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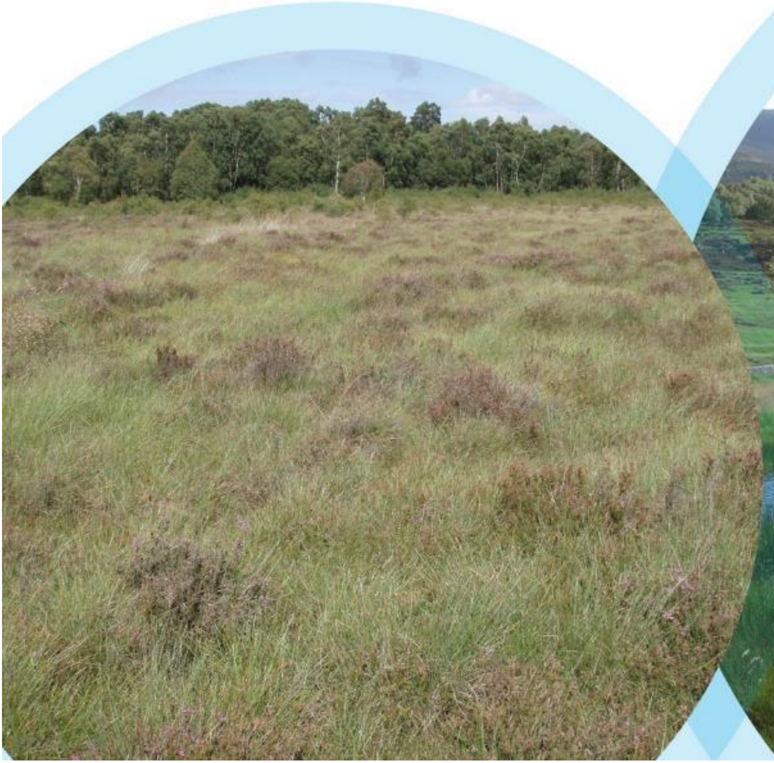
Moderating extremes in water availability in Scotland: a review of the role of functioning wetlands



Moderating extremes in water availability in Scotland: a review of the role of functioning wetlands

Combined Technical Appendices

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Cover photographs courtesy of: Top-right image: Basin fen at Whitlaw Mosses, Scottish Borders (Andrew McBride, Land and Habitats Consultancy); **Bottom-left image:** Raised bog at Threepwood Moss in the Scottish Borders (Andrew McBride, Land and Habitats Consultancy); **Bottom-right image:** A backwater swamp in the floodplain of the upper River Dee in Aberdeenshire (Stephen Addy, The James Hutton Institute).

Preface

This CREW Combined Technical Appendices document informed the basis of the Main Report on *'Moderating extremes in water availability in Scotland: a review of the role of functioning wetlands'* (ISBN 978-0-902701-94-6) and a Policy Note that were commissioned by the Centre of Expertise for Waters (CREW).

This combined document consists of eight appendices:

- Appendix I – Definitions of Wetland Characteristics
- Appendix II – Water Holding Capacity of Wetlands
- Appendix III – Buffering Mechanisms
- Appendix IV – Wetland Health
- Appendix V – Key Aspects of Biodiversity (species, habitats and communities) Intrinsic to Wetlands
- Appendix VI – Climate Change Impacts
- Appendix VII – Biodiversity Impacts
- Appendix VIII – HOST-DSM of Wetlands in Scotland

Executive Summary

The overall aim of this project was to review the role of functioning wetlands in moderating extremes in water availability in a Scottish context. This was achieved by undertaking a comprehensive assessment of the current and future buffering capacity of Scotland's wetlands to high and low water flows. The four research questions (RQs) posed, and our key findings (KFs), given in the Main Report are summarised below:

RQ1: How do a broad range of wetlands in Scotland buffer extremes of water availability? What are the mechanisms for this and their relative importance?

- **KF1.1: Buffering capacity is wetland type-, health- and location-specific.**
    - The main buffering capacity mechanisms are the storage of water and the delayed movement of water out of a wetland.
    - They are controlled by the complex interaction of topography; hydrological connectivity to ground- and surface waters; soil type and condition, vegetation cover and surface roughness.
    - Seasonal variability of used and free water storage capacity is key to buffering.
    - Knowledge on the buffering capacity of the 18 specific wetland types considered was often limited, thus a cautious assessment was made. The majority were found to have limited buffering capacities for low and high flows when in a healthy state.
    - However, there are a number of wetland types that do provide good but variable high and/or low flow buffering capacity (Table E.1). These wetland types should be prioritised for appropriate restoration and management.

Table E.1 Wetland types with high and/or low flow buffering capacities rated "good", when in a healthy state.

High flow buffering	Low flow buffering
Wet meadows Fen meadows Alder and Fen wet woodlands Basin fens Transition grasslands	Floodplain fens Swamps Reedbeds
High and low flow buffering Floodplain fens Swamps Reedbeds	

- **KF1.2: Buffering capacity is catchment- and wetland-specific but improving total wetland extent through restoration and appropriate management can improve buffering capacity.**
    - Beyond prioritising those wetlands summarised in Table E.1, given the loss or poor health status of many wetlands, restoration and allowing expansion of all wetlands is expected to improve buffering capacity.
    - Depending on the hydrological connectivity and nature of the catchment, a greater total extent of healthy wetlands, potentially increases the high and low flow buffering capacity regardless of whether wetlands are riparian or isolated.
- **KF1.3: Site-specific monitoring is key to understanding buffering capacity of a particular wetland.**

RQ2: How is this buffering capability compromised when wetlands are degraded due to land use conversion or climate change?

- **KF2.1: Land use conversion, land use management and climate change have impacts across the full range of buffering mechanism controls.**
    - The exact impacts of such change on wetland buffering capacities are dependent on the site-specific nature of buffering mechanism controls and wetland health for which there is often insufficient data, knowledge and a lack of monitoring.
    - Knowledge on the impact of land use management on buffering capacity is greater than the impact of climate change; there are large uncertainties as to whether wetlands are more resilient to climate change than land management changes.
- **KF2.2: Due to climate change, there is likely to be greater variability in weather conditions, with altered seasonality and more frequent extremes of weather affecting wetlands.**
    - Water availability, particularly climate change-driven combinations of droughts followed by flooding are key sources of impact risk to wetland buffering capacity.
    - The future health of most types of wetlands is likely to decrease as a result of climate change if no remedial action is taken; eastern and southern Scotland are likely to see increased drying, whereas the north-west may become wetter. All locations are likely to experience both drier and wetter years.

RQ3: What are the impacts, caused by extremes of water availability, on the biodiversity of Scottish wetlands?

