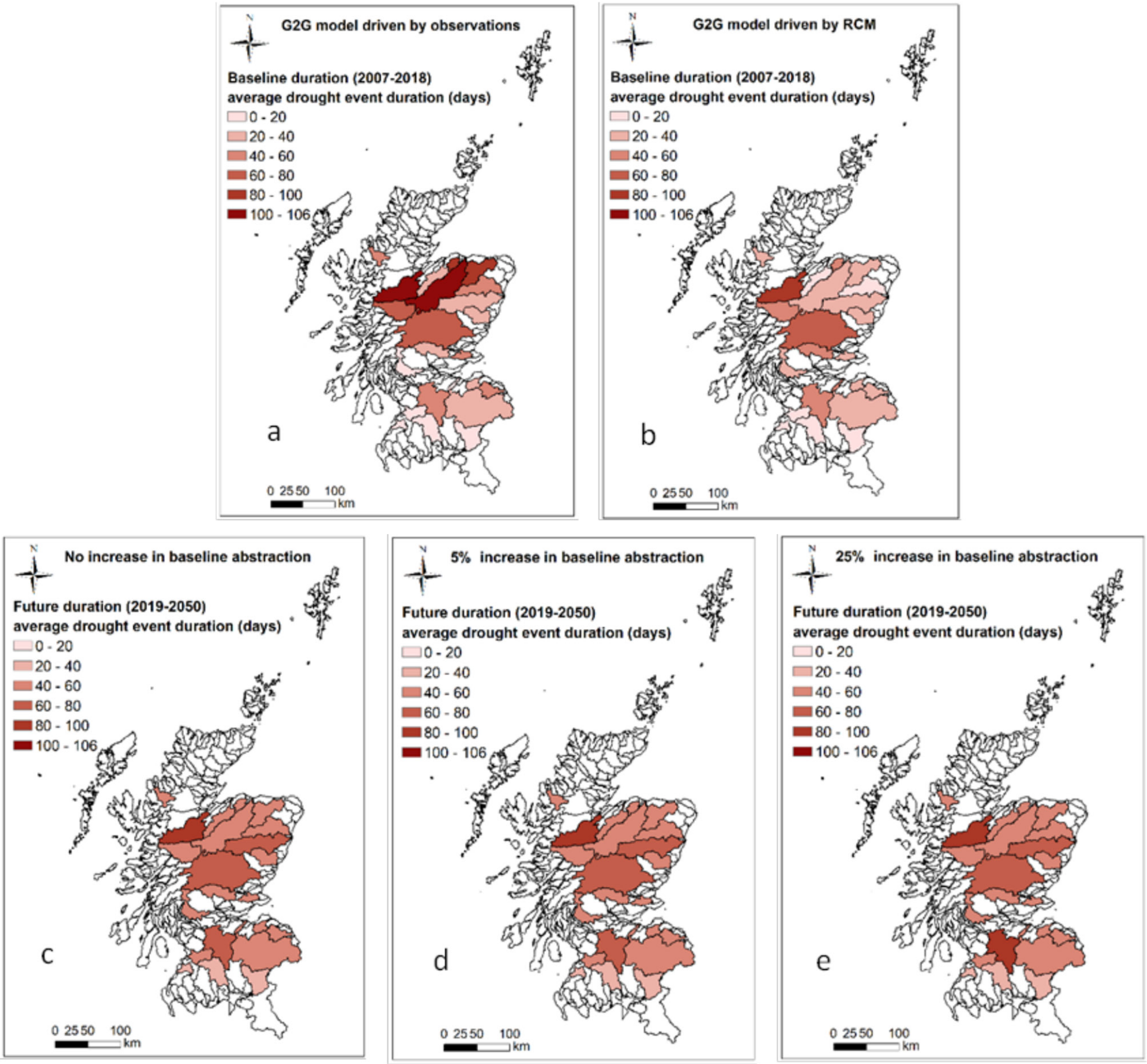

Figure A3.7: Average drought duration (in days) extracted from the drought profiling framework for the (a) historical period (2007 – 2018) driven by G2G model simulated flows using observations and baseline abstractions (b) historical period (2007 – 2018) driven by G2G model simulated flows using RCM and baseline abstractions (c) future (2019 – 2050) using G2G projected flows and baseline abstractions. (d) future period (2019 – 2050) using G2G projected flows and 5% increase in baseline abstractions. (e) future (2019 – 2050) using G2G projected flows and 25% increase in baseline abstractions. Catchments in white were not included in the analysis due to lack of data.

Limitations

- Despite the availability of river flow data at the upstream of some catchments, we had to restrict our analysis only to the downstream most station for every catchment. This is because abstractions were aggregated at the catchment level (as raw SW data not available), restricting us to capture the impact upstream abstractions might have on downstream water availability.
- This study defined drought as flows which fall below a long-term Q95 threshold for a duration equal to, or greater than, 30-days, however the specification of a constant threshold introduces a level of bias in the results. This may be addressed in the future through consideration of a moving threshold in conjunction with abstraction returns reflecting seasonal demand.
- Despite the availability of three different hydrological models within eFlaG, we did not consider the uncertainties that could arise from different model structures and parameters. This is because we believe there might be a need for renaturalisation of the recorded streamflows (by adding back abstracted volumes upstream the monitoring point), as the observed data from the NRFA already account for abstractions implicitly. Similarly, the models like GR6J and PDM within eFlaG, to predict future streamflow are calibrated against the observed flow, which means the model prediction is biased.

Conclusions

- We found an increase in mean, minimum and maximum frequency and drought duration between the baseline (2007 – 2018) and future periods (2019 – 2050). Mean drought frequency increased from 0.33 to 0.65, while average drought duration increased from 31 to 51 days across the 23 study catchments.
- Up to 25% increase in historical abstractions is not anticipated to significantly affect future water availability across catchments in Scotland. Therefore, the observed increase in future drought duration and frequency can be primarily attributed to the hydrological model projections of decreased future flows.

Appendix 4 Current and Future Climate Risks to Groundwater Availability for Distilling and Agriculture in Scotland

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Summary

This report provides an initial assessment of the potential risk to future groundwater availability in Scotland due to climate change, with a particular focus on groundwater supplies for agriculture and distilling. We (1) provide a review of the very limited published evidence of the (observed) past and (modelled) future changes in groundwater recharge and storage (level) under the effects of climate change, and (2) develop a framework to map areas where groundwater may be most vulnerable to drought and long-term depletion using existing national scale datasets of Scotland's aquifer properties and potential groundwater recharge. The report does not consider groundwater quality dimensions or other pressures, such as increasing demand or land use change, which are also likely to have an influence on future groundwater availability in parts in Scotland. The risk assessment uses a water security framework to analyse the relationship between groundwater storage and groundwater recharge, highlighting parts of the country that are relatively more or less resilient to drought and long-term depletion. In parts of Scotland where long-term average recharge is relatively low (generally eastern Scotland), significant groundwater storage within sandstone aquifers can provide a buffer during dry periods, making abstractions from these aquifers potentially more resilient to drought. Conversely, large abstraction from relatively low-storage aquifers, such as those found within old crystalline rocks and many superficial deposits, will be more vulnerable to drought. An assessment of the eFLaG (enhanced Future Flows and Groundwater) dataset (Hannaford *et. al.,* 2022) indicates that projected increases in the frequency and intensity of droughts may increase the vulnerability of groundwater sources, particularly those abstracting from low-storage aquifers in eastern and central Scotland. This work highlights significant knowledge gaps in our understanding of the potential response of different types of aquifers to drought and long-term change in Scotland.

Introduction

Groundwater is an important and valuable natural resource in Scotland, particularly in rural areas. Groundwater underpins the majority of private water supplies in Scotland, of which there are >22,800 (DWQR, 2023), and supports public water supply for several major rural towns. Groundwater is also important for Scotland's economy, supplying water for agricultural activities and key industries such as whisky distilling, brewing and bottled water (Teedon *et. al.,* 2020). During recent droughts, most notably the summers of 2018 and 2023, the vulnerability of private water supply, including those dependent on groundwater, became clear as hundreds of supplies in Scotland ran dry[3] with significant associated socio-economic costs.

Groundwater information for Scotland is relatively scarce, limiting our understanding of current and future groundwater availability. There are also significant gaps in our understanding of groundwater quality issues, including groundwater temperature, which although outside the scope of this report are an important consideration for assessing the current and future availability of groundwater for different uses.

This report aims to provide an initial assessment of the potential future risk to groundwater availability in Scotland due to climate change. The risk assessment uses a water security framework to analyse the relationship between groundwater storage, groundwater recharge, and groundwater abstraction. Using existing national-scale groundwater datasets for Scotland, the report presents a new groundwater storage map for Scotland, showing areas where aquifers have the ability to store relatively large or small volumes of groundwater, which respectively increases or decreases their capacity to continue to support groundwater supplies during drought. It combines this storage map with a map of long-term average

[3] www.bbc.co.uk/news/uk-scotland-highlands-islands-65913891; www.bbc.co.uk/news/uk-scotland-44865968

potential groundwater recharge derived from the eFLaG (enhanced Future Flows and Groundwater) dataset (Hannaford *et. al.,* 2022), which gives an indication of the renewability of the groundwater resource. This combined analysis highlights those parts of the country that are relatively more or less resilient to drought and long-term groundwater depletion and allows an assessment of risk based on their importance for groundwater abstraction. Although no new analysis of future groundwater recharge scenarios is made, we summarise the projections from the eFLaG dataset, providing an assessment for what climate change might mean for future groundwater availability and risk in different parts of the country.

The report provides a summary of relevant literature but demonstrates significant knowledge gaps in our understanding of current and future groundwater availability in Scotland at a catchment scale, the potential response of different aquifer types to future pressures, and options for mitigating risks to future groundwater availability in different contexts.

General Literature and Evidence Review of Groundwater and Drought in Scotland

Limitations

The past and future impacts of meteorological droughts on groundwater resources and the role of groundwater in periods of water scarcity in Scotland have received little attention to date, and therefore the topics suffer from limited evidence in the academic or grey literature. This shortage of data and knowledge has been consistently highlighted in recent works, including a number of CREW review and/or synthesis reports (e.g. (Rivington *et. al.,* 2020; Boca, White and Bertram, 2022; Geris *et. al.,* 2023). In particular, Boca *et. al.* (2022) noted a "dearth of research towards groundwater quantity and the effects of climate change on groundwater availability" and recommended research to be "undertaken in the area of climate change effects on groundwater quantity". They further highlighted that only 50 Scottish Environmental Protection Agency (SEPA) water level monitoring stations out of a total of 392 stations, are for groundwater levels, i.e. only 13%. These are mostly located in major aquifers in Eastern parts of Scotland.

Most published academic evidence relates to the impact of water scarcity on (potential) groundwater recharge, usually through surface water balance modelling approaches, applied at local or catchment scales. Much less has been published relating to in situ changes in groundwater level/storage or spring discharge, including their future prediction. Larger scale (regional to national) evidence of the past impacts of droughts is available through the records of the SEPA groundwater monitoring well network, and comparison with previous long term groundwater levels are summarised in the SEPA's summer Water Scarcity Reports (SEPA, 2024). Future predictions of groundwater recharge and groundwater levels are available through the modelling results of the eFLaG project (UKCEH, 2024).

Academic literature evidence

As part of the published academic evidence providing insights on future groundwater recharge in Scotland, Rivington *et. al.,* (2020) reported, using the UKCP18 data, that total annual precipitation will generally decrease across Scotland, which combined with higher temperatures and evapotranspiration poses a risk of reduced groundwater recharge and storage. Hughes *et. al.* (2021) used a country-scale groundwater recharge model, and rainfall and potential evaporation predictions created by the Future Flows and Groundwater Levels project, to investigate future groundwater recharge across mainland UK. For Scotland specifically (and elsewhere in the UK) they found that whilst groundwater recharge is likely to decrease over the summer due to drier, longer summers, and the winter recharge period to shorten, the total potential annual recharge might not change significantly due to a predicted increase in winter recharge caused by wetter winters. Yawson *et. al.* (2019) examined the impacts of climate change on potential groundwater recharge in barley crop fields across the UK considering UKCP09 scenarios up to the 2050s and found an increase in potential recharge over baseline values across Scotland, but to a larger extent in western Scotland compared to eastern Scotland. More locally, Afzal and Ragab (2020) applied a distributed catchment-scale model to the Eden catchment, Northeast Scotland, underlain by highly to moderately productive aquifers, and predicted a decrease in summer groundwater recharge as a result of drier summers, but no increase in winter recharge as a result of wetter winters. At Paisley, West Scotland, Herrera-Pantoja and Hiscock (2008) modelled the effect of climate change on potential groundwater recharge and found that under future scenarios of increased persistence of dry periods, groundwater recharge would also decrease by about 7%. Waajen (2019) did not examine groundwater specifically but suggested that in Scotland, projected increased winter precipitation will not compensate for the deficits associated with drier summers, which will increase the pressures on water supplies and ecosystems in groundwater-dependent areas.

With respect to groundwater levels, storage, and contribution to river flow, Parry *et. al.* (2024) reported the eFLaG results at mainland-UK scale, which for the four studied wells located in eastern and southwestern Scotland, suggest up to a 20% decline in groundwater levels in East Scotland in the far future (2050 – 2079), but little change in groundwater levels in Southwest Scotland. Fennel *et. al.* (2020) and Soulsby *et. al.* (2021) reported consistent observations regarding the impact of the 2018 drought on groundwater at an upland catchment in Moray supplying water for Scottish distilleries (Moray), and at a headwater catchment in the Cairngorm mountains, respectively. They found that during the 2018 drought, river flows were sustained almost entirely by groundwater drainage at both locations. In the Cairngorms, the 2018 drought (which followed two anomalously dry winters) caused the largest catchment storage deficit observed for over a decade, but that groundwater stores rapidly returned to normal conditions in autumn/winter 2018. In Moray, the depleted groundwater reserves during the 2018 drought recovered at the end of 2019 thanks to above average rainfall. Fennel *et. al.* (2023a) further used a distributed hydrological model (MIKE-SHE) at the Moray upland catchment site to show that nature-based solutions (especially runoff attenuation features) may increase groundwater recharge, storage, and baseflow, and therefore mitigate against increased frequency and magnitude of floods and droughts supporting more resilient groundwater supplies.

There is a lack of studies in Scotland comparing the vulnerability/resilience of groundwater to water scarcity between shallow groundwater, including springs, versus deeper groundwater. In many parts of the world, rural water supplies based on groundwater are relied on as the most resilient to drought (e.g. MacAllister *et. al.,* 2020). Likewise, in Scotland, accessing deeper groundwater where available, through boreholes, may offer much greater resilience to drought, and make use of the natural storage afforded by aquifers. This research is the focus of a Hydro Nation PhD project that commenced in autumn 2023 (Mr Brady Johnson, University of Aberdeen, British Geological Survey, James Hutton Institute; Hydro Nation, 2024).

SEPA Groundwater Monitoring Data and Scarcity Reports

During the summer months, usually between April to October, SEPA publishes weekly to fortnightly water scarcity reports, which includes an analysis of groundwater levels from less than a dozen groundwater monitoring wells across Scotland. The most recent report, for October 2023, is available online at the time of writing, while previous reports can be requested from SEPA. Unlike rainfall and river flow monitoring which comprise a larger number of monitoring stations spread across mainland Scotland, the reported groundwater monitoring data are mostly restricted to major aquifers in the East (Northeast and East) and in the extreme Southwest of Scotland. No monitoring of spring discharge or spring level is available. Figure A4.1 shows the groundwater level maps for 2023, specifically. Reported groundwater level data for the wider recent period 2019 – 2023 showed:

- In the Moray Firth area (highly productive Devonian sandstone aquifers), recent groundwater levels have been relatively close to the normal range observed during the preceding decade (2009–2019) during the winter month, but slightly lower during the summer months.
- In the Northeast region (low productivity basement and igneous aquifers), winter groundwater levels have been within their normal range, but summer groundwater levels have been lower than the levels observed during the preceding decade (2009 – 2019).
- In the eastern region (moderate to high productivity Devonian and Carboniferous sandstone aquifers of the Midland Valley), winter groundwater levels have generally been within their normal winter range, yet closer to the low end of it for some wells, and summer groundwater levels have been lower than the levels observed during the preceding decade (2009 – 2019), with particularly anomalously low levels during the summers of 2022 and 2023.
- In the Southwest region (highly productive Permo-triassic sandstone aquifers), winter groundwater levels have generally been around or higher than their normal winter range, and summer groundwater levels were around or lower than the levels observed during the preceding ~25 years (1993 – 2019).

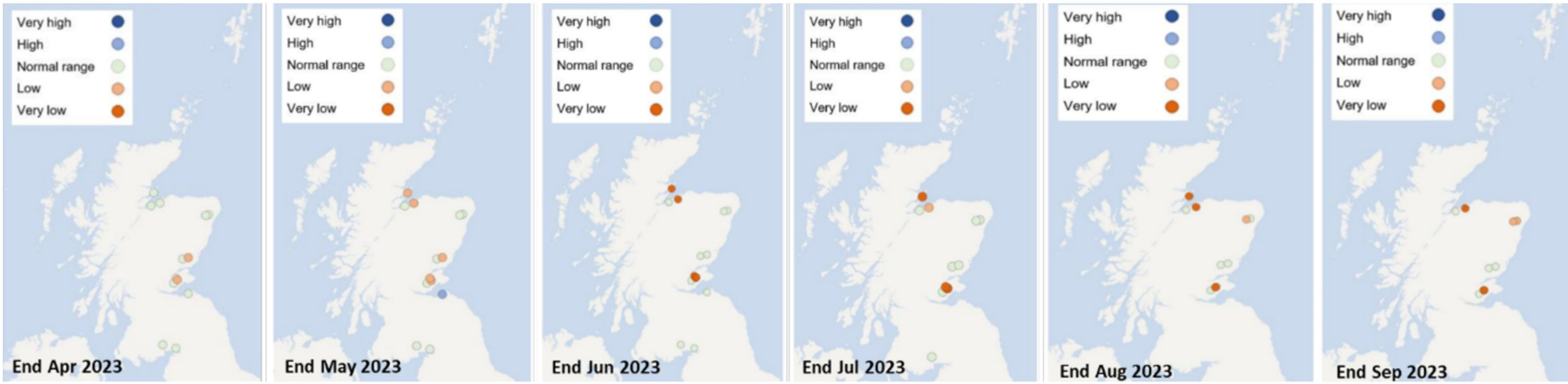

Figure A4.1: 2023 groundwater level comparison with historical monthly normal ranges as reported in the 2023 SEPA Water Scarcity Reports (©SEPA, 2024)

The eFLaG Groundwater Projections

The eFLaG open-access dataset further reports modelled future predictions of droughts, surface water flows, and groundwater levels and recharge in the UK for the near (2020–2049) and far (2050–2079) future as compared to the 1989–2018 observed historical baseline (Hannaford *et. al.,* 2022). For Scotland specifically, while recharge models cover all groundwater bodies of mainland Scotland, aquifer models report groundwater level predictions for only three (3) observation points, located in moderately to highly productive aquifers in the East and the extreme Southwest of Scotland.

The eFLaG seasonal groundwater recharge model prediction broadly agree with:

- No change, or an increase in potential recharge in the winter months, with a more marked increase in Central Scotland, by up to +30% in the far future;
- No change, or a decrease in recharge in the summer months, with a more marked decrease in eastern and southern Scotland, by more than -50% in the far future;
- In the Spring and Autumn months, contrasted predictions between western and eastern Scotland, whereby recharge in the West is not predicted to change significantly in the near future, but significantly increase in the far future, by up to +25% in the Northwest coastal regions; whereas in the East, recharge is consistently predicted to decrease in both near and far future, by up to -35% in the Southeast in the far future;
- Overall, far future predictions suggest that in western Scotland, especially in western coastal regions, recharge will increase throughout the year in the future, apart from the three summer months where no significant change is predicted in the Northwest but a significant decrease is predicted in the Southwest. By contrast, in eastern Scotland, far future predictions suggest a general decrease in recharge throughout the year, apart from the three winter months whereby recharge is predicted to increase.