- **KF3.1: Wetlands provide a habitat for many of Scotland's rare species and are a major contributor to Scotland's biodiversity.**
    - Ninety-eight out of 700 species on the Scottish Biodiversity List in the two highest categories of concern "conservation action needed" and "avoid negative impacts", are associated with wetlands.
- **KF3.2: We have very limited ability to predict the impacts of hydrological change on wetland biodiversity.**
    - We lack comprehensive data on most species' niches as well as site-specific hydrological conditions.
- **KF3.3: We can identify wetland plant species at risk within each national vegetation community class and whether they are rare species.**
    - Most wetland vegetation communities possess some species at risk of being affected by increased dryness and some at risk of increased wetness.
- **KF3.4: Changes in vegetation communities can change the buffering capacity of wetlands (e.g., changes to *Sphagnum* cover).**

RQ4: Are there opportunities or potential changes in land or water management, which could enhance this buffering capability of wetlands in Scotland?

- **KF4.1: A favourable policy environment, Brexit-driven changes in funding mechanisms, and public and private sector organisations' management of natural capital assets could offer key opportunities in land or water management for enhancing wetland buffering capacity in Scotland.**
- **KF4.2: The active management of wetland water balances to maintain seasonal variability and expansion of wetland networks through restoration and allowing growth of existing wetlands, could help to improve resilience to climate change.**
    - Investment in local community employment to implement such activities. Our assessment suggests that prioritising efforts on for example floodplain fens, wet grasslands and deciduous wet woodlands may be more effective (Table E.1).

- **KF4.3: Key barriers to implementing potential changes in land or water management for enhancing wetland buffering capacity in Scotland were also identified, including:**
    - Significant requirements for funding, human resources, and monitoring.
    - Reaching agreements with landowners and other actors.
    - Conflicts between the achievement of different policy aims and/or climate mitigation strategies (e.g., wetland restoration, carbon sequestration, tree planting, food production and water management).

Recommendations

- Create, restore, and maintain networks of healthy wetlands at the catchment scale.
- Target additional funds, within and outwith designated sites, for restoration and maintenance of:
    - Wetlands that are less in the policy spotlight that nevertheless have the most potential to buffer low and high flows (Table E.1).
    - Wetlands in catchment areas that overlaps those areas vulnerable to flooding or droughts.
- Review the current system of Site Condition Monitoring with consideration to:
    - Focussing the new approach on wetland health and functional mechanisms.
    - Re-evaluating the current designated site series and its purpose.
- Complete the Scottish Wetland Inventory by:
    - Investing in site-specific wetland assessment and long-term monitoring.
    - Developing a network of representative reference wetlands across Scotland.
- Improve future projection and modelling capabilities to fill gaps in our understanding of impacts on the complex controls determining wetland buffering capacities.
    - For example, to better understand how key species, particularly *Sphagnum*, may respond to climate change.
- Raise the profile in policy documents of the capacity of wetlands to buffer low flows.

Contents

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Glossary

Alluvial. Sediment deposited by rivers.

Attenuation (in relation to hydrology). The reduction in flow peak height due to storage of water and slowing of runoff caused by hydraulic roughness.

Baseflow. Low magnitude flows in watercourses mainly supplied by groundwater that sustains water flow in drier periods between precipitation events.

Baseflow Index (BFI). A measure of the proportion of annual flow (0-1) that is contributed towards sustaining baseflows.

Base-poor. Indicates low pH wetlands, deficient in base cations; pH range 4.5-5.5.

Base-rich. Indicates high pH wetlands, rich in base cations and often bicarbonate; pH range 5.5 or above.

Basins. Basins are bowl-like depressions, but may differ considerably in shape, size, openness and topographical irregularity.

Blanket bog. Mire type of ombrotrophic peatland where the surface relief follows the underlying soil like a blanket.

Bog. A wetland that accumulates peat and is mainly fed by precipitation.

Bog woodland. Areas where woodland and bog co-exist. The tree growth is very slow, and the hydraulic function of the bog remains intact.

Bottom. Bottom is used mainly as a generic term for a range of topogenous situations (basins, flats, floodplains and troughs).

Community. An interacting group of various species in a common location, sometimes split up into parts such as "plant community".

Degraded. Condition of a bog with dysfunctional hydrology due to drainage, erosion, and management.

Digital Soil Mapping (DSM). DSM is a form of predictive mathematical or statistical modelling that relates information from soil maps and observations with their environmental covariates to produce maps of soil properties and soil functions.

Discharge. A measure of the volumetric flow rate of water in a watercourse. Typically measured in cubic metres per second.

Drift deposit. The material overlying solid bedrock in a landscape. Examples include glacial material or river deposited sediment (alluvium).

European Nature Information System (EUNIS). In the context of this report, it is used to describe the Habitat Classification system used in describing and mapping vegetation in a common framework across Europe.

Evapotranspiration. The loss of water from the earth's surface and vegetation to the atmosphere as vapour through both evaporation and transpiration.

Favourable Condition. A condition category relating to Site Condition Monitoring. The category relates to the good condition of the wetland community, but also absence of negative factors like tree encroachment.

Fen. A peatland that receives water that has been in contact with bedrock or mineral soil.

Floodplains. Floodplains are usually more or less flat valley-bottom surfaces alongside relatively mature watercourses which are episodically flooded by these.

Groundwater. Groundwater refers to water in, or sourced from, a bedrock or drift aquifer.

Headwaters. The smaller water courses in the upper part of a catchment.

Hydraulic conductivity. A measure of the rate of water movement through a material.

Hydrology. The study of the water cycle including rainfall, evapotranspiration, its storage within catchments and runoff.

Hydrological drought. Prolonged periods of low water availability in surface and groundwater arising from reduced water input (Meteorological drought) and drainage over proceeding months or years.

Hydrological wetland types. Wetlands are categorised into headwater or floodplain wetland hydrological types. Headwater wetland types are further subdivided depending on the presence or absence of hydraulic connectivity with groundwater or of direct outlet connectivity with the river network.

Hydrology of Soil Types (HOST). HOST is a soil hydrological classification devised to predict river flows at ungauged catchments in the UK based on the rate and pathways of water movement through the soil.

Hyper-oceanic. A climate in which there is little difference between the warmest and coldest months of the year – typically <10 degrees centigrade.

Indicator. Ecological indicators are used to reduce the complexity of ecosystems to communicate information, to aid in monitoring or to assist in making management decisions.

Kettle hole. A hollow resulting from the melting of a trapped mass of ice in glacial drift. The hollow fills with water and can become a wetland.

Lagg fen. A fen immediately adjacent to a raised bog and separating it from adjacent habitats with mineral substrates. Fed by a mixture of water from the bog and more minerotrophic water.

Meteoric water. Water of recent atmospheric origin, that is, direct precipitation.

Meteorological drought. Periods of reduced precipitation input to surface level and increased water loss due to evapotranspiration, usually over short periods (days, weeks) due to weather conditions. Contrast with Hydrological drought.

Minerotrophic water. Water containing nutrients derived from mineral soil.

Mire. A peatland where peat is currently being formed and accumulating.

National Vegetation Classification (NVC). A comprehensive classification and description of the plant communities of Britain, each systematically named and arranged and with standardised descriptions for each.

Niche. Ecological niche is a term for the position of a species within an ecosystem, describing both the range of conditions necessary for persistence of the species, and its ecological role in the ecosystem.

Oligotrophic. Low fertility, nutrient poor (not necessarily also base-poor).

Ombrotrophic. Where nutrient supply is derived from precipitation (rain, snow or mist), also referred to as rain-fed.

Peat. The remains of plant and animal litter accumulating under more or less water saturated conditions through incomplete decomposition. It is the result of anoxic conditions, low temperatures, low decomposability of the material and other complex causes.

Peatland. A peat-covered terrain. In Scotland the minimum depth of peat is required for a site to be classified as peatland is 50cm.

Permeability. A measure of the ease at which water can flow through a material.

Poor fens. Fens where the water is derived from base-poor rock such as sandstones and granites occur mainly in the uplands, or are associated with lowland heaths. They are characterised by short vegetation with a high proportion of bog mosses *Sphagnum* spp. and acid water (pH of 5 or less).

Porosity. A measure of the void or empty spaces available within a material that can influence the movement and storage of water.

Precipitation. The transfer of water from the Earth's atmosphere in the form of rainfall, hail, sleet, snow or as occult precipitation (dew, hoar frost, fog, cloud or rime).

Quagmire, quaking mat, floating mat, schwingmoor. Peat-forming vegetation floating on water. Often with a *Sphagnum* or brown moss covering but held together and kept afloat by the roots and rhizomes.

Rich fens. Fens which are fed by mineral-enriched calcareous waters (pH 5 or more) where there are localised occurrences of base-rich rocks such as limestone in the uplands. Fen habitats support a diversity of plant and animal communities.

Riparian. An area of land including the riverbank that is close to a watercourse.

Roughness. A measure of the resistance to water movement over the earth's surface and within watercourses.

Runoff. The movement of water over land surfaces and down watercourses.

Scottish Biodiversity List (SBL). A list of animals, plants and habitats that Scottish Ministers consider to be of principal importance for biodiversity conservation in Scotland.

Soligenous wetlands. Wetlands which occur on sloping ground, where water supply from precipitation, surface runoff or groundwater inflow exceeds the outflow rate. Water movement is predominantly lateral through the soil or discharging from the rock, such as spring fens or flushes.

Standard Percentage Runoff (SPR). The % of rainfall expected to occur as surface runoff in a rainfall event.

Substratum. The layer of soil beneath the wetland.

Telluric water. Telluric water refers to water that has been in contact with mineral soil. It encompasses (most) groundwater and surface water.

Terrestrialisation. The transition of a wetland from wet ground to dry ground, which occurs as the wetland infills with material or drainage patterns change diverting water away from the wetland.

Throughflow. The movement of water through the soil.

Topogenous wetlands. Wetlands which occur where water collects on flattish ground or in hollows. Topogenous wetlands are maintained by retention of precipitation, surface runoff or groundwater. Water movement is predominantly vertical and overland, resulting in water ponding in depressions such as valleys, basins and floodplains.

UKCP18. Climate projections for the UK produced by the Meteorological Office in 2018.

Water table. The level to which water will rise in a hole in the peatland, i.e. the upper surface of the groundwater.

Wetland health. Through observation and monitoring of the current wetland structure and function, provides an indication of a state where vital functions are performed normally.

Wetland mosaic. An area of wetland containing complex of many different wetland vegetation types.

Note: Key wetland glossary definitions sourced from (Bruneau and Johnson, 2014; Rydin and Jeglum, 2013; Acreman et al., 2011; McBride et al., 2011).

1. Appendix I: Definitions of Wetland Characteristics

by Gillian Donaldson-Selby and Stephen Addy

0.1 Research questions

The key research question that this appendix sought to answer were:

- *What is meant by wetland and the different hydrological wetland types?*
- *What are the water supply mechanisms?*
- *What are the different characteristics of wetland habitats in Scotland?*
- *What are their physico-ecological supporting conditions?*
- *What are the possible habitat conversion trajectories of these wetlands resulting from land use change and other factors?*

0.2 Objective

To undertake a literature review to provide the project's working definitions of wetland types and the water balance, as well as to present an introductory overview of the different habitats within the typology of wetlands, describing their key characteristics and, where available, information about the form of land use which may be found on them.

This objective also prepares the ground for the estimation of wetland health as covered in Appendix IV. It also includes discussion of what is meant by a degraded or healthy wetland by gathering information from the literature on possible habitat conversion trajectories (transitions) for each of the wetland habitats. This identifies drivers of wetland degradation as well as possible consequences, for example, in terms of transitions in species composition and habitat.

0.3 Approach and structure

The literature research used search engines (Google Scholar, WOS etc.) and collated/summarised an initial selection of scientific literature as well as the SEPA-commissioned report on water supply mechanisms (SNIFFER, 2014). It has also made use of grey, non-peer reviewed research that, although preliminary and less certain, provides valuable new knowledge.

Section 1 provides introduction on wetland concepts. It provides the project's working definitions of wetlands and of the five hydrological wetland types that have been adopted to categorise the broad range of wetland habitats upon which the project focuses. The section concludes by introducing the approach to wetland water balance calculations.

Thereafter, in Section 2, information from a large body of literature has been compiled for each specific wetland habitat grouped according to hydrological wetland types:

- Characteristics
- Land uses found in the habitat
- Possible habitat conversion trajectories

This Appendix concludes with:

- A list of knowledge gaps
- References

1. An overview of wetlands and hydrological wetland types

1.1 Defining wetlands

The UNESCO Convention on Wetlands, otherwise known as the Ramsar Convention, defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". It notes that "wetlands include a wide variety of inland habitats such as marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves, intertidal mudflats and seagrass beds, and also coral reefs and other marine areas no deeper than six metres at low tide, as well as human-made wetlands such as dams, reservoirs, rice paddies and wastewater treatment ponds and lagoons" (Ramsar Convention Secretariat, 2016,p9).