The eFLaG groundwater level predictions for the three (3) modelled well locations are consistent with the recharge predictions:

- For the single point located in the moderate to highly productive Devonian aquifer in East Scotland, models agree with an overall decrease of groundwater level/storage in the near future, which will further accelerate in the far future;
- For the two points located in highly productive Permo-Triassic aquifers in Southwest Scotland, models agree with an insignificant change in groundwater level (storage) in the near future, but with a more significant level/storage increase in the far future.

It should be noted that there are uncertainties associated with these model predictions; small or insignificant predicted changes in recharge and/or storage should therefore be treated with caution. Furthermore, further work is needed to understand how national-scale predictions translate to observed changes at a local scale.

Methodology

Water Security Framework

Water security is defined by UN-Water as: *"The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability"* (UN-Water, 2013). There are socioeconomic and political dimensions to this concept that extend far beyond the physical water resource itself. This report focusses on the contribution that groundwater makes to water security in Scotland, assessing current and potential future risks to groundwater availability due to climate change. The assessment takes account of both the renewability and storage of groundwater within Scotland's aquifers (Foster and MacDonald, 2014) and considers risk relative to how groundwater is used for abstraction. The water security framework used to assess current and future groundwater availability has previously been used to assess water security in Africa (MacDonald *et. al.,* 2021) and is illustrated in Figure A4.2.

Groundwater recharge (along the horizontal axis of Figure A4.2) is the water that infiltrates from the land surface to reach the water table. Groundwater recharge can be diffuse – when water, usually from rainfall, infiltrates over a large area – or localised – when infiltrating water originates from surface water features such as streams or lakes. There are different definitions of groundwater renewability and they are often contested (e.g. Cuthbert *et. al.*, 2023), but a simplistic definition equates renewable groundwater with the rate of natural recharge. For the purposes of this work, groundwater recharge is used to indicate the renewability of an aquifer.

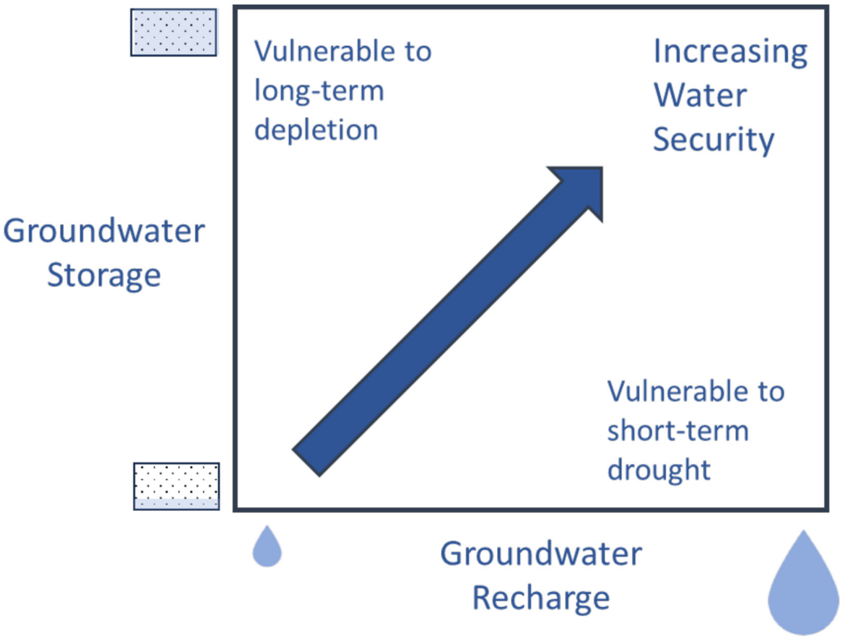

Figure A4.2: Water security framework adapted from MacDonald *et. al.* (2021).

Groundwater storage (along the vertical axis in Figure A4.2) is the total volume of water able to be held within an aquifer and which can subsequently be released through surface water discharge (spring and river baseflow) or well discharge. This is usually correlated with permeability and porosity of rocks whereby high permeability aquifers often also have high storage capacity. Groundwater is either held within pore spaces within sediments or sedimentary rocks or is contained within fractures in consolidated rocks. Storage is defined here as a product of total available (drainable) porosity, here defined as effective porosity, and the saturated thickness of the aquifer.

In the bottom left quadrant of Figure A4.2, groundwater recharge and storage are both low. Aquifers in this context will have limited ability to sustainably support large levels of abstraction and limited capacity to buffer against the effects of drought and short- and long-term climate variability. As groundwater recharge increases along the horizontal axis, renewable groundwater resources increase thus aquifers have greater capacity to sustainably support higher levels of abstraction in the long-term. However, limited storage means aquifers will still be vulnerable to drought. As groundwater storage increases along the vertical axis, aquifers have greater capacity to buffer against the effects of drought, however low recharge means aquifers in this context remain vulnerable to long-term depletion if levels of abstraction consistently exceed the renewability of the resource. In the top right, groundwater storage and recharge are high. Aquifers in this context will have the greatest capacity to support higher levels of abstraction in the long-term and to be able to continue to support abstraction during periods of drought.

The framework outlined above and in Figure A4.2 provides a useful way of considering groundwater availability and risk at a national scale. It does not take account of groundwater quality or groundwater's use within the wider environment, e.g. discharge to rivers or groundwater-dependent ecosystems. Furthermore, it does not consider the actual volumes of water that can be sustainably abstracted from an aquifer, which in addition to storage and recharge, will be influenced by the transmissivity of the aquifer and the design and construction of the infrastructure being used for abstraction.

Groundwater Storage Assessment

Groundwater storage was assessed using existing national-scale datasets of Scotland's aquifers (Ó Dochartaigh, Doce, *et. al,* 2015; Ó Dochartaigh, MacDonald, *et. al.,* 2015). Maps of bedrock aquifer productivity and superficial deposit aquifer productivity describe the flow type – dominantly intergranular, dominantly through fractures, or a combination of both – and expected productivity – the ability of the aquifer to sustain different levels of borehole supply – for all of Scotland's aquifers and groundwater bodies. This dataset is defined by the underlying geology, along with permeability data, pumping test data, laboratory hydraulic testing data and downhole geophysical logs. Storage characteristics are closely related to aquifer productivity, however, the productivity classes were further subdivided into dominant aquifer units to account for variations in storage for different lithologies. For example, within the 'Fracture Low Productivity' class, igneous rocks have lower storage capacity than Precambrian Torridonian metasedimentary rocks, due to having lower porosity and saturated thickness. Similarly, within the 'Intergranular/Fracture High Productivity' class, despite having similar porosity characteristics, Permo-Triassic sandstones in the north of Scotland generally have lower saturated thickness and therefore lower storage capacity than Devonian sandstones.

For each bedrock aquifer unit within each productivity class, effective porosity and saturated thickness were estimated, either based on published values or from expert knowledge. Bedrock groundwater storage (water depth in m) was calculated by multiplying effective porosity by saturated thickness. The dataset was then converted to a raster to give a country wide assessment at 1 km gridded scale. For superficial aquifers, all deposits classified as 'Not a significant aquifer' were disregarded, this includes all glacial till deposits and others dominated by silt and clay. The thickness of superficial deposits was estimated from BGS' Superficial Thickness Model (Lawley & Garcia-Bajo, 2010). Data on the porosity or effective porosity of superficial deposits in Scotland is very sparce and values are likely to vary significantly, even within individual deposits, due to horizontal and vertical heterogeneity – the majority of productive superficial aquifers will comprise layers of more productive sand and gravel, interbedded with less productive silt and clay layers. To account for this heterogeneity, and for the fact that deposits may not be fully saturated – for the majority of productive superficial aquifers groundwater levels are estimated to be at depths of <3m, and almost always <10m – an effective porosity of 10% was used across all superficial deposits. This was multiplied by superficial thickness to provide an estimate of superficial aquifer storage.

Given the uncertainty associated with a national level assessment, and a lack of quantitative data, bedrock and superficial aquifer storage are presented on qualitative scales, with a description of each classification provided in the Results section below.

Groundwater Recharge Assessment

Directly measuring groundwater recharge is very difficult and where locally possible, it is very difficult to upscale to reflect larger catchment scale heterogeneity. Because of this, there are a lack of data on actual values of aquifer recharge, including in Scotland, and recharge is usually assessed through land surface distributed water balance modelling approaches which provide a potential recharge regardless of the aquifer capacity to accept this recharge.

To assess potential groundwater recharge at a national scale for Scotland, the eFLaG dataset was used (Hannaford *et. al.,* 2022). This dataset provides gridded potential recharge (2 km squares) over a historic time-period (1961 – 2018), simulated using the ZOODRM distributed groundwater recharge model (Mansour *et. al.,* 2018). The model is driven by observed climate data (precipitation and potential evapotranspiration) and takes account of soil hydrology, vegetation, and surface topography to partition rainfall into actual evapotranspiration, soil moisture, runoff and potential groundwater recharge using the FAO approach.

Long-term average (LTA) annual potential groundwater recharge was calculated from the eFLaG dataset for the historic time-period 1980-2018. The term potential recharge is used as this describes the water infiltrating to the ground and not necessarily arriving at the water table. Processes in the unsaturated zone, such as the presence of low permeability materials that limit the downward movement of water, may reduce the amount of water that arrives at the saturated aquifer. To account for the role of unsaturated zone processes, LTA potential recharge was modified using a recharge coefficient. The recharge coefficient was defined using a modified version of the methodology used by the Geological Survey of Ireland, which has also been applied by the Geological Survey of Northern Ireland to develop national-scale groundwater recharge maps (Misstear, Brown and Daly, 2009; Wilson *et. al.,* 2023). The methodology uses a national-scale groundwater vulnerability map for Scotland (Ó Dochartaigh, Doce, *et. al,* 2015; Ó Dochartaigh, MacDonald, *et. al.,* 2015) and assigns a recharge coefficient to each of the vulnerability classes, as outlined in Table A4.1.

Table A4.1: Recharge coefficient based on Scotland's groundwater vulnerability classification.					
Superficial characteristics (based on Misstear *et. al.*, 2009)	**Recharge Coefficient Range (%)**	**Northern Ireland Vulnerability Classification**	**Northern Ireland Recharge Coefficient**	**Scotland Vulnerability Classification**	**Recharge Coefficient (%)**
High permeability	80-90	4,5	85	4a,4b,5	80,85,90
Moderate permeability (well-drained soils)	50-70	3	60	3	60
Moderate permeability (poorly drained soils)	20-40	2	30	2	30
Low permeability	20	1	20	1	20

The storage capacity of the aquifer and its level of filling also limit the amount of recharge that is accepted at the water table. This was not accounted for in the recharge calculation as the combination of this data with groundwater storage within the water security framework will highlight those areas where low storage may limit the amount of recharge accepted by the aquifer. Due to a lack of groundwater level data, we do not account for areas where very high water levels or confined aquifer conditions may limit the acceptance of recharge by an aquifer. For that reason, the term potential groundwater recharge is used throughout the study.

The eFLaG dataset provides future projections of groundwater recharge based on an ensemble of UKCP18 climate projections. It was beyond the scope of this project to undertake a detailed analysis of future scenarios of recharge potential for Scotland, particularly given the uncertainty associated with the projections, however a discussion of the expected patterns and trends for future groundwater recharge and potential implications for water security are included in the Discussion section below.

Abstraction

Abstraction data from SEPA was disaggregated to pull out different types of groundwater abstraction (spring or borehole) for different purposes (agriculture, distilling, and other). Some sites contained sparse information on rates of abstraction, but due to the incompleteness of this data it was not used for any further analysis.

Results

The bedrock and superficial groundwater storage maps are presented in Figures A4.3 and A4.4 with a description of the storage classifications provided in Tables A4.2 and A4.3. The map of LTA annual potential groundwater recharge is provided in Figure A4.5 with a description of the recharge classifications provided in Table A4.4. The storage and recharge analyses are combined into a single water security map, also showing groundwater abstraction, in Figure A4.6.

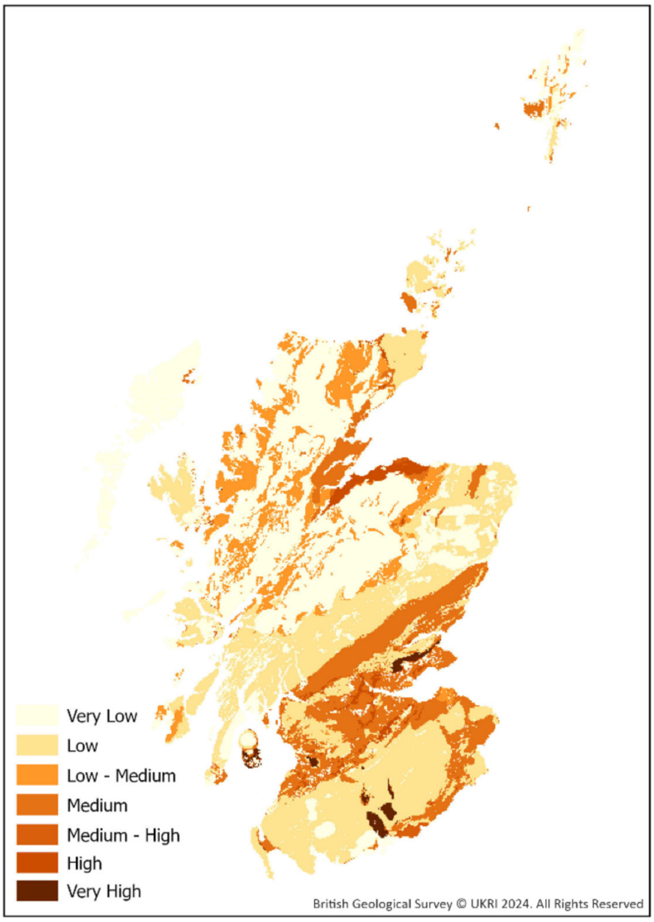

Figure A4.3: Bedrock aquifer storage map.

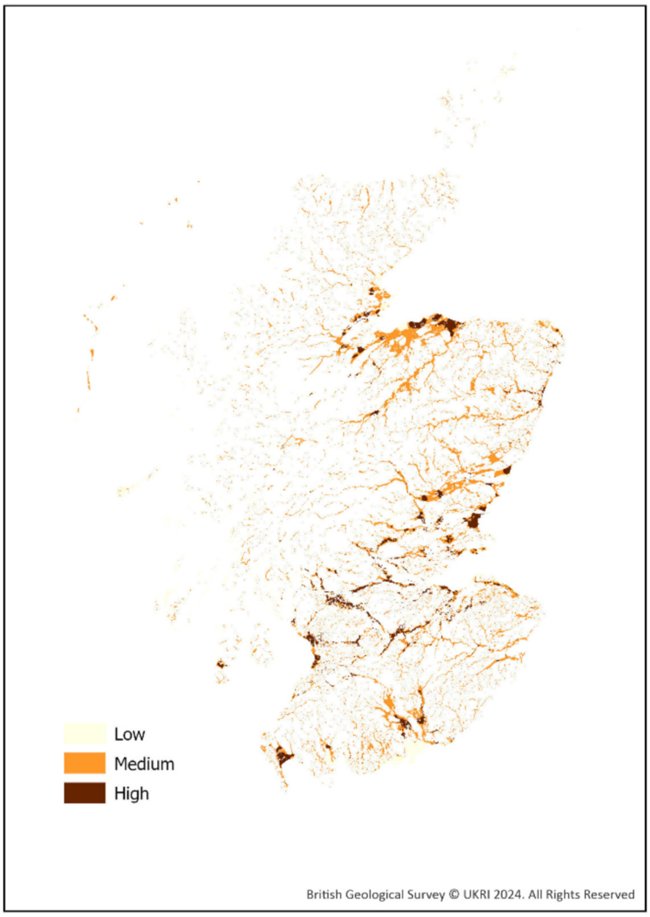

Figure A4.4: Superficial aquifer storage map.

Table A4.2: Bedrock aquifer storage classifications and descriptions.

Bedrock aquifer storage class	Estimated storage (water depth in m)	Main aquifer units	Aquifer productivity class
Very low	<0.5	Precambrian Moine & Lewisian; intrusive igneous	Fracture Very Low
Low	0.5-1	Precambrian Dalradian; Igneous volcanic; Silurian/Ordovician	Fracture Low
Low-Medium	1-2	Precambrian Torridonian; Precambrian/Cambrian calcareous	Fracture Low
Medium	2-5	Carboniferous; Devonian (northern)	Intergranular/Fracture Moderate
Medium-High	5-10	Permo-Triassic (north)	Intergranular/Fracture High
High	10-30	Lower Devonian (Midland Valley); Upper Devonian (south); Devonian (Moray); Carboniferous	Intergranular/Fracture High; Significantly Intergranular High
Very High	>30	Permo-Triassic (south); Upper Devonian (Midland Valley)	Significantly Intergranular Very High

Table A4.3: Superficial aquifer storage classifications and descriptions.			
Superficial aquifer storage class	**Estimated storage (water depth in m)**	**Main aquifer units**	**Aquifer productivity class**
Low	0-0.1	Marine deposits; Beach deposits (Dornoch & coastal Tayside)	Intergranular Low
Medium	0.1-1	Alluvium (Speyside & Tayside); Glacial deposits (Angus & Dumfries)	Intergranular Moderate
High	>1	Glacial deposits, alluvium and blown sands (Moray) Other areas of blown sands (Tayport)	Intergranular High

Within bedrock aquifers (Figure A4.3), groundwater storage is highest within the Permo-Triassic sandstone aquifers in southwest Scotland and the Devonian sandstone aquifers in Fife. Other areas of significant groundwater storage include the Devonian sandstone aquifers of Strathmore and Moray. Groundwater storage is lowest in the ancient crystalline rocks that are found across much of Northern Scotland, for example the Lewisian Gneiss and Moine metasedimentary aquifers in the Northwest and igneous and Dalradian metasedimentary aquifers in the Northeast. Superficial deposits (Figure A4.4) form locally important, but generally low storage aquifers. Notable examples are the glaciofluvial and alluvial sand and gravel aquifers in Speyside.

Potential groundwater recharge is strongly linked to rainfall with a west to east bias, whereby highest potential recharge is seen in western Scotland and lowest potential recharge is seen in Eastern and Southern Scotland (Figure A4.5).

The majority of licensed groundwater abstractions for agriculture are in Eastern Scotland (Figure A4.6). Most appear to be abstracting from the high storage Devonian and Carboniferous sandstone aquifers in Fife, Angus and Moray; however, no information on the depth of groundwater sources is included in the SEPA dataset, so the target aquifer cannot be determined with certainty. Abstraction from springs and relatively low storage superficial aquifers is important for distilling in Speyside.

The combined recharge and storage map provided in Figure A4.6 helps to illustrate the areas of the country that fall within the four quadrants of the water security framework (Figure A4.2) and how these relate to abstraction.