Although wetlands may occur in a wide range of landscapes, a common feature is the saturation or waterlogging of their substratum for all or part of the year. Waterlogging occurs either when water movement is either impeded by impermeable layers or when an underlying aquifer forces it to rise (Acreman et al., 2011). Wheeler and Shaw (1995) observe that waterlogging occurs in three main conditions of water source and topography:

- Topogenous wetlands occur where water from precipitation, surface runoff or groundwater is retained in hollows (Figure 1).
- Soligenous wetlands occurs on sloping ground where inflow from precipitation, surface runoff or groundwater exceeds outflow (Figure 2).
- Ombrotrophic wetlands are exclusively fed by direct precipitation (Figure 3).

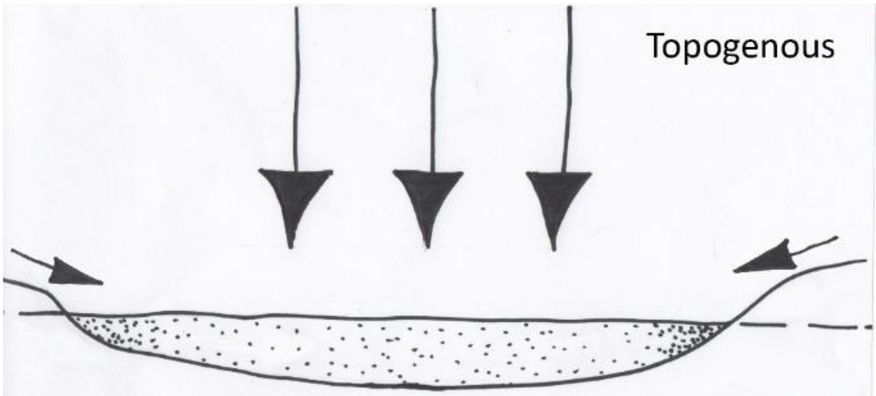


Figure 1. Water source in a topogenous wetland (E. Donaldson-Selby).

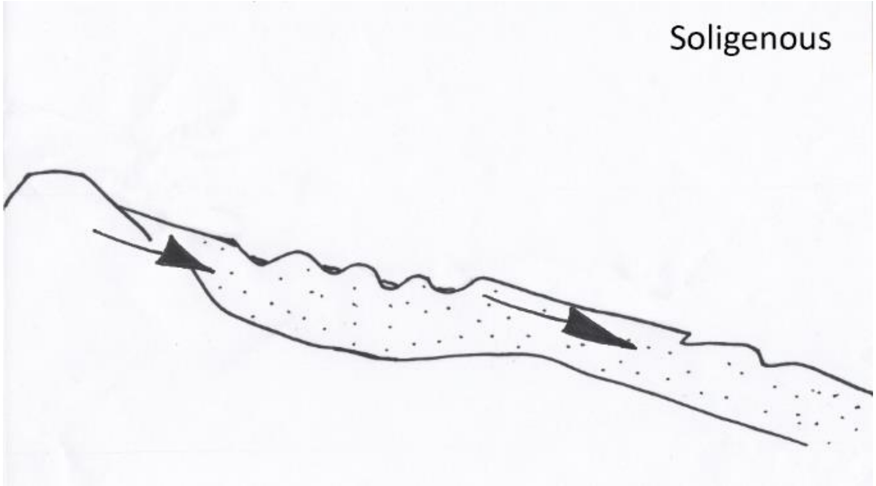


Figure 2. Water source in a soligenous wetland (E. Donaldson-Selby).

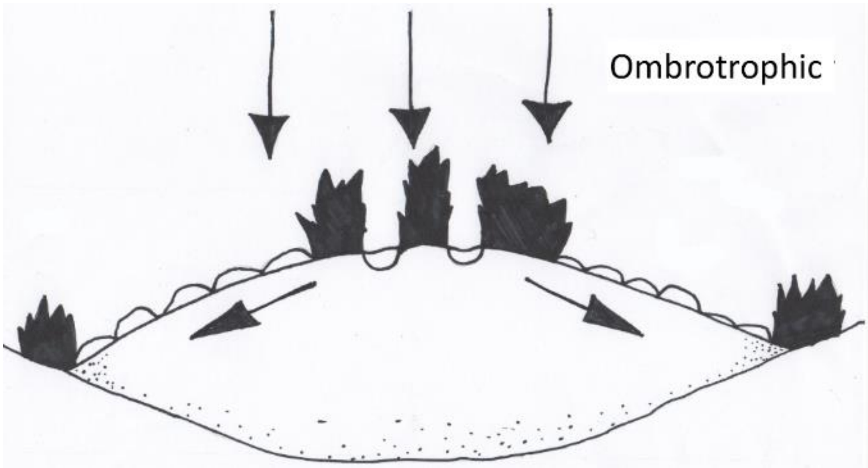


Figure 3. Water source in an ombrotrophic wetland (E. Donaldson-Selby).

Water is the primary factor controlling the environment and the associated plant and animal life. Mitsch and Gosselink (2015, p112) note that hydrology is the "single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes". Hydrology influences physical and chemical properties including:

- soil and water salinity
- nutrient availability
- soil oxidative state
- sediment dynamics

As well as substrate characteristics such as:

- texture
- pH

Hydrology also influences ecological aspects of wetland ecosystems for example the depth and duration of water inundation determines the type, extent, and distribution of wetland vegetation communities. In turn the type and health of the wetland vegetation has implications for the hydrology of the wetland.

1.2. Hydrological wetland types

Bullock and Acreman (2003) thus categorise wetlands into five types, based on three broad hydrological features:

- General catchment location (headwater vs floodplain)
- Connectivity to water sources
- Connectivity with downstream channels

In Section 2, we describe each wetland habitat's fit to these hydrological categories.

1.2.1 Surface water slope

Physico-ecological supporting conditions

Surface water slope wetlands occur on fairly flat and gentle slopes and are generally associated with headwaters (Figure 4). Their water source inputs include rainfall and snowfall, and they are not fed by stream sources or groundwater. There is direct outlet connectivity with the river system (Bullock and Acreman, 2003; Acreman et al., 2011).

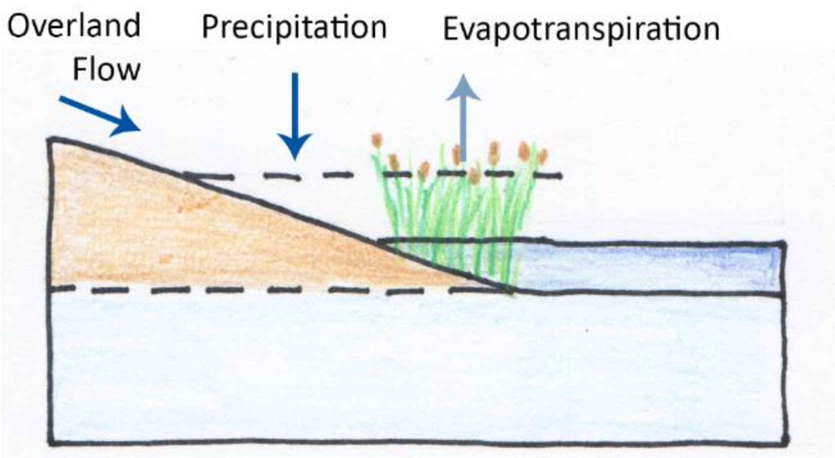


Figure 4. Surface water slope (S. Donaldson-Selby). Adapted from Cooper and Merritt (2012).