Areas of high potential recharge and low to moderate storage are characterised by fractured crystalline aquifers in West and Northwest Scotland. Aquifers in these areas have reliable LTA potential

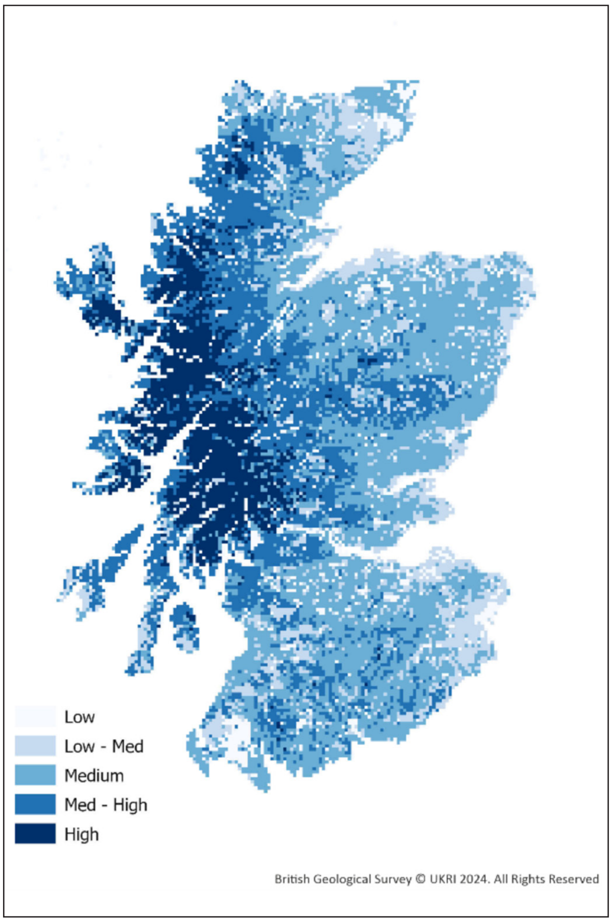

Figure A4.5: LTA annual potential groundwater recharge produced by BGS using eFLaG Modelling CEH Dataset https://eip.ceh.ac.uk/hydrology/eflag/ released under the Open Government Licence (nationalarchives.gov.uk).

Table A4.4: LTA annual potential groundwater recharge classifications.	
LTA potential recharge classification	**Estimated LTA annual potential recharge (mm/yr)**
Low	0-100
Low-Medium	100-200
Medium	200-500
Medium-High	500-1000
High	>1000

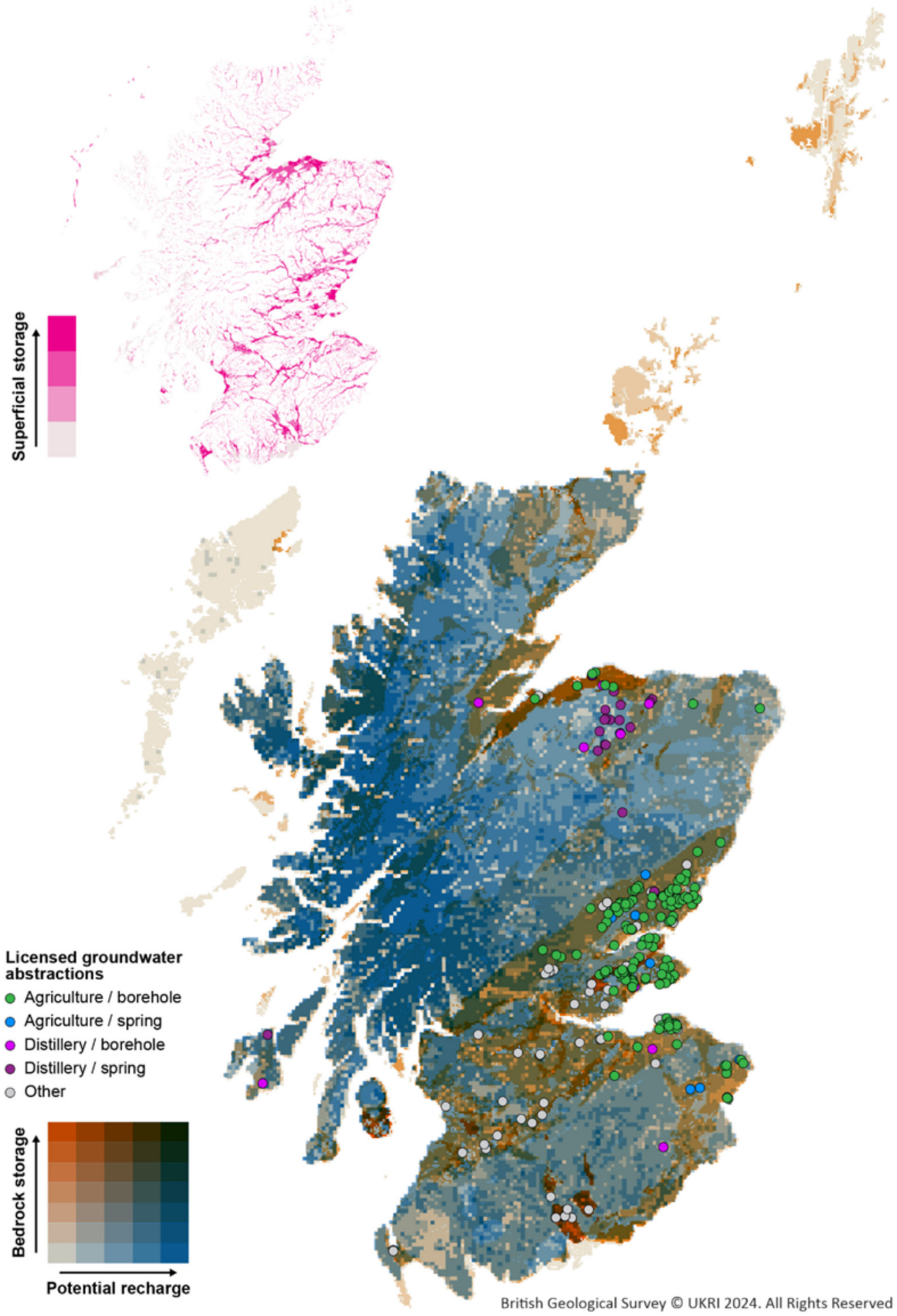

Figure A4.6: Water security analysis. Main map shows combined bedrock aquifer storage and LTA potential recharge with licensed groundwater abstractions for agriculture and distilling. Licensed groundwater abstraction records supplied by SEPA (Permissions received © SEPA 2024). Inset map shows superficial aquifer storage map. Note that potential groundwater recharge is only available for the mainland and larger islands of the Inner Hebrides.

recharge but their physical properties (generally low permeability and storage) will limit the amount of potential recharge that is accepted by the aquifer. These aquifers are generally therefore only capable of supporting relatively small-scale supply and will be vulnerable to drought. There are very few licensed abstractions exploiting these aquifers, however, we know they are commonly used for private/household sources in areas not supplied by Scottish Water. Further work is required to understand the response of these aquifers to both single and multi-year drought events in order to fully assess current and future risk to supplies.

Areas of low to moderate potential recharge and storage are characterised by fractured crystalline aquifers and superficial aquifers in North and Northeast Scotland and Silurian-Ordovician sedimentary aquifers in Southern Scotland. As for the aquifers described above, low recharge and storage mean these aquifers are generally capable of supporting relatively small-scale supply and will be vulnerable to drought. **Abstraction for distilling in Speyside, most of which are expected to exploit springs and shallow superficial aquifers, fall into this category.** A small number of agricultural abstractions are also visible in the bedrock aquifers, however, in the Northeast, these abstractions may be situated in areas of deep bedrock weathering, which are common in Aberdeenshire, and which locally increase the storage and productivity of the aquifer in the upper 10 – 50 m (Meritt *et. al.,* 2003). Further work is required to understand the response of these aquifers to future pressures and potential adaptation measures.

Areas of low recharge and high storage are characterised by Devonian sandstone aquifers in Eastern Scotland, particularly along the Moray Coast and in parts of Fife. The high storage capacity of these aquifers provides some measure of resilience to drought, but they may be vulnerable to long-term depletion if high levels of abstraction consistently exceed LTA recharge. As shown on Figure S4.6, these aquifers are extensively used for agricultural abstraction and further work is needed to understand the response of these aquifers to future pressures of increasing demand and decreasing recharge.

There are very few areas of high recharge and high storage in Scotland. Permo-triassic sandstones in the Dumfries Basin and other localised areas in Southwest Scotland fall into this category and appropriately constructed groundwater sources in these aquifers would therefore be considered relatively secure.

Devonian and Carboniferous sedimentary aquifers across the Midland valley fall close to the middle of the water security framework, with moderate to high storage and moderate recharge. These aquifers will have a measure of resilience to drought and long-term change, however further work is needed to understand interacting future pressures of abstraction, recharge, and groundwater quality issues.

Discussion

Those areas highlighted as most important for water supply in the agriculture and distilling sectors currently fall within the top and bottom left quadrants of the water security framework. Abstractions from sandstone aquifers in Eastern Scotland, which are important for supporting agricultural water supply, fall within the top left quadrant (low recharge and high storage), while abstractions from superficial aquifers in Speyside, which are particularly important for supporting distilleries, fall within the bottom left quadrant (low recharge and low storage). Both contexts in Eastern Scotland have relatively low LTA potential recharge, but the groundwater abstractions from high-storage sedimentary aquifers are likely to be more secure through drought periods than those from shallow, lower storage superficial deposits. In the west of Scotland, where long-term average potential recharge is relatively high, we would expect low-storage aquifers to continue to be able to support small-scale abstraction into the future, but these sources will remain vulnerable to drought. Projected changes in the frequency and intensity of droughts may increase the future vulnerability of groundwater sources, particularly those abstracting from low storage aquifers, and further work is required to understand the potential impact that drought may have on groundwater's contribution to wider environmental flows.

Future projections indicate that eastern and central Scotland are likely to experience continued or accentuated reductions in potential groundwater recharge over most of the year, with possible insignificant to moderate increases in winter recharge unlikely to offset the summer deficits. In contrast, western Scotland is likely to experience a moderate increase in future groundwater recharge over most of the year apart from the summer months. The implication of these projections is that groundwater resources in Eastern Scotland are predicted to move further towards the left side of the water security framework. If current levels of abstraction continue while LTA annual groundwater recharge reduces, aquifers become at increased risk of long-term groundwater depletion. Further work is needed to understand the response of these aquifers to future pressures and their capacity to maintain an equilibrium that allows future human and environmental water demands to be met.

Changes in groundwater recharge do not necessarily equate to equivalent changes in available water resources; however, limited projections of groundwater levels at four sites across Scotland are consistent with recharge projections predicting an accelerated decrease in groundwater levels in the moderate to highly productive aquifers of eastern Scotland in the near and far future, while highly productive aquifers in southwest Scotland are likely to experience either no significant change, or increasing groundwater levels.

Within the context of the results of this study, there is a pressing need for further work to understand the likely response of different groundwater systems to future pressures and subsequent impacts on future groundwater availability in Scotland. This particularly applies to low and high storage aquifers in Eastern Scotland, which are critically important for economic activities such as agriculture and distilling and which are expected to see a decrease in future LTA recharge. But it also applies to low storage aquifers in Western Scotland, which are locally important for small-scale water supply. **Future work will need to understand how individual sources within different aquifer systems respond to changes in demand and recharge, but also how these changes manifest at the catchment scale, how multiple sources within a catchment interact, how changes in the groundwater system translate to and from other parts of the hydrological system, and how these changes are felt in terms of socioeconomic impacts.**

Future work into potential adaptation measures would also be beneficial for future water security planning. This might include an assessment of areas where groundwater could provide more resilient supplies compared to other source types, a cost-benefit analysis of exploiting deeper groundwater, or the potential for augmenting recharge through, for example, nature-based solutions such as managed aquifer recharge.

This improved understanding could be achieved through an expansion of the long-term groundwater monitoring network, further collation and analysis of existing groundwater data, including the development of numerical models of strategically important aquifers, and more detailed localised studies to collect new data in areas where future pressures are expected to be greatest.

Limitations

- Future projections of potential groundwater recharge do not consider the flow and storage properties of the aquifer itself, how the aquifer interacts with the wider environment (e.g. through spring or stream discharge), or how water is abstracted from the aquifer; these projections do not therefore allow a full assessment of future groundwater availability.
- This work has not considered groundwater quality or temperature, data for which are also relatively sparse in Scotland, and which will also have an impact on future groundwater availability.

Appendix 5 Report on Farmer and Distillery Focus Groups: How water is used; how it might change; and how the sectors might adapt

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With thanks to Josie Geris, Miriam Glendell, Mark Wilkinson and Kirsten Williams for their contributions during the focus groups, and to Malt Distillers Association of Scotland, NFU Scotland and The Scotch Whisky Association personnel for helping arrange the focus groups.

Executive summary

Four focus groups were held with stakeholders working in or connected to either agriculture or distilling in Scotland. The aims of these focus groups were to:

- Raise awareness of water scarcity projections for Scotland,
- Understand how those working in, and with, agriculture and distilling in Scotland are currently adapting to water scarcity or will adapt in the future, and
- To confirm the conceptual models being built from the evidence review.

In total 59 participants took part (33 from agriculture and 26 from distilleries) covering livestock, arable, horticulture (field vegetables) and Scotch whisky production. Participants came from all over mainland Scotland, but there were more from Eastern areas, which are predicted to have more issues with water scarcity in the future.

The focus groups confirmed that water scarcity was a threat to their sector and/or region and in most cases to their individual businesses, although some individuals felt less exposed as they had already taken steps to adapt and/or lived in an area not yet suffering water scarcity restrictions. The livestock, mixed and arable farmers were aware that lack of rain or irrigation would impact yield of their grass, fodder and food crops and increase their input costs where they had to buy in fodder. Horticulturalists were vulnerable to total loss of crops if irrigation was prevented at specific growing times; and cereal producers had suffered crop loss or low quality crops due to water scarcity at germination stages. Distilleries use most water in processing whisky and find it difficult to reduce cooling water use if they are distilling large quantities seven days a week in response to the growing global demand for the product.

Most participants were thinking about how to adapt to projections of increased frequency and duration of water scarcity, including attention to water efficiency (particularly in the distilling sector) and seeking ways to conserve soil moisture and find drought resistant crops and grass varieties. The need to store water on farms and for distilleries was recognised but costs were seen as a barrier to implementation and rainwater harvesting was not seen as practical for arable and distillery sectors. Water resources are a common pool good, and there was a recognition that water scarcity can be compounded or improved depending on the actions of others up- and down-stream (and in other sectors) – however, there was limited enthusiasm for collective action solutions to managing water access in conditions of scarcity.

Overall, water scarcity can be seen as an important business risk but it is less clear how the agricultural sector is prepared to invest in adaptations; whilst the distillery sector adaptations are premised on implementing energy intensive technologies, which may be cancelled out by projected increases in production.

Introduction

Four focus groups were held with stakeholders working in or connected to either agriculture or distilling in Scotland. The aims of these focus groups were to:

- Raise awareness of water scarcity projections for Scotland,
- Understand how to improve scientific communication in this field,
- Understand how those working in, and with, agriculture and distilling in Scotland are currently adapting to water scarcity or will adapt in the future, and
- To confirm the conceptual models being built from the evidence review.

The report sets out the methodology used before turning to reporting the findings. The findings covered what was learnt about how different focus group participants used water, whether they perceived water scarcity as a risk; how they understood the evidence presented; and what scarcity or drought might mean to these participants. There are also sections on barriers and enablers for adaptation and how the participants also discussed interactions with other sectors. The penultimate section of the findings illustrates how the focus group findings extend or nuance the conceptual models built from the evidence review; before a final section on how participants advised us to disseminate the findings to the wider farming and distilling communities.

Methodology

A focus group methodology was used, as recommended by the project steering group. A focus group is a structured and facilitated conversation with a group of people, to draw out their understandings and perceptions of a topic (Ritchie and Lewis, 2003). The approach allowed the participants to ask questions about the available data on projected water scarcity and collect real-time testimony about how water scarcity affects different sectors and geographies, in a relatively cost-effective manner. Focus groups are designed to explore topics rather than provide quantitative findings that can be generalised to the overall farming or distilling community.

Four focus groups were hosted from mid-February to mid-March 2024. Three of these focus groups were targeting people working in and with agriculture. One focused on the North-East of Scotland due to predictions of increased water scarcity in this area, including private water supplies in particular (Rivington *et. al.,* 2020), one on crop production in the Fife area due to the importance of irrigation in the area and exposure to water scarcity measures, and one on livestock and dairy farming across Scotland. A further focus group with national horticultural participants was planned but time constraints and illness meant this did not take place. The fourth focus group targeted those working in the distilling sector in the Speyside area where there are over 50 distilleries in a region predicted to suffer from water scarcity. This focus group aimed to engage distillery managers and technicians. Email invitations were created following the input of sector experts and the steering committee during the stakeholder mapping phase of the project. These invitations were shared with sector representative organisations, who distributed the information to members. There was also a press release in the farming press that attracted participants to the North-East focus group; and information sent via the Soil Association and Scottish Society for Crop Research for the Fife focus group. People interested were then redirected to an online form with further information on the project and information on informed consent before being invited to register their interest.

Focus groups for the North-East and livestock farmers were hosted online during weekday evenings. Focus groups were held during lambing and calving seasons and it was hoped that by hosting these online – and therefore removing the need for travel – attendance would be increased. Focus groups for crop farmers and distilleries were held in person during the day in Cupar and Aberlour respectively.

In total 59 stakeholders attended the focus groups (see Table A5.1 below). The livestock focus group was attended by 13, of whom 9 were solely livestock farmers, 3 had mixed farms, and 1 was a researcher. The North-East focus group was attended by 11, of whom 2 were livestock farmers, 3 had mixed farms, 4 arable, one was a NFU Scotland representative and one was a landowner keeping horses. The Fife focus group had 9 attendees, of whom 3 were arable farmers, 3 had mixed farms, 1 was a NFU Scotland representative, and 2 from a sustainable catchment group with an interest in land use and fisheries. 26 people attended the distilleries focus group.

Overall the farming focus group participants covered the grass-based 'extensive' livestock sector (n=17) and the arable sector (n=17) well but had more limited data on 'intensive' housed livestock and dairy (n=4) and horticulture (n=7). Horticulture participants mainly discussed field vegetables with only one participant discussing salad crops and we had no soft fruit participants attending. Geographically, we did not have any participants from the North-West Highlands or Islands, although some of the distillery participants included these areas in their portfolio. There were only six females out of 35 farming participants, but 10 out of 26 distillery participants. Whilst we did not ask for ages, we observed few visibly young farmers (aged 40 years or below) but there were more younger faces in the distillery focus group. Therefore, our findings will reflect these patterns and a different composition may have provided further insights, particularly in the soft fruit and dairy sectors.

Table A5.1: Stakeholder details.