1.2.2 Surface water depression

Physico-ecological supporting conditions

Surface water depression wetlands occur where precipitation and overland flow are collected in a ground depression (Figure 5) and may be found in uplands and lowlands. There is limited or no hydraulic connectivity with groundwater and no surface water outlet. The water table is usually below the ground level of the wetland. Water may only leave by ground infiltration and/or evaporation/transpiration (Bullock and Acreman, 2003; Acreman et al., 2011).

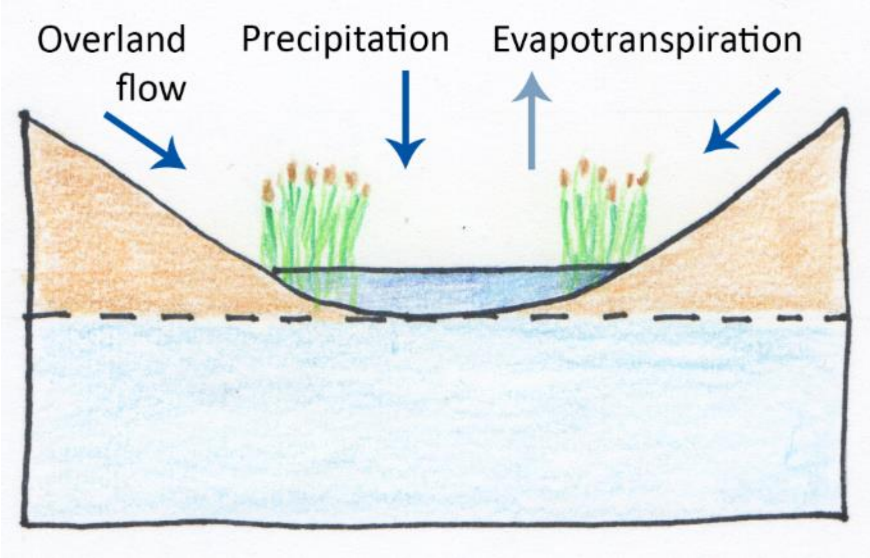


Figure 5. Surface water depression (S. Donaldson-Selby). Adapted from Cooper and Merritt (2012).

1.2.3 Groundwater depression

Physico-ecological supporting conditions

Groundwater depression wetlands occur in surface depressions that connect with the groundwater table (Figure 6) and are usually found in the lowlands. Their water sources include precipitation, runoff and groundwater inflows. There is little or no surface drainage away from the wetland or connectivity with the river system (Bullock and Acreman, 2003; Acreman et al., 2011).

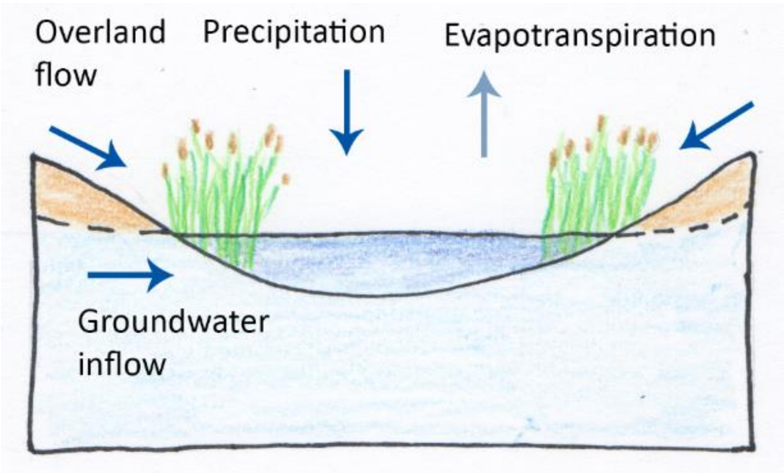


Figure 6. Ground water depression (S. Donaldson-Selby). Adapted from Cooper and Merritt (2012).

1.2.4 Groundwater slope

Physico-ecological supporting conditions

Groundwater slope wetlands occur where geological conditions restrict the downward flow of water (Figure 7) and are usually found in the uplands. There is hydraulic connectivity with the groundwater which discharges as springs into the wetland. Water sources may also include precipitation and overland flow. Water from the wetland may flow from the downslope of the wetland. There is direct connectivity with the river system (Bullock and Acreman, 2003; Acreman et al., 2011).

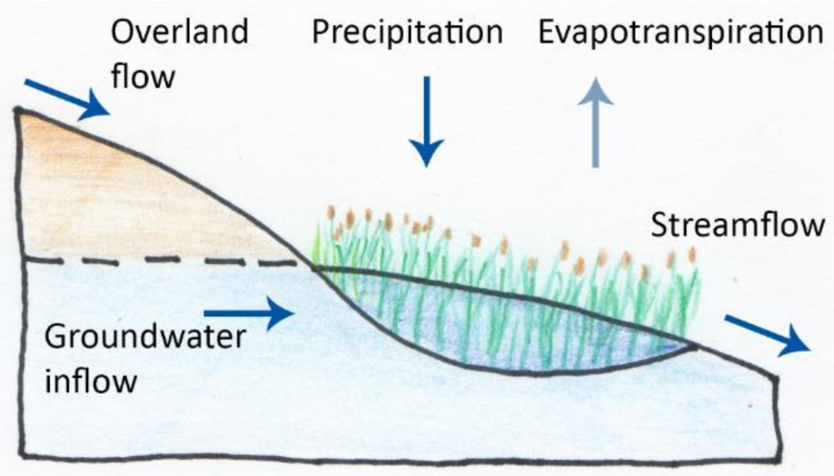


Figure 7. Ground water slope (S. Donaldson-Selby). Adapted from Cooper and Merritt (2012).

1.2.5 Floodplain

Physico-ecological supporting conditions

Floodplain mires occur on relatively flat valley-bottom surfaces alongside major, mature watercourses and are episodically flooded through overspill from the watercourse (Figure 8). Water Inputs are dominantly upstream river flows. They are predominantly topogenous with a high water table maintained primarily by the topography of the site (Wheeler, 1984; Bullock and Acreman, 2003; Wheeler, Shaw and Tanner, 2009).

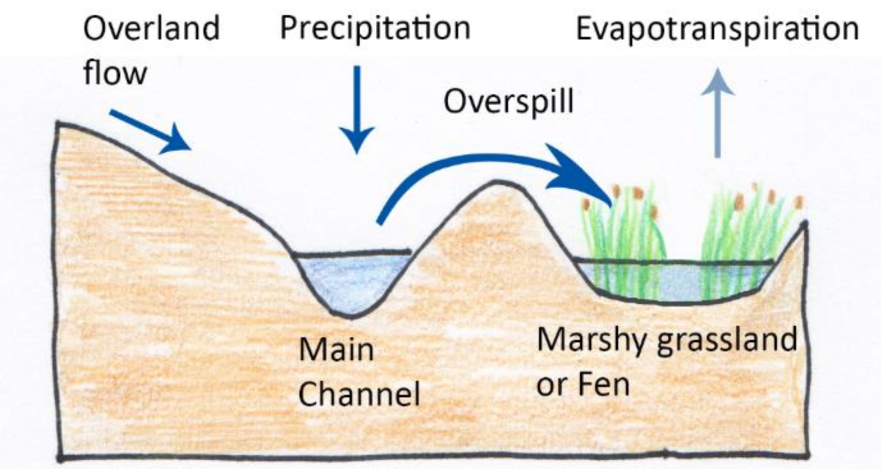


Figure 8. A floodplain system (S. Donaldson-Selby). The height of ground between main channel and fen has been deliberately exaggerated.

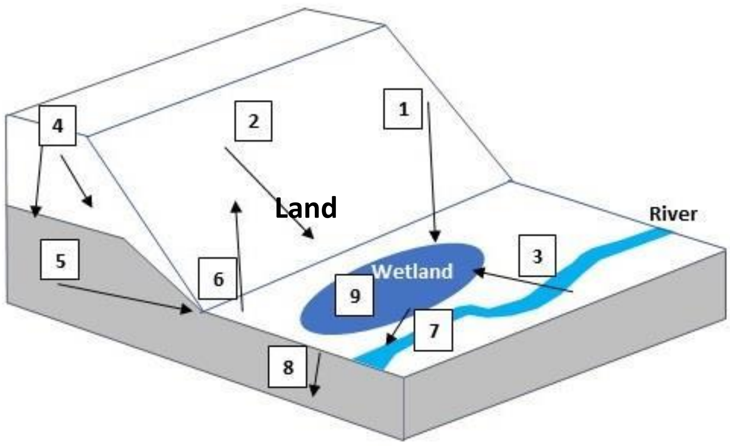
1.3 Calculating wetland water balances

The volume of surface and sub-surface storage of water in a wetland will vary depending on the relative contribution of inflows and outflows of water (Figure 9). Understanding the nature of these fluxes is central to determining the water balance or change in net water storage. Quantifying water balance is a commonly used tool to evaluate the hydrology of ecosystems (Baker, Thompson and Simpson, 2009). It conveys the relationship between hydrological inputs and outputs, facilitating a determination regarding the increase or decrease of water within a wetland as well as the underlying hydrological processes responsible for the changes (Baker, Thompson and Simpson, 2009). The water balance of a freshwater wetland can be expressed in the following equation (Baker, Thompson and Simpson, 2009):

$$\Delta S = (P_I - I_O) + O_I + U_I + I_I + G_I - ET_O - O_O - C_O - G_O$$

Where:

ΔS is change in storage within the wetland
P_I is precipitation directly onto the wetland
I_O is water intercepted by and subsequently evaporated from vegetation within the wetland
O_I are inputs from overland flow (both infiltration-excess and saturation-excess)
U_I are inflows from the unsaturated zone
I_I is inundation from water bodies (e.g., sea, rivers, lakes and estuaries)
G_I are groundwater inflows from the saturated zone
ET_O is evaporation from open water and the soil and transpiration from wetland vegetation
O_O are outflows via overland flow
C_O are outflows carried within channels
G_O are outflows resulting from seepage and groundwater recharge beneath the wetland
$H_{I/O}$ are any inflows and outflows resulting from human activities



Inputs	Outputs	Storage
1 – Precipitation (P_I)	6 – Evapo- transpiration (ET_O)	9 – Water storage areas (ΔS)
2 – Overland flow (O_I)	7 – Overland flow (O_O)	
3 – Inundation (I_I)	8 – Groundwater recharge (G_O)	
4 – Subsurface stormflow (U_I)		
5 – Groundwater discharge (G_I)		

Figure 9. The water balance of a wetland (based on Baker, Thompson and Simpson, 2009).

Where inputs exceed outputs, water is stored either in the wetland soils and/or on the surface. Where outputs exceed inputs there is a net loss of water from the wetland and the water table drops below the surface (Tiner, 2016). All wetlands are affected by direct input via precipitation and outflow via evapotranspiration. However, other inflow and outflow processes, and their relative influences, varies both spatially and temporally. Spatial variations depend on differences of landscape position, topography, geomorphology, hydrological connectivity, soil and vegetation across a landscape. Temporal variations for example over a year, may occur due to the seasonality of precipitation, evapotranspiration and river flooding. Over longer timescales (e.g. annual or decadal) temporal variations may occur as a result of alternating flood rich and flood poor periods observed in the UK and Europe (Pattison and Lane, 2012). Longer term changes in climate or land use can also affect wetland hydrology and can lead to changes in type, associated vegetation communities and, or characteristic functioning. Although wetland types can be broadly differentiated by differences in hydrology, within a single wetland type there can be considerable variation in one or more of the variables determining its water balance (Baker, Thompson and Simpson, 2009). This means the hydrological functioning of a wetland is site specific.

2. Characteristics and habitat trajectories of wetland habitats

The wetland habitat types considered in this project and their relationship to the existing broader hydrological classification of Bullock and Acreman (2003) and broad landscape position classes are summarised in Table 1. In total 18 wetland habitat types relevant to Scotland were considered. These are grouped according to four landscape locations: upland wetlands, lowland wetlands, wet woodlands and wet grassland/floodplain meadows.

Table 1. Wetland habitat types considered in this study in relation to hydrological wetland type (Bullock and Acreman, 2003) and landscape position.

Lowland Wetlands	Hydrological wetland type
Raised bogs	Surface water depression
Transition Mires and quaking bogs	
Open water transition fens	
Base-rich fens	Groundwater slope
Reedbeds and swamps	
Basin fens	Groundwater depression
Floodplain fens	Floodplain

Upland Wetlands	Hydrological wetland type.
Blanket bog	Surface water slope
Wet heath	
Depressions on peat substrates of the *Rhynchosporion*	Surface water depression
Base-rich fens, alkaline fens	Groundwater slope

Wet Woodlands	Hydrological wetland type.
Fen woodland	Groundwater depression; Groundwater slope; Floodplain
Alder woodland	
Bog woodland	Surface water slope

Wet grassland/flood plain meadow	Hydrological wetland type
Fen meadow	Groundwater slope; Floodplain
Wet meadows, marshy grassland	Floodplain
Transition grasslands	
Transition saltmarsh	

2.1 Upland Wetlands: Surface water slope

2.1.1 Blanket bog

Characteristics

Blanket bogs (ombrotrophic peatlands) are the most common form of upland peatland in Scotland and hyper-oceanic areas of the world. They can also be found in the lowlands in northern Scotland.