Focus group	Stakeholder Number	Location	Farm type (if applicable)
Livestock	SH1	Argyll	Livestock
	SH2	Aberdeenshire	Livestock
	SH3	Caithness	Livestock
	SH4	Borders	Mixed farming
	SH5	N/A	Researcher
	SH6	Inverness-shire	Livestock
	SH7	Aberdeenshire	Mixed farming
	SH8	Aberdeenshire	Livestock
	SH9	Aberdeenshire	Livestock
	SH10	Dumfries and Galloway	Livestock
	SH11	South Lanarkshire	Livestock
	SH12	Perthshire	Livestock
	SH13	Dumfriesshire	Mixed farming
North-East	SH14	Aberdeenshire	Livestock (horses)
	SH15	Aberdeenshire	NFU Scotland
	SH16	Aberdeenshire	Arable
	SH17	Aberdeenshire	Mixed farming
	SH18	Morayshire	Arable
	SH19	Kincardineshire	Arable
	SH20	Aberdeenshire	Arable
	SH21	Aberdeenshire	Livestock
	SH22	Aberdeenshire	Mixed farming
	SH23	Aberdeenshire	Mixed farming
	SH24	Aberdeenshire	Arable
Fife	SH25	Fife	Angling
	SH26	Fife	Catchment group
	SH27	Fife	NFU Scotland
	SH28	Fife	Arable
	SH29	Fife	Arable
	SH30	Fife	Mixed farming
	SH31	Perthshire	Mixed farming
	SH32	Fife	Mixed farming
	SH33	Fife and Lothian	Arable

Table A5.1: Stakeholder details.			
Focus group	Stakeholder Number	Location	Farm type (if applicable)
Distilleries	SH34	Moray	Distillery
	SH35	Nairnshire	Distillery
	SH36	Moray	Distillery
	SH37	Inverness-shire	Distillery
	SH38	Moray	Distillery
	SH39	Moray	Distillery
	SH40	Moray	Distillery
	SH41	Fife	Distillery
	SH42	Moray	Distillery
	SH43	Moray	Distillery
	SH44	Scotland[4]	Distillery
	SH45	Moray	Distillery
	SH46	Scotland	Distillery
	SH47	Moray	Distillery
	SH48	Perth and Kinross	Distillery
	SH49	Moray	Distillery
	SH50	Moray	Distillery
	SH51	Moray	Distillery
	SH52	Aberdeenshire	Distillery
	SH53	Moray	Distillery
	SH54	Scotland	Distillery
	SH55	Scotland	Distillery
	SH56	West Dunbartonshire	Distillery
	SH57	Moray	Distillery
	SH58	Moray	Distillery
	SH59	Scotland	Distillery

[4]Works across multiple distilleries

Focus groups began with introductions and some short questions asking whether stakeholders felt their businesses were currently being impacted by water scarcity or would be in the future. Poll responses were collected from these questions. For the online focus groups these responses were anonymous and therefore cannot be associated with a particular farm type.

Following this, a presentation was given on the Rapid Evidence Review (RER), with time for questions at a halfway point and at the end. Focus groups were then opened to discussion (either in one plenary group or multiple breakout groups, depending on size of group), aiming to address the following questions:

- How stakeholders felt changes to water scarcity presented in the RER could affect them.
- Whether stakeholders are already planning for the future with respect to water scarcity.
- What stakeholders think could make it easier for them to adapt to projections of water scarcity.

The online focus groups were constrained to 1.5 hours in length, which limited discussion and data collection available. The in-person focus groups had slightly longer, yielding richer data.

The research team took notes and recordings, and after completion these were analysed using deductive thematic analysis based on the following themes:

- How sectors are using water.
- Views on water scarcity.
- Reactions to evidence.
- What water scarcity might mean for these sectors:
    - o How are the sectors affected? Perceived costs and benefits
    - o What are, or could, participants do to prepare for scarcity?

o Barriers or enablers for change?

o Interactions with other sectors and actors.

- Insights on communication or dissemination.
- Inputs to revised conceptual models.

The findings presented are therefore provisional, based on the views of the participants. We achieved relatively strong saturation (repeating themes that can be explained) in some areas, but we would not claim that the findings were generalisable to all sectors or all geographies. However, the data does fill some evidence gaps in existing reports on water scarcity. In other areas, such as strategies for adaptation, there is resonance with existing literature, suggesting that there are some areas of generalisation possibly based on shared concepts and theories used to describe and understand human behaviour in similar contexts or industries.

Results

How sectors are using water

When asked what water sources they were using, the stakeholders from all focus groups responded that they knew where their water was coming from. Those who attended from the North-East responded with the highest proportion of PWS usage (27% of responses; see Figure A5.1).

Note that many participants were interested in the interaction of different sources of water. For example, the participants in the Fife focus group discussed how the River Eden was 'aquifer fed' and distillery participants talked about the interaction between spring filled lochs feeding the burns; whilst over abstraction of shallow aquifers might affect the level of the nearby river.

Amongst the farmers there was a surprisingly large amount of ground water usage (91% in the Northeast, 100% in Fife, and 90% in the livestock focus group; see Figure A5.1). Our research was focussed on how water scarcity may affect rain-fed agriculture and abstractions from surface or groundwaters, but we included an option for mains supplied water. There were relatively high levels of mains water usage in the Fife farmers group (56% of respondents) and for the distilleries (70% of respondents; see Figure A5.2). For the Fife farmers this was for livestock watering and hygiene, and for distilleries one stakeholder said this was sometimes used during production, though the chemical makeup of the water was not ideal and it did come at significant cost to the business.

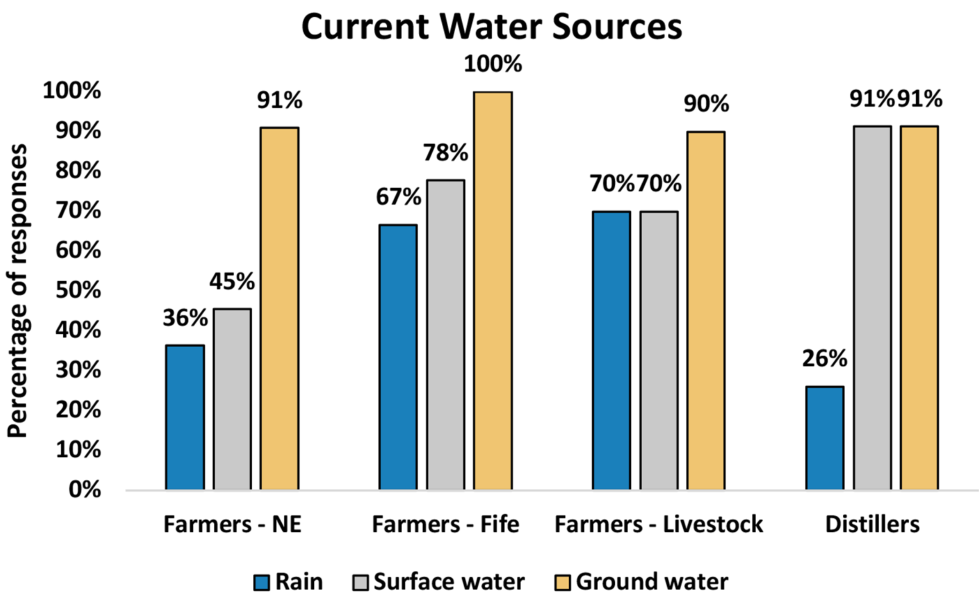


Figure A5.1: Percentage of focus group participants using different sources of water used by sector and location. Note that the figures do not add up to 100% as participants could select more than one option, as most had multiple sources of water.

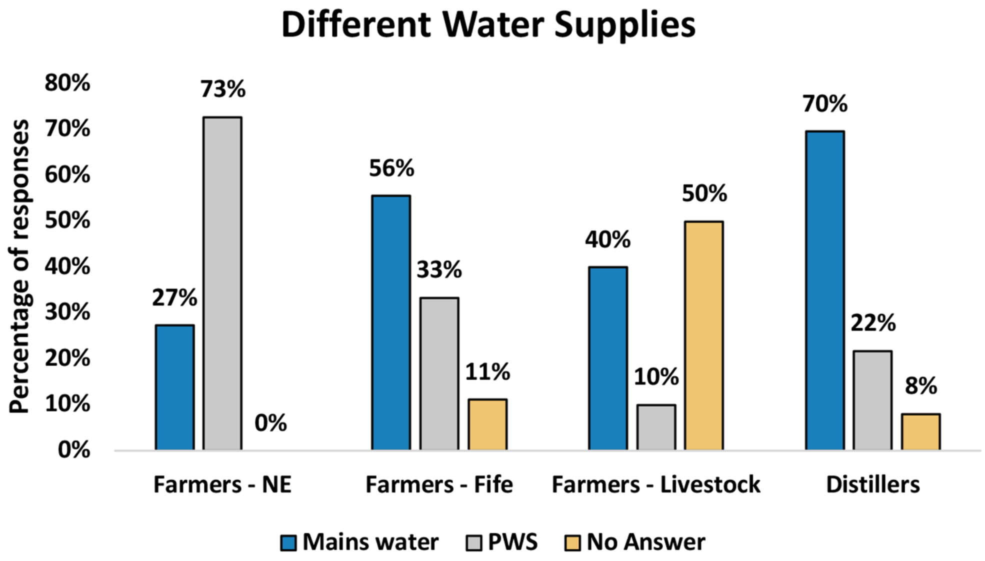


Figure A5.2: Number of focus group participants using either mains or private water supplies (PWS).

Responses during the focus groups suggest that the different stakeholder types hold different abstraction licences. When discussing licences, most livestock farmers suggested that they would be on general binding rules, using less than 10,000 cubic meters a year. One stakeholder who farms livestock commented that until the focus group they had been unaware there were different types of regulation. There were exceptions to this general trend amongst livestock farmers, with one North-East based pig farmer holding a registration licence and estimating use at 30 cubic meters a day. Water is used mainly for drinking by livestock, with some also being used for cleaning and disinfecting. It was suggested that dairy production requires the highest level of water input when farming livestock, and that farms in Scotland expect to be milking for at least 6-8 months of the year[5]. Most livestock farmers involved in the focus groups did not irrigate silage or grass, but there were cases around Fife that have been doing so.

Discussion during the focus groups suggested that arable farmers are using, and expect to continue to use, more water than livestock farmers and therefore more likely to have registration or licence authorisation to abstract water, particularly for field vegetables. One example was given of a couple of farms growing carrots and potatoes in Morayshire that are using registration licences and estimate use between 10,000 and 15,000 cubic meters per annum. However, this was usually needed in about 15 to 20 days of irrigation application – the usage is not year-round. However, most of the specialist cereal growers practiced rainfed cropping, with exceptions where farmers in Fife already had access to irrigation infrastructure and would irrigate wheat and barley in very dry spells.

In contrast to the farming groups, all of those present at the distillery focus group said they used simple/complex abstraction licences, reflecting a much higher water abstraction rate for this sector.

During whisky processing, water was used by the stakeholders for mash, to dilute the drink itself, for cooling, for cleaning, and for domestic use on site. Stakeholders did point out that most of the water they abstract is returned to the water sources after use for cooling, which for SH37 is 95% of the water used in whisky making at their distillery. SH52 estimated water use at their distillery as 40 million litres a week, ranging from 140 litres of water per litre of alcohol in winter to 230 litres of water per litre of alcohol in summer, when more water is needed due to the increased temperature of water used for cooling. At the distillery of SH58, 210 litres of water per litre of alcohol is needed for cooling.

Overall, most farming participants who were not licenced or authorised did not know how much water they were abstracting or using but there was strong resistance to the introduction of metering water consumption. This resistance was based on a concern that metering would become associated with payment for water consumption, as occurs in England. Distillery managers also knew how much water was being used on-site but did not have access to data to help them know how their local sources were doing in conditions of dry weather. For example, SH37 and SH35 referring to having

[5]This is a low estimate and depends on calving patterns according to our livestock expert (Williams). Year-round calving would suggest year-round milking; with block calving still likely to have only 6-8 weeks without milk production.

local anglers telling them if water levels were getting low.

Views on water scarcity

When asked during the focus groups if they felt water scarcity impacted the farmers/businesses in their areas, most respondents said yes, farmers/businesses were impacted. In the livestock farmers focus group this figure rose to 100% of respondents (see Figure A5.3). For the Fife focus group, the participant who did not agree was in another, wetter, region that they perceived not yet at risk. For the Distillery focus group, one participant answered no because the industry was already acting. We do not know who answered 'no' in the North-East group or the reason for their answer due to anonymous polling data.

When asked whether water scarcity was felt to be a current risk for their business, 'Yes' responses were marginally lower – though most respondents still felt water scarcity was a risk (see Figure A5.4.).

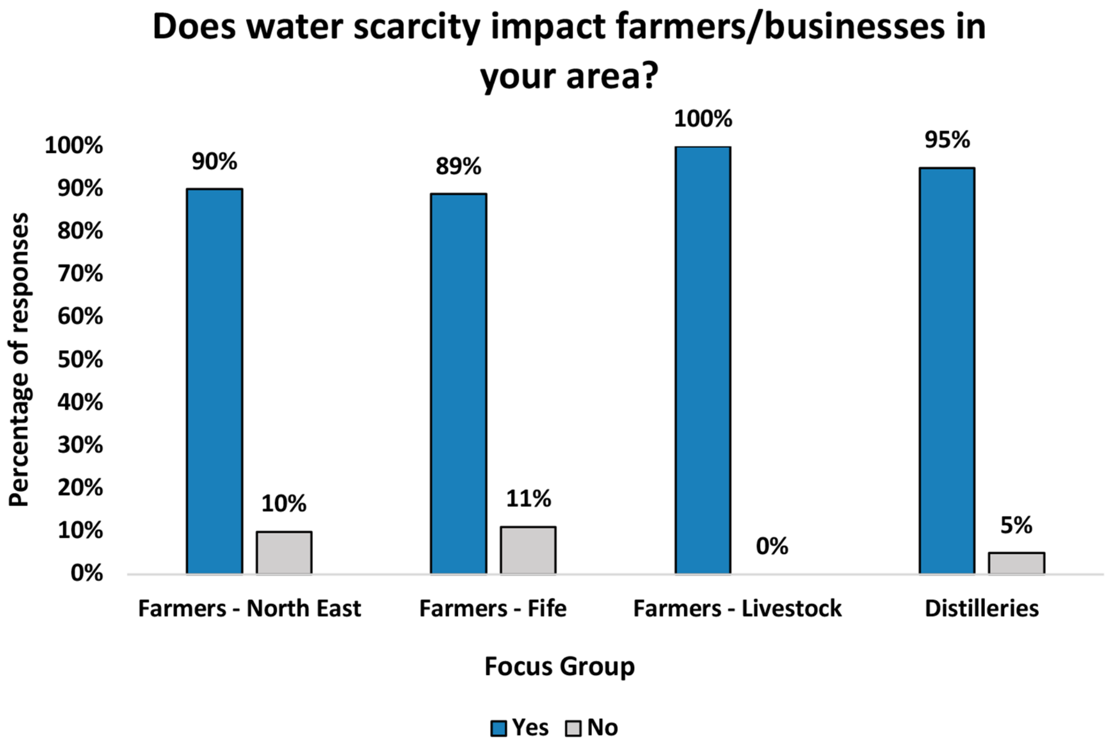


Figure A5.3: Water scarcity impact in area poll.

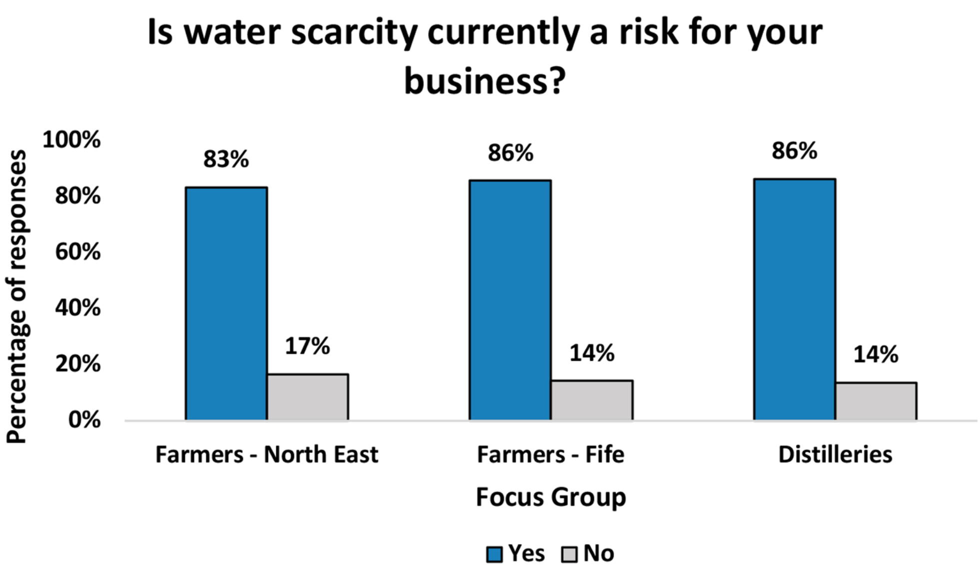


Figure A5.4: Water scarcity risk to business poll.

The differences between Figure A5.4 and A5.3 can be explained by the importance of distillery and farm context, whereby soil type, access to water sources, and microclimate made some respondents feel less vulnerable than the other businesses in their area. There was not time to ask this question (risk to individual business) during the livestock focus group.

During discussion, all focus groups had stakeholders present who believed water shortages were becoming an increasing problem. In the livestock focus group, SH12 pointed to increasingly dry summers, and felt that they would have once expected 1 in every 10 years, they were now seeing 1 in every 2 or 3 years. SH13, who also farmed livestock, commented that in 2023 they ran short on grass because of water shortage during the growing season. These responses were like many of those in the North-East focus group, where, for example, SH18 in Moray has faced struggling crops for 3 of the last 5 years due to water shortages, and SH23 was recently unable to house their cows until November due to increased water shortages. In Fife, stakeholders present raised concerns particularly about fruit and vegetable crops, which can die within a day of being short of water. It seems that those dependent on surface water, particularly smaller burns, were vulnerable, with sources drying up before any official stop notices are issued.

Distillers also mentioned problems with water scarcity, with one stakeholder commenting that they would be surprised if anyone in the room hadn't previously had a problem. September of 2023 was pointed to by SH42 as a particularly painful dry period for their business. There was suggestion of recently changed attitudes within distilling when considering water scarcity; with SH58 suggesting that it has been in the last 3 or 4 years that it has become important for them. SH57 echoed this, saying that one prolonged dry spell changed attitudes completely.

Whilst there were stakeholders across all four focus groups who were vocal about the impact they saw from water scarcity on their businesses or those of their neighbours, some stakeholders in the livestock and North-East farming groups were not so worried. In the livestock focus group, SH11 commented that they haven't yet suffered many water shortages. SH22 in the North-East felt fairly secure but did suggest that geography would play a key role in who was impacted. Some of the farmers who were not yet impacted were aware that it may become a problem and commented that it was something they were keeping an eye on.

Reactions to Evidence

Stakeholders were given the opportunity to ask questions about the RER halfway through the presentation, and at the end of the presentation. During the livestock focus group there were very few questions, just one comment from SH7 that the difference between abstracting water from a borehole and taking water out of a natural spring is confusing.

Several comments and questions were made during the North-East focus group. SH23 felt that the data underestimated drought in Scotland and was surprised to see data suggesting May seemed to be improving compared to the last 20 years, as that was not their experience. SH14 and SH24 agreed with the data and felt that it was clear there are 6 months of the year where there isn't enough water, and 6 months that there is too much. SH20 would have liked a longer historical view of the data, rather than starting in 1990, pointing out that, for example, 1976 was a particularly dry year. SH24 felt that a long-term view was important, and that this is something often missing in data used for farm decision-making.

During the Fife workshop, SH29 asked for the bases of the maps used during the evidence review, and the use of 12 different climate models to create them was explained to the group by the research team. SH31 asked whether they were correct in assuming models were based on 3.5 degrees Celsius warming, which was confirmed by the research team. The stakeholder then pointed out that if that was the case then actual future water scarcity could be worse. It was felt by SH28 that the maps presented would get policy makers worried. SH29 agreed with the projections and felt that they were already happening. Members of the focus group agreed with them on this.

In the distillery focus group SH46 felt that their experience agreed with projections shown during the presentation, and that they had been seeing the dry periods extend as far as September already. SH57 agreed with the general trend presented but had comments about the data. They were concerned that most research is based on data presented by SEPA, which uses only one monitoring point on the river Spey. They felt that more monitoring sites, and better data, would be good for the distilleries and researchers to have. SH48 shared another source of data they have seen, the EnviroCentre Ltd Q95 report, which looks at different points of abstraction and discharge compared to SEPA licences.

Questions and comments made by stakeholders in attendance suggested that those who came to the focus groups were already interested in or thinking about water scarcity and well-equipped to understand the data presented.

What might scarcity mean to these sectors?

How are the sectors affected? Perceived costs and benefits.