They initially begin development in concave hollows and gentle convex crests and gradually spread, following the underlying topography of the landscape like a blanket (Figure 10). Blanket bogs can occur on g slopes of up to 35° in the north-west Highlands. Blanket bogs are dependent on precipitation (rainfall, snow and mist) and require that an equilibrium must exist between the supply of water by precipitation, lateral drainage and evapotranspiration (Bragg, 2002; SNIFFER, 2014). Blanket bog develops through a mixture of paludification and infilling and may, in time, incorporate other types of peatlands such as basin and raised bogs. Threshold climatic conditions for the formation of blanket bogs is high rainfall (>1000mm p.a., >160 rain days p.a.), limited seasonal variability, a mean temperature < 15°C in the warmest month (limiting evaporation), and impeded drainage (Lindsay et al., 1988; Tallis, 1998; SNIFFER, 2014).

Figure 10. Blanket bog at Balmoral Estate in Aberdeenshire (G. Donaldson-Selby).

Land uses found on blanket bog

Land uses found on blanket bog may include: forestry (coniferous trees such as Sitka Spruce and Lodgepole Pine), sheep grazing, wild harvest products (venison and grouse), limited peat extraction (horticulture), recreation (wildlife watching, hiking, and fishing) (Worrall et al., 2010; Bruneau and Johnson, 2014; Thom et al., 2019).

Habitat conversion trajectories

Blanket bog habitat may be negatively affected by burning, drainage, pollution, poaching, peat extraction and climate change. This can result in changes in species composition (disappearance of dwarf shrubs and *Sphagnum*) towards wet heath, dry heath, swamp, fen, bog woodland, wet woodland, dry scrub, marshy grassland, montane grassland and bare eroded peatland (Table 2)

(Ramchunder, Brown and Holden, 2009; Bruneau and Johnson, 2014). Increased winter rains may then lead to stripping of the peat, bog bursts and peat slides (Evans and Warburton, 2007). With changes in species composition the peatland may change from a carbon (CO_2) sink to a carbon source.

Table 2. Possible trajectories for blanket bog in the event of drainage, erosion, peat cutting, lowered water tables, excessive grazing or increased nutrition. Adapted from SNIFFER (2014).

	Cause			
	• Severe erosion removing all or most bare peat	• Drainage • Peat cutting to mineral floor • (increased nutrition)	• Lowered water table followed by scrub and tree invasion	• Drainage • Chronic excessive grazing • Increased nutrition
Resulting habitat conversion	• Wet Heath • Dry Heath	• Swamp • Fen • Wet heath[1]	• Bog Woodland, • Other Wet Woodland • Dry Scrub / Woodland	• Marshy Grassland • Montane Grassland

2.1.2 Wet heath

Characteristics

Wet heath usually occurs on gently sloping, acidic, shallow peats (< 500 mm) or sandy soils with impeded drainage, resulting in seasonal waterlogging. The water table is near ground level for a part of the year. *Erica tetralix* tends to be the dominant species, rather than heather (found in dry heath), as well as sedges and *Sphagnum* (Figure 11). Wet heath are typically found in the north and west of the United Kingdom at altitudes of 177m to 290m, rising to >500 m in the Cairngorms (SNIFFER, 2014), requiring a rainfall of between 1200mm to 1600mm per annum (Holden et al., 2007; Hampton, 2008; Wheeler, Shaw and Tanner, 2009; SNIFFER, 2009a; SNIFFER, 2009b; Rydin and Jeglum, 2013; Bruneau and Johnson, 2014; SNIFFER, 2014).

[1] Expert opinion from PSG member D. Spray, 22 September, 2021.

Figure 11. Wet heath, at Gartly in Aberdeenshire (Andrew McBride).

Land uses found on wet heath

Land use on wet heath may include: forestry, livestock, recreation (hiking, and mountain biking), wild harvest products (venison and grouse) and construction (roads, buildings and wind farms) (Hampton, 2008; SNIFFER, 2014).

Habitat conversion trajectories

Wet heath habitat may be negatively affected by burning, drainage, pollution, poaching, peat extraction, climate-change induced temperature changes, changes in hydrological characteristics, and alteration of water chemistry. This can result in changes in species composition (disappearance of dwarf shrubs and *Sphagnum*) towards dry heath, woodland, peat bog, acidic / neutral grassland, bare peat, and eroded peat (Table 3; Hampton, 2008). SNIFFER (2014) observes that management for livestock and game (including burning) prevents wet heath from reverting to blanket bog or wet woodland.

Table 3. Possible trajectories for wet heath in the event of lowered water tables, insufficient or excessive grazing, raised water tables, or increased nutrition. Adapted from SNIFFER (2014).

	Cause					
	• Lowered water table	• Lack of grazing or burning • Excessive grazing or burning	• Increased nutrition	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition
Resulting habitat conversion	• Dry Heath	• Molinia dominated Wet Heath • Woodland • Erosion and Dry Heath	• Other Marshy Grassland	• Peat Bog	• Dry Heath • or very Acidic Grassland	• Acidic or Neutral Grassland

2.2 Upland Wetlands: Surface water depression

2.2.1 Depressions on peat substrates of the Rhynchosporion

Characteristics

Depressions on peat substrates of the *Rhynchosporion* (Figure 12) occur in complex mosaics on humid, exposed peat on:

- the edges of lowland wet-heath seasonal bog pools;
- the patterned areas of valley mire;
- transition mires;
- the stripped areas and margins of bog pools and hollows in both raised and blanket bogs.

The typically open vegetation is characterised by the presence of:

- *Rhynchospora alba*
- *Sphagnum denticulatum*
- *Drosera rotundifolia*
- *Drosera intermedia*
- *Drepanocladus revolvens*
- *Scorpidium scorpioides*
- *Rhynchospora fusca*
- *Lycopodiella inundata*
- *Sphagnum cuspidatum*
- *Sphagnum pulchrum*
- *Drosera anglica*

And the absence of:

- *Molinia caerulea*
- *Trichophorum cespitosum*

(Joint Nature Conservation Committee, 2002b; European Commission: DG Environment, 2013; Mountford, 2018)

Figure 12. Depressions on peat substrates with *Rhynchosporion* at Methven Moss, Perth and Kinross (Andrew McBride).