At all the focus groups, sector representatives believed that water scarcity would mean additional costs to their businesses. Some costs are common between livestock farming, arable farming, and distilling, whilst others are more sector specific.

A common cost of water scarcity across sectors was reduced production. For livestock farmers, water scarcity would mean lower yields of forage that they produce themselves. SH11 said that 3 – 4 weeks of dry weather would be okay, but any more than that and they would expect to see impact on their grass. SH4 had experience of feed barley failing due to dry weather. Lack of quality fodder has an impact on the livestock; SH4 explained that drought in summer causes cows to stop cycling and therefore reduced calf numbers in spring. SH23, a farmer based in the North-East, felt that in 2023 Scotland was not far off a national problem of there not being enough fodder for the livestock industry. These are not only immediate impacts but have knock-on effects on the individual and the herd's welfare and productivity for subsequent years.

Arable farmers in both the North-East and Fife pointed to reduced crop production as a direct result of water scarcity. SH22 was confident that dry periods will cost arable farmers in terms of reduced yield, and SH28 suggested that they may not want to be growing vegetables in three years' time if water scarcity patterns continue as predicted.

Like livestock and arable farmers, reduced production is a cost of water scarcity for the distillers. For SH38, many of their sites run 7 days a week, leaving no room to make up time if production has to be stopped for low flows. They said that the last two years have seen some sites forced to adopt complete shut down due to water scarcity. SH34 pointed out that if they were forced to shut down for longer in the summer it would not only impact production, but also jobs, pay, and the ability to employ people year-round. SH37 expected impact on maltsters and other supply chain organisations if there were continued periods of shut-downs, which would in turn impact whisky distilleries.

Another cost common to all sectors was financial cost of production. Livestock farmers in the focus groups have already faced increases in the cost of straw due to impacts of water scarcity on arable farmers. SH1 said that through this mechanism, the lack of water in arable lowlands is having a direct impact on the livestock systems in the uplands. SH4 is seeing more arable farmers using straw on their own farms as a natural mulch, which increases the price paid for any straw that is sold off farm. Additionally, reduction in production of fodder leads to more being bought in, which in turn increases the cost of production.

There are impacts on costs for arable farmers too, though these tend to relate more directly to water. SH24 highlighted the cost of using more water sources, in particular costs associated with constructing boreholes. SH30 talked of the costs of increased electricity or diesel use as the need for irrigation increases. A third cost discussed by arable farmers was that of water storage. SH24, an arable farmer in Aberdeenshire, commented on the need for cheap water storage. Similarly, SH23 and SH20, both also farming in the North-East, felt that the cost of water storage was not being properly funded. The landscape was seen as a contributing factor here, with SH22 pointing out that rolling countryside would likely mean that storage would need to be pumped to fields for use, again adding to the financial burden. For distilleries, increased costs mentioned were those of using mains water for processing during dry spells, and the increased energy costs associated with increased water scarcity for distilleries using chillers for cooling waters. SH37 shared how their distillery has the means to pump water from an alternative source during low flows, but that as energy prices have gone up this has become increasingly unaffordable.

One cost only discussed by the livestock farming focus group was disease burden change. SH5 suggested that worm, tick, and fly burdens would be likely to change with changing water patterns. This matched SH6's experience; patterns of fluke in livestock are changing drastically from year to year and are no longer predictable. SH6 also felt that fly burdens have increased with increasing water scarcity – seeing a bigger fly problem in 2023 than they ever had before. This confirms wider findings in the literature about increasing parasites due to warmer summers (Carson *et. al.,* 2023).

The number of costs raised by stakeholders outweigh the number of benefits. However, in both the livestock focus group and the North-East focus group benefits of water scarcity were mentioned. SH12 said that water scarcity in spring could bring benefits for livestock farming, as it would lead to better weather conditions for lambing. However, they followed this with comment that they would expect to pay for a dry spring later in the season. SH21, a livestock farmer, said that longer dry seasons could allow for the growth of different crops. No benefits were mentioned during the Fife or distillery focus groups.

What are, or could, participants do to prepare for scarcity?

During focus groups, stakeholders were asked whether they were currently doing anything to prepare for water scarcity. The majority responded that they were, however, some said they were not – 38% of responses in the North-East focus group, 33% in the Fife focus group, and 8% in the livestock focus group (see Figure A5.5). At the distillery focus group all responders said they were doing something to prepare for water scarcity. Some 'Other' responses were selected. At the North-East focus group there was one, which referred to a stakeholder considering an extra borehole. At Fife there was one, which was a stakeholder improving soil to hold more water. At the distillers focus group there were four, three of which were expanded on by stakeholders; one was investigating installation of a cooling tower, the second looking at cooling technologies, and the third referenced a Q95 assessment.

Farmers with livestock are already doing several things to prepare for scarcity. SH12 talked about how they have already been storing extra fodder to provide a buffer if needed due to unpredictable water shortages. They have been doing this for 6 years, and have already needed it once or twice, though they accepted that it wouldn't be possible for everyone to do. SH32, a farmer with livestock in Fife, has also been looking at fodder use, and has at times in the recent past bought vegetables as extra feed to their livestock . SH29 has changed to mob grazing, which helps to increase their grass yield. Another thing already being done by livestock farmers is the harvesting of rainwater. SH9, SH10, and SH11 all spoke about their experiences with this, and how they use the harvested rainwater for the washing of sheds. One livestock farmer, SH4, has been working with technological advances to trial drought resistance grass swards on their farm, and other farmers felt that changing grass types could be a good way to cope with water scarcity going forward.

Looking to the future, livestock farmers had several ideas for adaptations to water scarcity. One of these was changing fodder crops used, and stakeholders drew inspiration from English farmers for this. SH2 felt that, looking at projections, they were potentially going to have a better March/April to do early grass crops, and could then swap to root crops for August as is done already further south. Farmers felt that there was room for improvement on current rainwater harvesting systems, including the use of new rainwater storage, although there were no grants to help with these adaptations. For the North-East group, a combination of on farm and off farm (i.e., Scottish Water reservoirs) storage was wanted. This was surprising given that some of these farmers did not access mains water. SH8 pointed to the example from Australia, where they had seen lagoons dug on farms to catch water for use during dry spells. Another idea from Australia raised by SH8 was the irrigation of grassland, commonly used in Tasmanian dairy systems.

When discussing what they were already doing to prepare for water scarcity, arable and horticultural farmers raised several things. SH24, in the North-East, talked about their investment in new boreholes to provide a guaranteed water supply when they need it. They also pointed to farmers they knew who relied on natural ponds as water storage for drier times of the year. A farmer in Fife talked about their experience irrigating, for both cereals and vegetable crops. They saw this investment as long lasting, having installed the infrastructure 50 years ago. They also focused on efficient water use, timing irrigation to avoid moisture loss as much as possible – though stated that in periods of water scarcity they may need to be irrigating 24 hours a day. SH29, in Fife, has been focusing on increasing the moisture retention properties of their soil by using carrot straw (50 tonnes per hectare) as a mulch. Farmers in the North-East were approaching soil management to increase moisture holding capacity similarly, stressing the importance of animal manure as a means of increasing organic matter. SH17 pointed out that soil varied by location, and that the sandier soils found in Moray were particularly challenging when trying to increase moisture retention. Like the livestock farmers, some of their water scarcity adaptations relied on technology. SH31 has made a change from larger to smaller equipment, which means they are better able to deal with extremely wet soils when weather becomes more extreme.

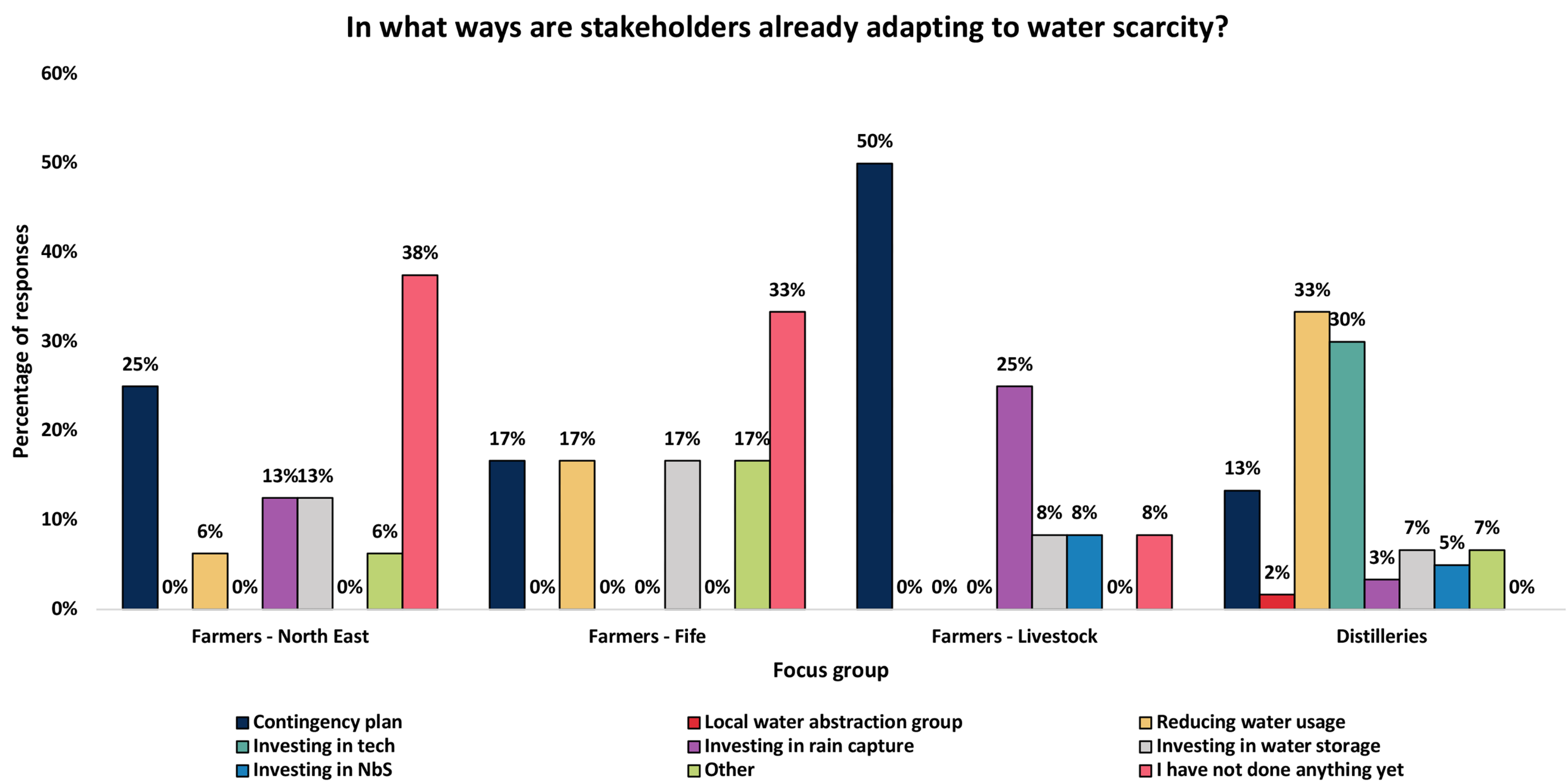


Figure A5.5: In what ways are stakeholders already adapting to water scarcity?

One final change that arable and horticultural farmers were already doing to deal with water scarcity was a change to their farming system. For SH29, this was a move to more livestock and less arable farming, as livestock farming is for them less water intensive.

Going forwards, there were several things that arable and horticultural farmers felt they could do to cope with water scarcity. SH24 felt that a change to crop types may be needed – looking at what might grow better in new conditions, however, as with the grass varieties, these new varieties have to cope with extremes of flooding and drought. As well as changing crop types, SH24 suggested changing where crops were grown – moving away from riparian areas. However, this is contrary to restoration arguments that state reconnecting floodplains would help with arable farming by helping to improve soil moisture. SH23 pointed out that there is a limited area where these high value crops can be grown, so they should not be moved. Like livestock farmers, arable and horticultural farmers in Fife believed that more reservoirs were needed, and that these should be built by Scottish Water. Although some participants had considered installing irrigation lagoons, there was common agreement across all three focus groups that the capital grants were too low and the application via the Agri-Environment Climate Scheme was too complicated and targeted meaning many farmers perceived they would not be eligible.

Finally, SH29 felt that collective action could help to mitigate water scarcity effects. They said that they have licences that they don't use every year but are currently not allowed to irrigate their neighbours' land. If it were changed so they were able to share the allocation then water scarcity impacts may be lessened.

All distillery respondents to the poll said that they were already doing something to prepare for water scarcity impacts (see Figure A5.5). For many distilleries, this centred around the use of technology. SH38 and SH48 have invested in chiller technologies. For SH48, this means they can now use water at 25 degrees Celsius and has halved the amount of cooling water they need to use overall. SH51 is currently installing a new Thermal Vapour Recompression (TVR) system, which they are expecting to reduce water use by upwards of 40%. SH36 shared an example of another distillery that uses reverse osmosis to save water use on site. SH40 received a Scottish Government Grant in 2021 to trial Manual Vapour Recompression (MVR) as a form of water saving technology. Some distilleries have water storage lagoons on site already, but the group felt that they probably overestimated how much water these hold due to years of them not being dredged. SH50 suggested that they cooperate as much as they can between distilleries on technology.

In the future, SH43 expects more distilleries to adapt their technologies on site, and in turn expects a reduction in water use. Several distilleries recycle their effluent on site or by sending it to biofuel digesters locally, which return the decontaminated water to the Spey as part of their process.

As well as technological advancements, SH38 was considering riparian tree planting to keep water temperatures down, meaning they would need to use less water, however SH37 had problems with riparian tree planting and SH43 said they had a moratorium on trees due to using too much water, suggesting that using tree planting as a potential water saving mechanism is quite contested. SH44 said they had discussed plans for reservoir building, but it had not yet progressed further than the discussion stage. Some distillers hope that there would be more working together. SH37 and SH39 were planning a meeting to discuss alterations to their site. In discussion at the end of one breakout group, distillery workers said that meeting together as a group had been helpful, and that they hoped to collaborate to make changes for the better with respect to water scarcity.

Across both the farming and distilling focus groups, some participants had, or were planning to, install more boreholes to access ground water as an alternative source when surface water sources were scarce. However, some others had explored this option but were unable to implement it as the local groundwater sources were too unreliable to be useful (SH37).

It should be noted that the farmers attending the focus group were possibly those who are already taking steps (see Figure A5.4 where only 8% of one focus group were not adapting to water scarcity). Therefore, the findings in this section show what is possible, but not necessarily what is common practice in the sectors.

Barriers or enablers for change?

Findings from discussions with the focus groups suggest several barriers to adaptation.

Across sectors, cost of intervention was a significant barrier to action. SH6 commented that for grass there is not much they can do, as returns on irrigation of forage are too low to be worth the investment. Arable and horticultural farmers in the Fife workshop also raised cost of irrigation as a barrier; SH29 and SH30 talked about the cost of the installation and energy needed to run successful irrigation systems. SH29 estimated that the total cost of irrigation is about £190 per hectare for a cubed inch of water – and that they might put on 3 inches per year. For distilleries, high energy costs of new technologies can make them prohibitive, for reasons not only of running costs (SH54), but also limitations of the power grid (SH36), expansion of which would also involve massive investment. Production shutdowns also have a financial impact on distilleries, impacting tourism and making it difficult to justify staff numbers. Costs are further discussed in D6 on socio-economic impacts.

Another barrier to action shared by the different sectors was lack of coordination between different actors. Farmers at the North-East workshop raised concerns about other sectors using water, suggesting that these sectors needed to take action to address water scarcity. In Fife, SH29 commented that although many farmers draw water from the same burns, they don't all communicate with each other. This means that sharing of the resource is limited and downstream farmers may not have water to abstract in times of low flows. Although local water abstraction groups are promoted as a measure in the national water scarcity plan, none of our farming participants had heard of these groups, let alone participated in them.

The distilleries faced similar issues, with one group agreeing that there is no communication between farmers and distilleries, or indeed between farmers and other farmers. SH36 noted the competition between different distilleries, and that it would be difficult to convince one of their distilleries to shut down or slow production if other distilleries in the same area were not also doing so.

Both arable farmers and distilleries felt that rainwater collection would not provide the volume of water they need. SH29, a farmer in Fife, felt that it might be able to be used as a top up, but would not make a significant dent in times of water scarcity. SH57, a distiller, felt the same. Distillers also raised the problem of disease risk with storing rainwater (SH36 and SH54). Specifically, contact with unclean roofs and long-term storage could increase risk of disease like legionella, rendering the water unusable.

A problem some distilleries had was the fact that many do not own the land that their water sources come from. This meant that they had limited say over the land management practices that were influencing their water supplies and limited ability to install nature-based solutions like leaky barriers that could recharge groundwater.

In some cases, where stakeholders could foresee water usage becoming more efficient, they feared that this would not actually reduce the overall use of water. Instead, following Jevons Paradox, some distillers suggested that overall production may increase, so abstraction would continue at the same rate as before. Furthermore, we found that where farmers have a licence to irrigate and infrastructure to do so, they will use their allocation to irrigate traditionally rain-fed crops and grassland rather than change their farming patterns.

There is also a role of outside bodies in encouraging change – though stakeholders suggested at times that can be a barrier. Stakeholders at the Fife focus group said that quality schemes by supermarkets and brands like PepsiCo (owners of Quaker Oats) were encouraging water efficiency. However, this was not always welcomed as it meant that farmers were expected to adhere to different standards at the same time raising compliance costs (SH30, SH33). They felt that it would be easier if there was one scheme, either government or otherwise, so farmers were able to follow just one set of standards. For distilling, the Scotch Whisky Association (SWA) water stewardship initiative aims to promote water saving within the industry. SH49 explained that member companies report anonymised data to allow distillers to benchmark against each other when looking at their own water usage. SH57 commented that there was once a SWA tool that allowed them to work out efficiency and felt that reintroduction of something like this would enable more change.

Interactions with other sectors and actors

Other uses of water were touched upon by stakeholders, as both concerns and conflicts. Both farming and distilling sectors mentioned issues of tension between industry and domestic water use. Four Aberdeenshire based farmers suggested that in their areas there was a domestic dependence on PWS, which at times conflicted with needs of livestock as the same water sources were used for both. SH23 also said that private homes who rely on field drains for water supplies have had issues maintaining supply. Farmers in Fife and Perthshire (SH 28, 31) highlighted the importance of on-farm tourism using PWS, when demand is likely to be highest in the summer. SH22 mentioned food processing facilities that also use a large amount of water in the area. Other competition for water mentioned by stakeholders included water use by trees from afforestation in the North-East. There was concern from SH24 that construction associated with a proposed windfarm may damage PWS where mains is not available.

As touched upon throughout the above findings, farmers in both the North-East and Fife focus groups felt that Scottish Water had a responsibility to invest in new reservoirs to help preserve domestic water supply, and in turn reduce competition between domestic and industrial water supplies during periods of water scarcity (SH20, SH28).

Farmers and distillers were keen that agronomists were involved in developing varieties of grass, barley, wheat and vegetables that could withstand heat, drought and floods. Whilst the farmers were keen to trial and use new varieties, they were not able to develop them.

Both farmers and distillers referred to the role of SEPA. Some distillers felt there was less public access to data since the cyber-attack on the organisation, and some distillers used these data to use to help monitor and evaluate water resources in their area. The resolution of monitoring data that trigger the national water scarcity plan hierarchy of actions was criticised as not being sufficiently sensitive to different sub-catchments. Most of the participants with licences had been contacted by SEPA during water scarcity events and that process worked well, although often once water was already scarce. However, several stakeholders referenced recently reaching out to SEPA for advice or support with adaptation to water scarcity (SH14, SH26, SH27, SH29, SH57). For some of these experiences were not wholly positive, with a few commenting on slow responses or action from SEPA (SH26, SH27, SH29). SH55 suggested that over the last few years communications from SEPA have not been as good as they once had been. Some of the distillery participants believed the sector plan had been useful to help the sector share knowledge and find common solutions. Many of the distillery participants were aware SEPA were conducting a review of their licence consent conditions as these were often quite dated, and whilst the main discussion was around temperature and location of ingress and return infrastructure, the speed and volume of abstraction may also be reduced in any review, with implications for production costs.

Revised conceptual models

As part of developing the Rapid Evidence Review, a series of conceptual models were generated that became the basis for farmer communication materials. Data presented above were synthesised and added to each model in purple font. The data sometime confirmed the evidence review findings but often added nuance or provided unexpected insights such as the use of groundwater sources, or the expectation that Scottish Water should build more reservoirs to service farms. One model is presented for each of the farm types (arable cereal crops; Figure A5.6, horticulture; Figure A5.7, intensive livestock; Figure A5.8, extensive livestock; Figure A5.9 and a model for the distillery sector; Figure A5.10.

The adaptation options discussed in the section "What are, or could, participants do to prepare for scarcity?" are further analysed to consider if the actions suggest transformation to production systems (Pretty *et. al.,* 2018). We found that in most cases there were limited efficiency measures (efficiency meaning making better use of existing resources, examples included: timing of irrigation applications, using trickle or drip rather than rain gun irrigation, and soil management to ensure moisture percolated into the soil) especially for rain-fed agriculture but there were many substitution measures discussed (substitution meaning looking for alternatives – in this case, water sources but also alternative plant varieties and fodder sources). However, our participants were not contemplating major changes (transformations) to what they produced in response to the water scarcity risks, indeed distillery participants felt increasing global demand was increasing pressures for production and therefore on water resources.

Updated Arable crop sector conceptual diagram with focus group data n = 17

What are the main sources of water for the sector?

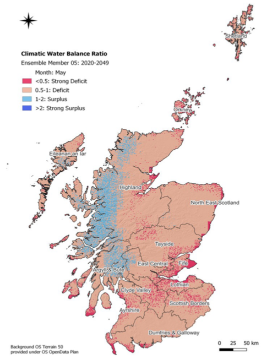
Predominantly Rainfed but some were irrigating barley using burns in dry months (SH32) as they had the infrastructure and access to water

How is water used by the sector?

Crops such as barley rely on rain-fed soil moisture during key growth stages

Did not present SWHC metrics but potentially these are important for farmers decisions

What are the future water projections?



Strong climatic water balance deficits are predicted during key growth months such as April

Drier spring seen as positive to get access to waterlogged fields – CWB may be in deficit but soils still wet from GW break through in Spring (SH27)

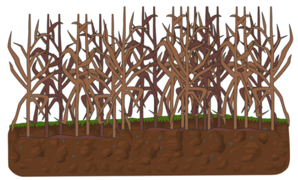
Will be variable year to year (SH23, SH28)

Already seeing these changes (SH29)

most problematic for East & sandy soils (poor soil moisture holding capacity) (SH17, 18, 22)

Majority believe threat to sector/business

What are the future risks?



Deficits in key growth stages could lead to crop failure

Germination problematic if topsoil too dry (SH9, 17, 32, 13; 23); also decreased yield (SH7, 18, 22) – SH4 lost spring barley crop 2023 and quality of crops/price achieved (SH4), Also noted by Distillers (SH 43, 44, 42)

What are the adaptation options?

Growing drought tolerant crops (SH2)

No **efficiency** possible (rainfed) although Soil management (SH27, 32, 33) might allow rain to be kept in soil - NbS not widely embraced, farmers want soil 'living' (SH 28, 29)

Substitution: On-farm lagoons/ponds (SH23, 28, 33) and/or Public reservoirs (SH28) for potential top up irrigation. Rainwater harvest insufficient volumes to help with arable (Fife)

New variants – resilience to wet and dry (SH 4, 24)

Change where plant (SH24; 23)

Transformation

Swap to livestock (SH24, 29)

Figure A5.6: Revised conceptual model for the arable crop sector, updated with the Focus Group data.

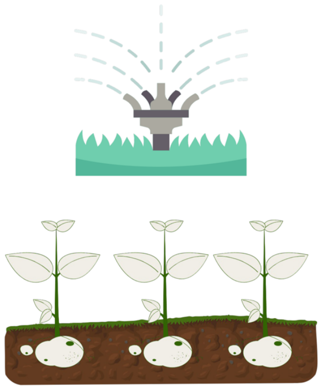
Updated Horticulture sector conceptual diagram with focus group data n = 7

What are the main sources of water for the sector?

Surface water & Groundwater

Many NE on GBR
SH18 registration for carrots and potatoes [we don't have data for authorisation types for Fife]
Fife participants recall restrictions in 2022
NE water use: 10/11 use GW, 5/11 use SW (total, anon polls)
Fife water use: 4 veg producers use both SW and GW
SH33 use of natural/artificial ponds

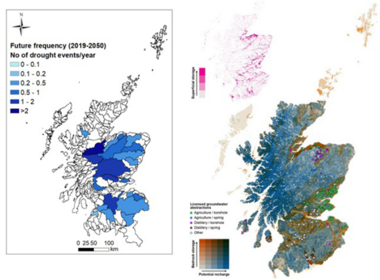
How is water used by the sector?



Horticultural crops such as potato and brassicas rely on surface water and groundwater sources for irrigation

Do not irrigate potatoes (SH20)
SH18 irrigation veg 15-20 days p.a.; 10-15,000m3 per annum.
SH30, 32, 33 irrigate when sow if dry, and to prevent scab; Irrigate later to ensure yield (July)
May be authorised to use water but there is insufficient burn water to use even before the stop notice is issued)

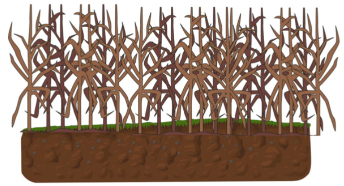
What are the future water projections?



Increased frequency and duration of surface water droughts and increased vulnerability for groundwater security

Sector struggled last 3/5 years (SH18); need to take long view (back to 1960) (SH20)
Already happening (SH29, SH18)
All agree threat to their sector and business
Widely held perception from Livestock focus group that vegetable growers most vulnerable to water scarcity SH3, 8)

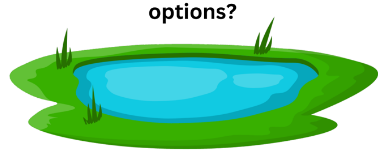
What are the future risks?



Limited access to surface water and groundwater sources could lead to crop failure

SH30, 32 – must irrigate for germination and when close to harvesting or can lose crops altogether
Most fruit and veg producers in this position (SH27)
Interest in whether and how SEPA will revise water scarcity guidance and when would prevent irrigation, recognise that SEPA working to keep production viable (Fife)

What are the adaptation options?



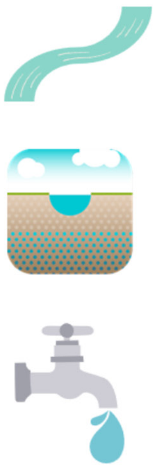
Access to finance for offline irrigation lagoons and nature-based solutions to increase soil infiltration

Efficiency: SH 32 – try to use efficiently but in hot spells irrigating 24 hours a day; SH29 move from rain guns to drip/trickle irrigation (but sunk costs of existing infrastructure, will only change systems when old equipment needs replacing particularly as only cost time to deploy SH32); soil management (SH29, 33); SH29 had to intervene to get neighbours to reduce demand in dry periods
Substitution: artificial or natural ponds (SH 28, 33) – however AECS funding too little and too complex to be attractive; also need public reservoirs (SH20; 28); but rainwater capture not sufficient quantity to be worth investment (general agreement in Fife, NE) SH29 has spare authorised capacity – would like to share with neighbours; Fife participants already had GW sources for resilience; agronomists working on new variants (SH28, 33)
Transformation: none

Figure A5.7: Revised conceptual model for the horticulture sector, updated with the Focus Group data.

Updated Livestock (intensive) sector conceptual diagram focus group data n= 4 (pigs, dairy)

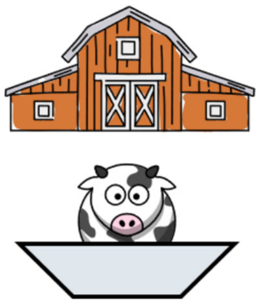
What are the main sources of water for the sector?



Mains/Private water supplies from surface water and groundwater sources

Overall results from Livestock and NE focus groups suggest all three sources are used; abstraction under registration for pigs (no data for dairy) using 30m3 per day from GW borehole (SH21)

How is water used by the sector?



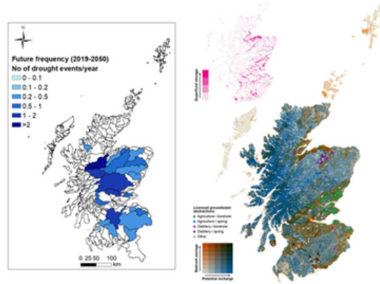
Housed livestock rely on either mains or private water supply sources for drinking water, health and hygiene

Used for drinking water and also cleaning equipment, people, animals and the units

Cows not lactating for up to 6 months of year – use less water (SH8)

Some livestock farmers are irrigating for silage (SH30) but dairy farmers did not expect to do this (SH8) although done in other settings (e.g. .Australia)

What are the future water projections?



Increased frequency and duration of surface water droughts and increased vulnerability for groundwater security

SH21 not had a problem yet but keeping an eye on what might happen

Scarcity will affect costs/availability of forage (SH8, SH10)

What are the future risks?

Limited access to surface water and groundwater sources could lead to livestock health risks

References to disease about grazed not housed herds (SH6)

General concern about effect of heat associated with water scarcity in the summer

Vulnerability is mainly due to costs/availability of forage (SH8)

What are the adaptation options?

Rainwater harvesting to increase source resilience

Efficiency of watering not discussed

Substitution: SH10 &11 already have rainwater harvesting – others feel that too expensive at the moment.

SH8 suggested installing lagoons in the future

Transformation: not discussed

Figure A5.8: Revised conceptual model for the livestock (intensive) sector, updated with the Focus Group data.

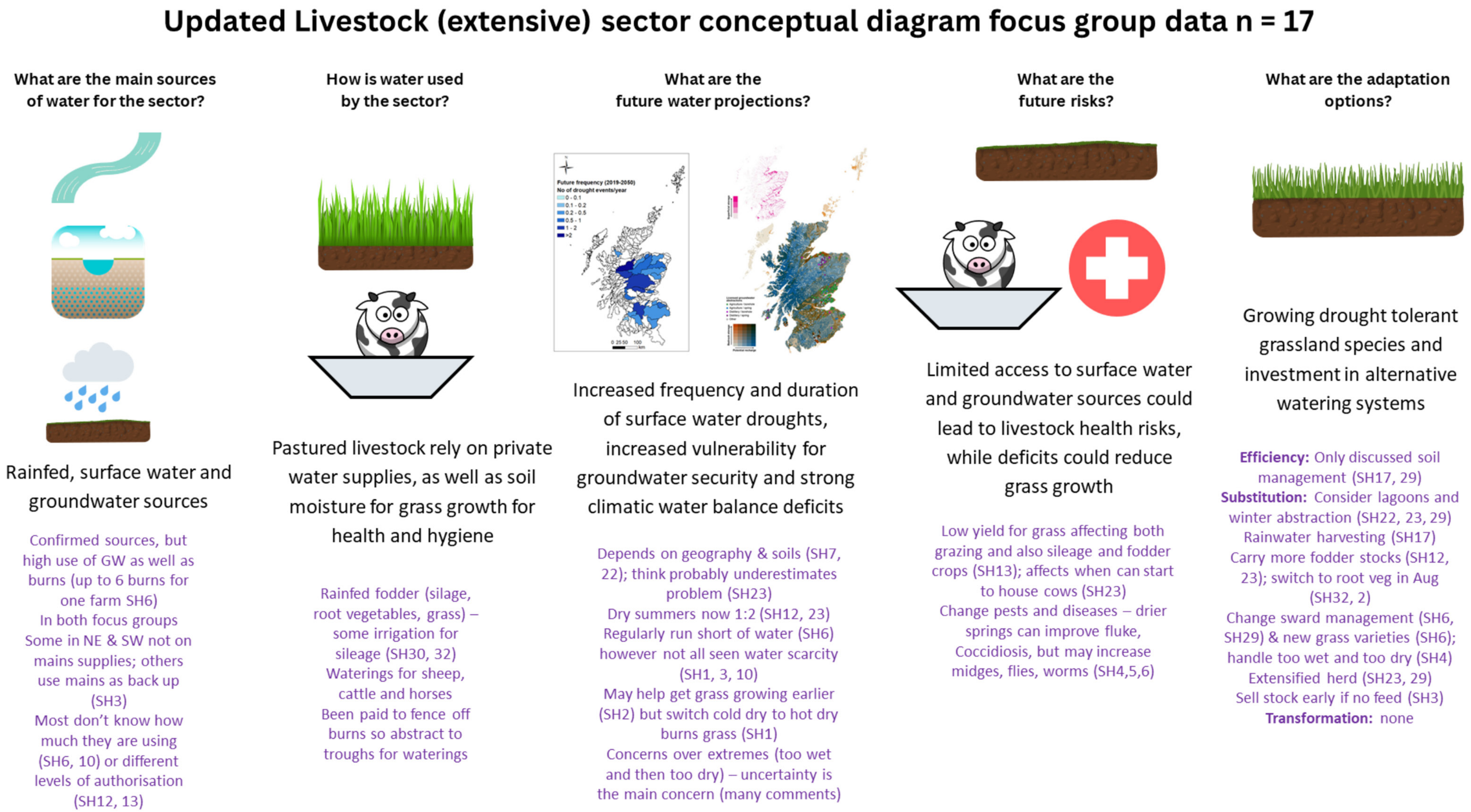
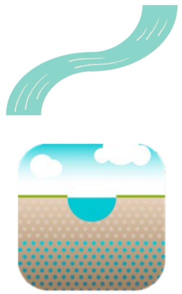


Figure A5.9: Revised conceptual model for the livestock (extensive) sector, updated with the Focus Group data.

Updated Distilling sector conceptual diagram focus group data n=26

What are the main sources of water for the sector?



Surface water and groundwater sources

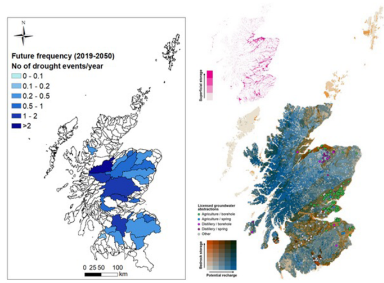
Also use seawater (SH52) and mains water when PWS getting low (SH 38)
Some would like to use GW but not productive (SH37)
Shared sources with competitors (SH36)
All authorised through Simple/complex licences
Know how much they are using; aware of limits and conditions
Often not using full consent (SH36) some using meters (SH45, 46, 58)

How is water used by the sector?

Distillers rely on surface water, groundwater and spring sources for processing and cooling

95% water for cooling (SH37)
Generally GW for production and SW for cooling but some use GW for cooling (SH58); mains water generally for washing & visitor services (SH43)
Use will depend on cooling infrastructure used
Seasonal differences: 140 to 230 Litres of Pure Alcohol p.w.(SH52)
Intensity: some distil 7 days per week (SH38); others 5 (SH43);
Increase in production driving increased use (SH57, 38, 42)
Water rights often very old (SH58); also consents (SH52)

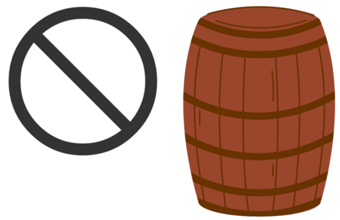
What are the future water projections?



Increased frequency and duration of surface water droughts, increased vulnerability for groundwater security.

Most had recent problems with scarcity (SH 42) in last 3-4 years; often can't take full consented volume (SH 36)
Has made water important issue (SH57)
Temperature & quantity are the constraint (SH42, 52)
Both in Spring (May) and autumn (Sept) new pattern (SH42, 43, 46, 49)
Also extremes – floods (SH37, 48)
Need more granularity – SEPA only one monitoring point on Spey but each distillery has different cooling water sources (SH57) lost access to SEPA data (SH37)

What are the future risks?



Limited access to surface water and groundwater sources could lead breaks in production

Forced shutdowns 3-4 weeks (SH42) others pulling back production not total shut down – biggest impacts when distilling 7 days a week, others can make it up (SH37, 43) impacts production – profit depends on price when sold (SH42)
Chill cooling water; pump from alternative sources costs money (SH37, 38, 50); mains water expensive (SH38)
Also increased cost of malting barley (SH42, 43, 44) & low supplies (SH44)

What are the adaptation options?

Nature-based solutions to increase soil infiltration and rainwater harvesting on-site

Efficiency: looking at TVR,MVR, adiabatic, reverse osmosis to reduce amount needed for cooling (SH 36, 37, 40, 47) but others too expensive, energy needs (SH36, 52)
Chiller to cool water (SH38, 48)
Some older distilleries have problems with leaks; minimise production water through high gravity mash (SH 45); recycle effluent (SH37, 38, 44, 47)
Substitution: SH42 uses mains when SW too low or too hot; Some exploring GW (SH36, 35), SH57 leaky barriers, SH44, 54 considering a reservoir, SH37 use main river not burn; alternative spring (SH34); Rainwater capture not enough, problems of contamination (SH34, 35, 37, 42, 43, 54); try to produce more in winter (SH34) and stagger shutdowns (SH43) but problems with this (SH34, 36,39, 37 42)
Transformation: none

Figure A5.10: Revised conceptual model for the distilling sector, updated with the Focus Group data.

Insights on communication or dissemination

At the end of the focus groups, stakeholders were asked to answer a poll giving their preferred dissemination options. They were able to select multiple options if they wished to do so. For all three farmer focus groups an article in industry press received the highest number of responses (24% of responses at the North-East, 23% at Fife, and 28% at the livestock focus group, see Figure A5.11). For distillers, a website summary received the highest number of responses (27% of responses, see Figure A5.11). One 'Other' response was given during the North-East focus group, which referred to 'Seeing something in action'. Similarly, one 'Other' response was given at the livestock focus group. This respondent expanded on this, saying it would be helpful to receive information through WhatsApp. At the distillers focus group 3 'Other' responses were given, one mentioning the World Whisky Conference, one a discussion with SEPA, and the last the Institute of Brewing and Distilling, who publish a magazine and host webinars.

As already mentioned, authorised abstractors with licences had received warnings from SEPA when stop notices were a potential threat to their practices, but there was an appetite for building a culture of using projections for business planning as well as more information about how low flows were impacting the ecology and why restrictions may become necessary. Licenced abstractors were familiar with, and using, the information provided by SEPA on water levels and forecasts, but those reliant on water under registration and general binding rules were less aware of the information sources. They tended to rely on observing their local conditions (e.g. burns running dry) rather than using projections. This situation means that such water users are reacting to water scarcity, rather than proactively checking and adapting to the projected conditions.

Participants also enjoyed meeting to discuss the topic and sought further opportunities to discuss possible adaptation responses with those who can advise on different options, funding mechanisms and encouraged practical visits to demonstrate new approaches.

Discussion

Overall, the four focus groups yielded fruitful insights into how the participants were thinking about water scarcity and how they were preparing for the future. There was general agreement with the data presented from the evidence review, though some had questions or comments on the data sources used and wanted more details. This probably reflects the fact that focus group participants self-selected and therefore attended due to existing interest and/or knowledge in the topic. Literature on climate change communication (Environment Agency 2023) highlights the importance of making the topic relevant to individuals, by linking it to business risks and resilience. Given the results

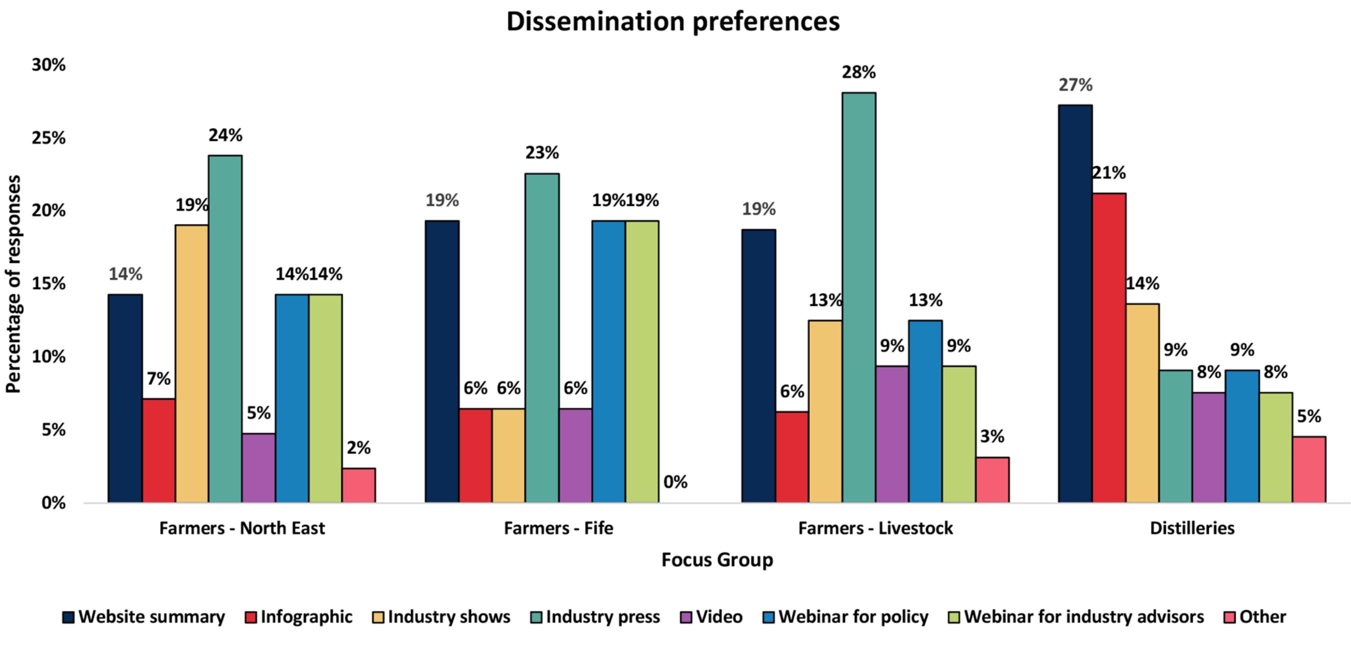


Figure A5.11: Stakeholder dissemination preferences.

shown in Figure A5.3, water scarcity is becoming more relevant to a wide variety of farming systems and to the distilling sector, however, discussions were framed in the context of Eastern Scotland experiencing several months of storms and high rainfall events and ongoing input cost inflation, meaning lack of water was not necessarily the most pressing issue for participants. The combination of floods and water scarcity, at a time of other pressures (high input costs, market instability) illustrates the finding that multiple stressors affecting farmers at the same time can create a tipping point for mental health (Rose *et. al.,* 2023). Most participants had concerns about water scarcity and many already had adaptations or plans for adaptations in place, though this was higher amongst distillers than livestock or arable farmers. Those attending were aware of how scarcity had already affected them, and how further periods of scarcity might impact them further. Whilst many were making adaptations, there were still some who had not made changes, and others were exploring options but had run into barriers such as cost. Although most were committed to efficiencies, there were a few concerning anecdotes such as leaking pipes in older distilleries and the fact that farmers were using more water than their neighbours when they had access to irrigation technologies. Although individuals reduce their water use, the overall increase in production may mean overall that water consumption increases, so efficiency adaptation need to be put in a wider picture of the overall trends in each sector.

Many participants were exploring potential substitution or alternatives to help with projected water scarcity. Most farmers were aware of the need to improve their soil moisture holding capacity in dry spells (and drainage in wet conditions) offering a strong overlap with policy signals from agricultural policy. This may assist with groundwater recharge and reduce the need for increased irrigation being predicted in the climate change literature (Blasco *et. al.,* 2015). Some livestock farmers were using rainwater harvesting and would welcome funding assistance for installation, but there was a widely held perception with arable farmers and distillers that this technology could not hold enough water to be cost-effective for prolonged dry spells and would incur water treatment costs or create health risks. Irrigation lagoons were being used by some farmers and distilleries but the cost of installation and running costs were seen as off-putting by many. Seeking alternative groundwater sources was found across all focus groups, although the lack of data on groundwater resources was seen as a limiting factor in making the investment decision. Financial cost of adaptations was raised by all groups as preventing change, alongside lack of cooperation between different parties. There was a sense that farmers and distillers had long-term use rights and some participants did not think of water as a common pool resource but a private good for their business. However, this did not translate into being prepared to pay for water use, only for the costs of accessing this water. This culture makes water allocation options from other settings e.g. reverse auctions (Grafton and Wheeler 2018) difficult to adopt.

In many of the discussions about adaptation, other stakeholders were involved, such as getting support from funding agencies, having new crop varieties developed by crop breeders and public reservoirs built by Scottish Water. Therefore, whilst our data suggests that many farmers recognise water scarcity as a business risk, there was less appetite for farmers to bear the costs or take action to make themselves less vulnerable to water scarcity beyond good soil, pasture and fodder management. Instead, the discussion focused on the fact that public infrastructure should ensure ongoing access to water resources and how the national water scarcity plan recognised the importance of horticultural production, and other sectors should reduce their consumption to allow food production to continue. However, distillers seemed to recognise the need to respond to the regulatory pressure from SEPA and were keen to use best available technologies and Nature-based solutions, where possible, to address scarcity projections. Here, the main risk appears to be the increased production pressures that mean overall pressure on water resources may increase. However, if the claims that TVR or MVR can reduce cooling water quantity by up to 70%, this could really help with projections, particularly in hotspots in the Speyside area.

Our findings have both confirmed, and extended, the recent review on drought and its impacts in the UK (Environment Agency 2023). Our results show the same pattern of impacts and the same resistance to investment in substitute sources and to collaborative water management arrangements. Furthermore, we have provided additional empirical insights into how different farming sectors (and distilleries) are responding, which was highlighted as missing in the UK evidence review. Our research is exploratory, and our participants attending the focus group were possibly those who are looking forward and adapting the businesses, however many in these sectors may not be as forward thinking. It was clear that even these forward-looking farmers and distillers were often unaware of how much water they were using (demand) nor how much water they could rely upon from rainfall, surface or groundwater sources (supply) and therefore were not able to factor this into their business planning. Although farm water use calculators exist in other contexts (e.g. Australia[6]), it would be useful for Scottish farmers to have a tool to estimate their water needs and to increase their appreciation of water as one of their natural assets on which their businesses depend (Fleming *et. al.,* 2022). Whilst the Water Stewardship Framework (Scotch Whisky Association, 2023a) sets out important strategic directions for the distilling sector, there is also a lack of water calculation tools for this sector.

[6]How much water does my farm need? | Farm water solutions | Water | Farm management | Agriculture Victoria

Appendix 6 Socio-economic assessment

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Summary

Drawing on the Rapid Evidence Review as well as on results from the sectoral focus group we assess (i) the costs of water scarcity on arable farming and horticulture; livestock agriculture and the distilling sector in a no-adaptation scenario and (ii) potential adaptation strategies and their costs.

There is little data available to systematically assess the impact of water scarcity. The analysis of past drought events provides some insights into the type and range of costs faced by farmers. In the arable and horticulture sector, rainfed crops have been impacted with reduced yields and decreased crop quality for barley, but there is no evidence of such reductions for irrigated crops (e.g. potatoes, vegetables or softs fruits) indicating that irrigation may have been sufficient to compensate for lower soil moisture levels so far. However, increased irrigation costs are noted for these crops and costs are potentially important in terms of abstraction restrictions for these high value crops. In the livestock sector, the main costs of drought events have been the increase in feed costs due to a combination of increased need for purchases, increased feed prices and early sale of livestock units. There was no report of direct impact of droughts on the distilling sector so far, but indirect effects through increased malt barley prices. However potential costs are to be expected in case of abstraction restrictions leading to reduced production capacity that cannot be compensated at other points in the year.

Adaptation strategies for rainfed crop include the uptake of irrigation, which is unlikely to be profitable for the sole purpose of irrigating cereals, but could be with the dual purpose of vegetable, potatoes and cereals irrigation. Drought resistant varieties or crops are seen as the most likely adaptation strategy for cereals, and also relevant for horticultural crops. For open-field irrigated crops, farmers could improve irrigation efficiency (e.g. trickle irrigation). Boreholes and water storage solutions (lagoons or reservoirs), potentially associated with rainwater harvesting systems, are identified as a solution for open-field irrigated crops as well as for protected/covered crop systems (e.g. soft fruits). These can also provide alternative sources of water for dairy and beef farms. The adaptation of pastures to water scarcity can be made through a change and diversification in species used for forage, and potentially irrigation could be envisaged in intensive grassland systems. The distilling sector have identified technological innovations increasing the efficiency of the cooling system as the main available solution, while alternative sources of water (groundwater abstraction or reservoirs) are also considered.

Introduction

According to the FAO (FAO 2023), drought is the hazard that has caused the most significant damage in agriculture between 2006 and 2022. The analysis of national crop production data under past drought episodes shows that, at the European level, agricultural crop production losses due to droughts and heatwaves tripled between the 1964 – 1990 and the 1991 – 2015 period (Bras *et. al.,* 2021). The same study shows that while cereals have suffered the most losses in percentage of overall production, the increase in losses between the two periods is much larger for non-cereal crops (such as roots and tubers, vegetables, oil crops, soft fruits). In particular, amongst all crops, vegetables, soft fruits, roots and tubers show the largest yield and production losses in drought episodes in temperate oceanic climate zones in Europe, to which most Scottish arable areas belongs (Bras *et. al.,* 2021). A report by SAC Consulting (2019) shows that the overall impact of the combination of heavy snow in March followed by drought conditions in the summer 2018 have led to a £161 million loss to the Scottish agricultural sector (6% of 2017 total output), due to reduced yields and livestock numbers. They identify 4 key sectors that suffered most of the losses: the sheep sector (estimated loss of £45 million), wheat (£34 million), beef (£28 million) and barley (£26 million). This also affected input prices to the distilling sector, with malting barley increasing from £150 per tonne, to over £200 per tonne in 2018/19, increasing costs to the distilling and brewing sector by £45 million (Scottish Parliament, 2018).

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[7] This is only accounting for droughts classified as a “disaster”, i.e. which has led to a call for international assistance or an emergency declaration. Water scarcity in general, including events of lower magnitude, will likely have a larger effect on agriculture.

With continued increase in droughts and frequency of episodes of water shortages in Scotland, we aim to assess what is currently known about the potential costs of water shortages to three main food and drink sectors reliant on water: arable farming and horticulture; livestock agriculture and the distilling sector; as well as potential adaptation strategies.

We draw on the results from the literature reviews in Appendices 1-4, as well as on results from the sectoral focus groups (Appendix 5). Where data available was limited, we expanded the search of data beyond Scotland to provide some insights into possible costs and adaptation strategies which could be adapted to Scotland – a note will indicate when this is the case. Where cost values are assessed for other contexts than Scotland, the values provided are illustrative but additional data should be collected and analysed to be able to increase the values' suitability for farmers and distillers in Scotland.

Section A addresses the question "How will deficits impact abstracting industries" while section B looks into "What adaptation measures have already been tested and what could be economically viable". Each sector is analysed independently in separate sub-sections. Where available from the literature, values of costs of water deficits as well as values of adaptation strategies are provided. Data gaps will be identified in the conclusion.

Section A: Potential costs of water scarcity for each sector in the absence of adaptation from the sector

Few robust economic assessments of regional and national impacts of water scarcity on crop production exist due to the challenges in disentangling its impact from that of other factors affecting the variability of agricultural economic performance in time and space (Environment Agency 2023). As the literature identified analyses the impact of specific episodes of droughts, and not the impact of water scarcity per se, we use this analysis of past drought events to assess how the sectors might be impacted by increased frequency of water deficits in soil moisture (for rainfed systems) as well as increased frequency in water abstraction restrictions (for sectors dependent on abstraction). In particular, the analysis of the impact of the 2018 and 2022 droughts provides relevant references (AHDB 2018, NFU Scotland 2023, SAC Consulting 2019). This can be put the context of the Climate-Water Balance Projections that show that lowland Scotland will be in deficit for longer (starting in April, extending to September); and whilst some areas of North-West Scotland may have less deficit in July – August; other areas of hill farmed cattle and sheep will also have more months of deficit (see section 3.2.1).

Costs for the arable and horticulture sector

We identify 4 main types of costs in the arable and horticulture sector related to water scarcity (Table A6.1) (i) reduced yields and production – mostly affecting rainfed agricultural productions; (ii) decreased crop quality; (iii) increased variability in yields and production levels; (iv) increased irrigation costs for irrigated crops.

(i) Reduced yields and production

A study by Bras *et. al.* 2021 shows that past droughts in the 1964 – 2015 period have caused an average yield loss of 9% for cereals, and 3.8% for non-cereal crops in the EU, meaning that during years in which a drought was recorded, yields were on average 9% lower for cereals and 3.8% lower for non-cereal crops. While these numbers are likely over-estimates for Scotland, their analysis by climatic regions shows that these yield losses can still be significant in temperate oceanic climate, to which the Scottish Lowlands belong, with production losses reaching an average of 6.4% of average production levels for cereals, and 5.4% for non-cereal crops. The total effect of droughts on production levels is due to a combination of yield losses and changes in harvested area. Table A6.1 presents detailed yield and production losses estimated for several crops. For barley, Bras *et. al.* (2021), show that reduction in yield can be partially offset, at the national level, by farmers by an increase in harvested area if land capability for arable cropping changes in prolonged dry summers. Arable farmers participating in the project focus groups, also indicated yield losses because of past drought episodes (See Appendix 5). However, potato yields in the UK have mostly been found to be unaffected by 2003 and 2006 dryer summers, which is attributed to the fact that potato growers are already equipped with irrigation systems and have been able to compensate soil water scarcity by increased irrigation levels. The main cost registered being therefore the increased costs of irrigation (AHDB 2018, SAC Consulting 2019). There was no evidence found for Scotland of the costs of droughts for vegetable production. NFU Scotland (2023) have reported that the abstraction restrictions in place in 2 catchment areas in the summer of 2022, were in place for a too short period of time to impact crop production, but longer restrictions could lead to important production losses. The yield reductions observed in Europe provide useful insights into the potential effects of future droughts in the Scottish context. More data on production levels under alternative water availability levels and irrigation conditions would be beneficial to be able to provide more reliable estimates. Indeed, the Environment Agency's report (2023) raises the issue of the lack of information on the areas and geographical location of open field irrigated crops, and current water storage capacity.

There was no evidence in the literature that soft fruit production in Scotland has so far been impacted by past episodes of droughts. Bras et al. (2021) report an average reduction in yields of 4.9% in the EU temperate oceanic climate area during drought episodes over the (1964–2015) period. It is possible that current irrigation systems have been sufficient in Scotland even in periods of water scarcity. The Environment Agency (2023) signals the lack of available data on areas of polytunnels, sources of water used for protected cropping (such as soft fruits) and whether these farms are already equipped with reservoirs or storage systems to assess the potential impact of droughts in this sector.

For crops relying on irrigation, we found little to no evidence on what the economic impact of abstraction bans could be, and how these would vary with the length and frequency of such bans.

(ii) Decreased crop quality

In addition, during the project focus groups it was reported that droughts at crucial points of the crop development have impacted the crop quality, especially for malting barley, which is also an issue reported by the Environment Agency (2023). Switching markets from malting to feedstock barley has important financial implications for the farm business – for example SH4 went from getting £280 per tonne to £140 per tonne during the summer of 2023 due to the problems with germination.

(iii) Increased variability in yields and production levels

A potential increase in yield variability has been mentioned for the case of barley in the literature (Roberts and Maslin 2021). This expected increase in yield variability can be expected to cause challenges to the supply chains and end users, for example barley and the whisky industry (Roberts and Maslin 2021), leading to adaptation costs at the food chain level.

(iv) Increased irrigation costs for irrigated crops

Open field irrigated crop (potatoes, vegetables mostly), that depend both on soil moisture from rain and irrigation, will likely need to compensate the reduced soil moisture levels in summers months by an increase in irrigation levels. The evidence review found that many of the areas with high concentrations of horticulture as their main farm type (Fife, Black Isle, Buchan, Tayside) had low soil moisture holding capacity (Rivington *et. al.,* 2022). Furthermore, the projections suggest that in catchments in the south and east of Scotland, drought events are likely to happen more often and for longer duration. In this section we look at the marginal cost of increased irrigation, while adoption of irrigation by producers not currently equipped is considered an adaptation strategy and discussed in the second part of the report.

Currently, irrigation costs are only available in the SAC handbook for potato production, we therefore illustrate the increase in irrigation costs through the example of potato production. The 2010 Scottish Survey of Agricultural Production Methods showed that 74% of irrigated area is producing potatoes, with a majority (72%) using sprinklers, while the remaining 28% used surface irrigation. The literature shows that irrigation needs for potato production vary depending on soil moisture: in high soil moisture and wetter agroclimatic zones around 45 mm per year of irrigation would be needed, but a drier agroclimatic zone with low soil moisture would need up to 195 mm per year (Knox *et al.,* 2007). If we assume that Scottish potato production areas pass from the former climatic condition to the latter in the next coming years, that is an increased cost between £240 and £456ha/year; £1,050 and £1,095ha/year including contract charge, according to irrigation variable costs reported in the SAC Handbook (SAC 2023). These costs include running costs of irrigation (e.g. energy), but water itself is free to use in Scotland.

The focus groups revealed that farmers also irrigate other crops than potatoes and vegetables, including malting barley and also sometimes silage and grassland. However, we found no data on how widespread this practice is. It can be expected that these farmers also bear additional costs for irrigation in the future.

Table A6.1: Costs of water deficits to arable and horticulture sector.			
Type of cost	**Details**	**Source**	**Value**
Yield losses	Farmers mentioned loss of yield on arable land	Focus groups with farmers	n.a.
Cereals (all)		Bras *et. al.* 2021	9% reduction in yields on average (1964-2015, EU level), ranging from 2% increase to 23% loss[0]. 6.4% reduction in production, 6.6% reduction in yield in the EU temperate oceanic climate area (1964-2015)[1].
		SAC Consulting, 2019	Reduction by 9% in average yield in 2018 (drought) compared to 2017 in Scotland, as well as reduction in area harvested, leading to 12% drop in production[2].
Barley		Bras *et. al.* 2021	5.7% reduction in production, 7.4% reduction in yield, but increase in harvested area by 1.7% in the EU temperate oceanic climate area (1964-2015) [1].
		WWF, 2019	-23.9% in total production in 2018 for winter barley, -9.3% for spring barley2 (Scotland).
		Roberts and Maslin 2021	7.9% decline in UK spring barley production in 2018.
Non-cereal (all)	Non cereal crops seem less impacted than cereal crops, which can be explained by more widespread irrigation for non-cereal crops.	Bras *et. al.* 2021	3.8% reduction in yields on average (1964-2015, EU level), ranging from 6% increase to 13% loss[0]. 5.4% reduction in production, 4.5% reduction in yield, but decrease in harvested area by 1.3% in the EU temperate oceanic climate area (1964-2015) [1].
Root and tubers		Bras *et al.* 2021	11% reduction in production, 11.1% reduction in yield in the EU temperate oceanic climate area (1964-2015) [1].
Potatoes	Yields largely unaffected as irrigation available	AHDB 2018 SAC Consulting 2019	Unaffected in Scotland 2003 and 2006 (AHDB), 2018 (WWF)
Field vegetables		Bras *et. al.* 2021	Reduction by 3.5% in yields in the EU temperate oceanic climate area (1964-2015) [1]
Soft fruits		Bras *et. al.* 2021	5.3% reduction in production, 4.9% reduction in yield in the EU temperate oceanic climate area (1964-2015) [1].
Decrease in crop quality	Lack of water at key growth stages can negatively impact crops' quality, and thereby selling price	Environment Agency 2023 Focus groups with farmers.	n.a.
Increased yield variability	Potential for higher yields in good years, but losses in case of drought	Roberts and Maslin 2021	n.a.
Increased irrigation costs	Increased need for irrigation for open field irrigated crops (e.g. potatoes, field vegetables)	AHDB 2018 WWF, 2019	Assuming investment already in place, variable costs for irrigation are: £1.6 to 1.9ha./mm plus contract charge ~£5.4ha./mm (SAC 2023)

Table notes:

0: Average impact of past drought episodes on production and yield levels
1: the impacts at the climatic region level combine the effect of drought and heatwave.
2: the impact on production and yields in 2018 combines the impact of heavy snow in March 2018 followed by water scarcity in the summer 2018.

Costs for the livestock sector

The most common cost for the livestock sector in past drought episodes, affecting all types of livestock farming relying on pasture, has been the increased need to purchase feed, to compensate for a decrease in forage productivity, either directly during the drought, or in the following winter as a consequence of lower stocks (AHDB 2018, SAC Consulting 2019) (Table A6.2). This finding was also echoed by livestock farmers in the project focus groups; but they also included the cost of bedding materials e.g. straw costs rising to over £100 per tonne.

An indirect effect of droughts has been the increase in feed prices through a combination of reduced feed supply availability and increased demand for livestock feed, which affected all livestock producers, with 20 to 25% higher input prices (UK HSA 2023, focus groups with livestock and mixed farmers).

Reports have found that some farmers have had to sell animals or destock early to reduce feed purchase needs both in the dairy and red meat sectors (AHDB 2018, UK HSA 2023) and to prioritise breeding stock, which was also mentioned as a coping strategy by some of the focus group participants. Possibly as a consequence of early sale of livestock, AHDB (2018) reported a reduction of the average carcase weight (red meat sector) of between 10 ang 15kg compared to the 5-year average during the 1995 and 2018 droughts. The focus group drew attention to geographical patterns including having less suckler herds on hillside farms over winter.

In the dairy sector, AHDB (2018) reported a reduction in milk production at the UK level in the August 1995 drought of 15 million litres.

Table A6.2: Costs of water deficits to livestock sector.

Type of cost	Details	Source	Value
All livestock			
Increased feed costs	With droughts usually affecting large areas simultaneously, past droughts have been found to increase feed costs	UK HSA 2023 Focus groups with farmers	During 2018 drought, 20 to 25% higher input prices.
Outdoor livestock			
Increased need for feed purchase	Due to decrease in **forage/ grass productivity,** need to increase off-farm feed purchase either during drought or in subsequent winter if own stocks used during drought.	AHDB 2018 SAC Consulting 2019 Focus groups with farmers	n.a.
Red meat			
Selling livestock	Selling early to reduce feed burden	AHDB 2018 UK HSA 2023 Focus groups with farmers	n.a.
Reduced carcase weights	Could be related to early destocking or shortage of feed	AHDB 2018	Average Carcase weight 10 to 15 kg lower than 5-year average at UK level during 1995 and 2018 droughts.
Dairy			
Reduction in milk yields		AHDB 2018	Estimated reduction in milk production at UK level during August 1995 drought: 15 million litres.
Increase in feed purchases		AHDB 2018	Estimated 15% increase in concentrate purchase in August 1995 drought at UK level, increasing milk production costs by around 0.8ppl.
Selling livestock	Destocking early to reduce feed burden	AHDB 2018 UK HSA 2023	n.a.

Costs for the distilling sector

The distilling sector depends largely on the Scottish malt barley production (85 to 90% of the barley used in the Whisky industry is produced in Scotland) (SAC Consulting 2019, Roberts and Maslin 2021). The increase in malt barley prices in 2018 reported in Table A6.3, is estimated by SAC Consulting (2019) to have costed the Scottish distilling and brewing sector a total of £45 million, £40 million for the Whisky industry alone, which is equivalent to 0.9% of the total value of whisky exports in 2018. Spring barley is usually preferred over winter barley for malting (Roberts and Maslin 2021) and seems to have been relatively less affected than winter barley during the 2018 drought episode (see Table A6.3).

Another major cost identified for the distilling sector is the loss of production due to restrictions to abstraction during droughts. Water is essential for cooling in the distilling process, which is the main water use by the distilling sector, and production would have to be stopped if water abstraction is restricted. All focus group participants at the distilling focus group agreed that they would have to reduce production under drier and warmer weather conditions. Without increased output prices, this would lead to a profit loss for distilleries.

In the case of Glenlivet, Fennell *et. al.* (2023b) estimate that 1 day of production generate 60,000 litres of raw spirit product valued at £2.5/l, so a total loss of £150,000 in production for each day lost. Note that the variable production costs saved (energy, inputs, labour) during each production day losses should be deducted from this value, but no published estimates are available.

Abstraction restrictions will have different impacts on distilleries depending on their production capacity and current operating conditions. Some participants of the focus groups reported that, to a certain extent, production days lost can be compensated for in the winter, if the distillery currently does not operate 7 days a week, leading to no overall loss. However, for those distilleries operating at full capacity, or planning to expand to full capacity, this flexibility does not exist. If abstraction restrictions last for long periods of time, leading to prolonged period of stopped production, it would endanger distilleries' capacity to retain staff, with knock on effects on local employment. Finally, the absence of production during peak tourist periods of the year may impact the attractiveness of distilleries' visitor centres for visitors, leading to further reduced income sources.

Roberts and Maslin (2021) anticipate that Speyside distilleries may be particularly impacted, being identified as a future drought hotspot, while Islay distilleries may face particular challenges due to the lack of water storage capacity on the island.

Table A6.3: Costs of water deficits to distilling sector.

Type of cost	Details	Source	Value
Production days lost due to abstraction restrictions		Roberts and Maslin 2021	Glenfarcas reported loss of 1 month of production (300,000 litres of whisky) in 2018.
		Fennell *et. al.* 2023b	Value of whisky produced per day: 60,000litres of raw spirit product at £2.5/l for Glenlivet distillery.
Increased costs of inputs (increased prices of malted barley)	Reduction in barley production in Scotland can have a knock-on effect on the distilling sector which relies on Scottish barley production, through increased malt barley prices	Ecosulis 2019	Increase in malt barley from £150/tonne in 2017 to £200/tonne during 2018 (dry summer)[1]. This increase in costs, scaled at sector level, represents 0.9% of the total value of whisky exports in 2018.
		Roberts and Maslin 2021	Increase in malting barley price from £145/tonne in 2017 to £179/tonne in 2018 drought. Total cost of £27 million for the industry with 800,000 tonnes/year.

Table notes:
1. The authors specify that this increase in price cannot be fully attributed to the weather

Section B: Adaptation strategies

Arable and horticulture sector

The 2010 Scottish Survey of Agricultural Production Methods (Scottish Government 2012) showed that under 2% of holdings had undertaken irrigation in the three years before 2010. Within these, 28% of holdings used surface irrigation, and 72% sprinkler irrigation. The vegetable, fruit and potato sectors are the main users of irrigation water. There are no updated figures since the 2010 survey for irrigation practices in the farming sector.

The adaption strategies for the arable and horticulture sector are different depending on current irrigation practices. We differentiate three main situations:

- Adaptation strategies for farmers currently fully reliant on rain for crop production (Table A6.4), whose first concern will be water scarcity due to reduced soil moisture,
- Adaptation strategies for the open-field arable sector, already equipped with an irrigation system, and that relies both on soil moisture and abstraction for crop production (Table A6.5), who will be impacted by both a reduction in soil moisture and the risk of reduced water availability for abstraction,
- Adaptation strategies for protected/covered crop systems, which rely exclusively on irrigation for crop production, and who will be impacted by the risk of reduced water availability for abstraction (Table A6.6).

Note that farmers currently belonging to the first category, may fall into the second category if the uptake of irrigation becomes more widespread.

An increase in water scarcity may lead more farmers to take up irrigation, increasing the overall abstraction levels from surface and ground water. The costs of irrigation estimated by SAC in the Farm management Handbook (for potato production) indicates an annual capital charge between £300 and £500 per hectare, to which the variable costs (e.g. energy for operating the system) should be added (Table A6.4). Put in perspective with average gross margins for cereals[8], investment in irrigation equipment uniquely for cereals does not appear as profitable. However, the expected gross margins for non-cereal crop, in particular potatoes[9], could justify the investment. Some farmers during the focus groups indicated that, when investments in irrigation systems have been made for vegetable or potato production, the additional cost of irrigating cereals can be a profitable solution.

Most non-irrigating cereal farmers in the focus groups identified improved soil management practices and switching to drought resistant varieties or crops as the most likely adaptation strategy to water scarcity.

For the irrigated, open field arable sector (Table A6.4), the NFU Scotland (2023) suggests three options to make the sector more resilient to future droughts: water storage (irrigation lagoons), bore-hole investment to switch to groundwater abstraction, and drip irrigation to increase irrigation efficiency. Funding exists to support the creation

Table A6.4: Adaptation strategies for rainfed arable sector.

Adaptation strategy	Source	Costs
Adoption of irrigation to counter deficit in soil moisture	SAC handbook (2023)	Costs for potato irrigation in SAC handbook: Annual capital charge: £300 to £500/ha Variable costs: £1.6 to 1.9/ha.mm plus contract charge ~£5.4/ha.mm (SAC 2023)
Improve soil management and soil organic matter	Focus group with farmers	May be minimal if they reuse waste e.g. carrot straw
Switch to drought resistant varieties or crops	Environmental agency 2023 Waajen (2019) Focus group with farmers	Costs fall on agronomists and/or research institutes to test new varieties

[8]The SAC 2023 farm management handbook indicates expected gross margins for winter wheat between £668/ha (@6.0t/ha and £190/t) and £1,533 (@6.0t/ha and £190/t) and slightly lower for spring wheat; for spring barley between £396/ha (@ 4t/ha and £170/t) and £1,103/ha (@7.5t/ha and £170/t) for feed markets, with and added £15 to £50/t for malting markets.

[9]The SAC 2023 farm management handbook indicates expected gross margins for potatoes varying in the range of ~£2,000/ha to ~£9,000/ha depending on the type of potato, its market price and yields.

of irrigation lagoons, with an Agri-Environment Climate Scheme (AECS) offering up to £40k capital costs, but there have been low adoption levels, due to high threshold points and restricted eligibility (must be within certain geographic areas and already have an abstraction licence). Therefore there is both a lack of awareness of the existence of such funding and/or the payment is considered too low (NFU Scotland 2024, confirmed in the focus groups). Farmers in the focus groups were also worried about the running costs and feasibility of such irrigation lagoons, including the opportunity cost of using good land for water storage. In addition to investment costs, additional energy costs for pumping, as well as labour time; and lack of suitable flat land to collect run-off, will also be associated with these irrigation lagoons.

With regard to boreholes as an alternative to surface water for abstraction, the focus groups held with farmers in the project indicated that the use of groundwater, and therefore presence of boreholes on farms, seems to already be more prevalent than was anticipated given the number of licensed abstraction points.

Increasing irrigation efficiency could be achieved through the replacement of surface and rain gun irrigation with trickle irrigation. The UK Irrigation Association (UKIA) indicates that trickle irrigation have higher capital costs than most common rain gun irrigation but they require less energy to function, meaning lower variable costs. UKIA also report that the use of trickle irrigation is becoming more widespread for field-scale vegetable production in many countries.

Solutions identified for the rainfed arable sector, improved soil management and switching to drought resistant varieties or crops are also relevant adaption strategies for the irrigated open-field arable sector.

Rainwater harvesting (collecting rainwater) from roofs and storage (Table A6.6) is considered a potential alternative to abstraction from surface or groundwater sources in areas likely to be affected by droughts (and related restrictions) in the future and for farms with high water demand such as dairy, beef and fruit farms (FAS 2022). In an example for the East of England (HDC 2013 p16), two examples show soft fruit farmers installing gutters on tunnels to harvest rainwater, with the tunnel covers being kept on throughout winter to maximise water collected and directed to tanks and reservoirs. In addition to the initial capital costs of installation, Rainwater Harvesting systems also require functioning costs for the operation of the pumps (energy costs). Additional needs for water filters and treatment equipment can be required depending on the expect water use. However, the focus group participants were less convinced that these technologies would be cost-effective.

Table A6.5: Adaptation strategies for irrigated open field arable sector (e.g. potato, field vegetables).

Adaptation strategy	Source	More resources	Costs
Switch to drought resistant varieties or crops	Waajen (2019) Focus group with farmers		Costs fall on agronomists and/or research institutes to test new varieties
Improve soil management and soil organic matter	Focus group with farmers		May be minimal if they reuse waste e.g. carrot straw
Increase irrigation efficiency (from rain guns to trickle systems)	NFU S 2023 Focus group with farmers	www.ukia.org/3d-flip-book/switching-technologies/ www.ukia.org	Higher capital costs, but variable costs are often much lower (energy).
Groundwater abstraction [10]	SEPA n.d. NFU S 2023	water-scarcity-guidance.pdf (sepa.org.uk)	n.a.
Storage lagoons/reservoirs	NFU S 2023 Focus group with farmers		Current payment under AECS is up to £40k, but judged as too low by focus group participants Opportunity costs of land

[10]Can be temporary abstractions in response to water scarcity events.

Livestock sector

As mentioned before, rainwater harvesting systems can be a potential alternative to abstraction from surface or groundwater sources in areas likely to be affected by droughts (and related restrictions) in the future and for farms with high water demand such as dairy and beef (FAS 2022). Water storage can also be envisaged using surface water abstraction in winter months, stored in tanks or reservoirs.

When looking at managing water scarcity in pastures, several adaptation strategies have been identified by focus groups participants and in the literature (Environment Agency 2023) (Table A6.7). First, a change and diversification in species used for forage has been proposed, switching to drought tolerant species, introducing more root crops in late summer, or increasing the nutritional value of forage by incorporating legume and herb species in forage. Irrigation is also envisaged in intensive grassland systems to reduce the need to buy feed (Environment Agency 2023), but currently only practiced by some of the farmers who have already invested in irrigation equipment for other farm activities (e.g. vegetable production), according to the focus groups.

Distilling sector

The adaptation strategies for the distilling sector have been identified during the focus groups discussions. To increase the efficiency of current cooling systems in the production process, 2 main technologies are identified: closed loop engineering (either Thermal or Manual Vapour Recompression technology), which reduces water needs by at least 70%, and process chillers, which, by chilling abstracted water, also reduces the overall need for water in the processing stage.

For the water that still needs to be abstracted, focus groups participants have envisaged switching from surface water to groundwater sources, though some indicating that there were insufficient sources to make the investment cost-effective for their current operations. Another alternative source of water would be reservoirs, filled when water is most available during the winter months if they had space at their sites or upstream.

Table A6.6: Adaptation strategies for soft fruit sector/protected crops.

Adaptation strategy	Source	More resources	Costs
Rainwater harvesting (RWH) system and water storage, combined with precision irrigation	HDC 2013	NIAB EMR Water Efficient Technology (WET) Centre: soft fruits	Estimated capital cost £32,000/ha with an estimated capital payback period of 4-6 years, based on a comparison with mains water at £1.37/m3 [11] (Kent, England, 2018)
	SAC handbook (2023)	FAS Scotland (not specific to soft fruits)	Simple 10,000litres storage tank: ~£1,000 Rainwater harvesting system larger tank: £2,600. Costs exclude VAT and installation.
	Morris *et al.* (2017)		Reservoir costs increase unit irrigation costs by about £0.40 m−3 to £0.50 m−3 (England 2017) compared to irrigation from direct abstraction.
Groundwater abstraction	SEPA n.d. NFUS 2023		n.a.
Storage lagoon/reservoir	NFUS 2023	water-scarcity-guidance.pdf (sepa.org.uk)	Current AECS one-off payment of £40k.

[11]Holistic Water for Horticulture "Assessing the potential of rainwater harvesting to improve local water security for the soft fruit sector", accessible here.

Table A6.7: Adaptation strategies for livestock sector.		
Adaptation strategy	**Source**	**Costs**
Solution for water used for livestock health and drinking		
Rainwater harvesting (RWH) system and/or water storage	FAS Scotland 2022 SAC handbook (2023) Focus group with farmers	Simple 10,000 litres storage tank: ~£1,000 Rainwater harvesting system larger tank: ~£2,600. Costs exclude VAT and installation.
Solutions for water deficit in pastures		
Introducing drought tolerant forage species	Environment Agency 2023 Focus groups with farmers	n.a.
Incorporating legume and herb forage species to provide greater nutrition into pastoral systems	Environment Agency 2023	n.a.
Species diversification	Environment Agency 2023	n.a.
Change fodder crops (e,g, root crops in late summer)	Focus groups with farmers	n.a.
Irrigation in intensive grassland systems	Environmental agency 2023 Focus groups with farmers	n.a.

Table A6.8: Adaptation strategies for distilling sector.			
Adaptation strategy	**Source**	**Additional information**	**Costs**
TVR technology	Focus group, distilling sector	Reduces the need for cooling water by 20 to 60%.	n.a.
Process chillers	Focus group, distilling sector	Reduces the need for water abstraction by chilling abstracted water	n.a.
Groundwater abstraction	Focus group, distilling sector		n.a.
Reservoir	Focus group, distilling sector		n.a.

Conclusions

Droughts seem to have so far mostly impacted economically the rainfed agricultural sectors – arable and livestock sectors. The rainfed agricultural sectors currently appear to be more vulnerable to future increase in water scarcity as few available and profitable adaptation strategies seem to have been identified for the sector. Where irrigation is already being used, farmers seem to have been able to avoid large production losses, while bearing additional irrigation costs. The more widespread availability of irrigation infrastructures for the horticultural sector might provide some resilience to the sector when facing reductions in soil moisture. Additional irrigation needs generated by reduced soil moisture levels may increase the pressure on surface water systems. Where these additional pressures lead to restrictions on water abstraction, the sector could face high losses given the high value of production. Similarly, distilleries face potentially high costs if abstraction restrictions require them to stop production. However, there is currently little evidence on the potential importance of the associated costs, and how these would vary with the duration, frequency and location of restrictions. Switching to groundwater sources for surface water abstractors may in the short term be seen as an alternative, but the lack of data on groundwater systems in Scotland does not allow to conclude on the longer-term sustainability of such a solution. Examples of the negative effects of groundwater over over-abstraction in several European countries demonstrates the need for careful monitoring and management of groundwater resources through an integrated management of water demand at river basin level (European Environment Agency 2022).

Margins for adaptation through increased efficiency in the water used seem to be higher in the distilling sector than in the agricultural sectors, given the adaptation strategies identified in the report. Most adaptation strategies in the agricultural sector appear to rely on a substitution approach, replacing current water resource with alternative sources or adapting their farming practices (e.g. new grass varieties). Adaptation strategies based on a transformation of the production system from one commodity to another, or swapping intensive for extensive approaches, are rarely evidenced.

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