Land uses found on depressions on peat substrates of the Rhynchosporion

No literature found. It occurs as a mosaic within more extensive/widespread habitats e.g. blanket bog, and is therefore subject to the management regimes/pressures acting on those - rather than being managed separately.

Habitat conversion trajectories

Depressions on peat substrates of the *Rhynchosporion* habitat may be negatively affected by air pollution, anthropogenic changes in hydraulic conditions, under- or overgrazing, invasive non-native species, fire and fire suppression (Countryside Council for Wales, 2011; Joint Nature Conservation Committee, 2013). No table of information was available from SNIFFER regarding possible trajectories.

2.3 Upland and lowland Wetlands: Groundwater slope

2.3.1 Base-rich / Alkaline fens

Characteristics

Base-rich fens are primarily fed by mineral-enriched calcareous groundwater and/or surface water, and are mainly confined to lowland and upland areas of base-rich rock (e.g. limestone). They are more limited in extent than acidic bogs but may be extensive around water bodies fed by base-rich catchments (e.g. spring-fed fens, flushes, basin fens, soligenous track and soakaways). Their hydrochemistry includes high calcium and magnesium and potassium cations with a pH >5.5, produced by the surface or ground water, while poor in nitrogen and phosphorus nutrients. Development of base-rich fens is in permanently waterlogged soils with minimal water level fluctuation. As in poor fens, the water level is at or near the surface of the substratum and peat formation depends on a permanently high water table. Vegetation includes a wider variety of plant - herbs, calcicolous sedges and 'brown' mosses (*Palustriella commutate*) - and animal communities than those fens fed by base-poor water. *Sphagnum* mosses are often, but not always, absent. Communities may vary widely between fens. They are extremely species-rich (Figure 13) , accounting for a third of UK native flora, > a half of UK dragonfly species, thousands of other insect species, and are an important habitat for aquatic beetles (Wheeler and Proctor, 2000; Joint Nature Conservation Committee, 2002c; Šefferová, Šeffer and Janák, 2008; McBride et al., 2011; SNIFFER, 2014; Diack et al., 2018; European Environment Agency, 2019).

Figure 13. Base rich Fen at Murder Moss, Scottish Borders (Andrew McBride).

Land uses found on base-rich/alkaline fens

Base rich fens often occurs within a mosaic within more extensive habitats and is therefore subject to the management regimes and pressures acting on those.

Habitat conversion trajectories

The loss of a healthy base-rich fen habitat can be observed in a change in species composition to scrub and woodland, which may result from a lack of management or cessation of traditional practices, or eutrophication caused by runoff of agricultural fertilisers and herbicides. Appropriate management, including grazing and cutting, can control the succession of rank species. Water abstraction may lead to lowered water tables thereby causing either a) drying out and desiccation of the fen habitat or b) inflow from other water sources, exacerbating eutrophication and fluctuating water levels (Šefferová, Šeffer and Janák, 2008; McBride et al., 2011). The current state of many Scottish fens is as a result of traditional land use, including seasonal grazing and mowing (SNIFFER, 2014).

2.4 Lowland wetlands: Surface water depression

2.4.1 Raised bogs

Characteristics

Raised bogs usually occur in lowland areas on wet floodplains, basins or depressions. They can be recognised by their convex surface (Figure 14). They often develop above minerotrophic fen peats, forming an ombrotrophic surface in the centre. They may also form upon sections of blanket bog. Where there is sufficient and regular precipitation, slower decomposition rates and faster peat development occurs in the wetter centre, thereby raising the vegetation above surface water and groundwater, in some cases approaching 10 metres above the surrounding landscape. Eventually the entire surface becomes exclusively rainfed, with different growth rates (higher in the centre, lower on the edges), to form a dome or raised bog. Surface and groundwater from the fairly level bog centre drains across the shoulder (rand) of the bog to the thinner margins of the bog (lagg), where nutrients from underlying mineral soils and minerotrophic groundwater support fen vegetation (lagg fen). The lagg may also contain a swamp habitat. Raised bogs require precipitation >475mm per annum (Wheeler and Shaw, 2000; Lindsay, 2010; Bruneau and Johnson, 2014; SNIFFER, 2014; Thom et al., 2019).

Raised bog in Scotland originally covered about 95,000 Ha, approximately 5% of the total UK bog area. Lowland raised bogs are now in decline (SNIFFER, 2014). Gallego-Sala et al. (2016) note that a survey of Scottish lowland bogs showed that of those raised bogs considered restorable:

- Almost all had been damaged
- 97% had been affected by ditches
- 74% had been affected by substantial areas of woodland, planted up until the 1980s
- 9% were subject to commercial peat cutting for horticulture and fuel

Figure 14. Lowland raised bog at Threepwood Moss, Scottish Borders (Andrew McBride).

Land uses found on raised bogs

Substantial areas of lowland raised bogs have been converted to forestry, cropland, or improved grassland for forage. Lindsay and Immirzi (1996) observe that the greatest proportion of habitat change to raised bogs is the result of agricultural land conversion. Those bogs used for arable or root crops are usually subject to deeper drainage than those used for grass production. Often the peat has been stripped rather than just drained. For example, near Stirling, where the area of a raised bog was once much more extensive[2]. In many cases the lagg fen is no longer present – with the land drained and agricultural land extending right up to the edge of the bog[3]. Lowland bogs continue to provide peat for the horticultural and whisky industry, and in the past have supplied peat for heating. The Scottish Government have committed to the cessation of peat extraction for horticulture. Although Scottish Government policy on new planting on deep peat has changed, there are still extensive areas of commercial forestry on raised bog. Where lowland peat cuttings have been abandoned the bogs have developed into scrub or heath or filled with water (Lindsay, 2010; Maltby et al., 2011; Aspinall et al., 2011; Bruneau and Johnson, 2014).

Habitat conversion trajectories

The loss of a healthy raised bog habitat can primarily be observed in the diminishment and deterioration of the characteristic peat dome, caused by the deep drainage required both for agriculture and mechanized peat extraction. When drained, the peat consolidates and desiccates, creating macropores which further increases downward seepage, leading to oxidation. Vegetation

[2] Expert opinion from PSG member D. Spray, 22 September, 2021.
[3] Expert opinion from PSG member D. Spray, 22 September, 2021.

composition (dwarf shrubs and *Sphagnum*) may become dominated by *Molinia* or *Calluna*[4] species, or give way to bare peat (Regan et al., 2019).

2.5 Lowland wetlands: Groundwater slope

2.5.1 Transition mires and quaking bogs

Characteristics

Transition mires form in areas of high groundwater input, surface water fed basins, and in floodplain settings (e.g. the Insh marshes on Speyside), and at the edge of bogs and valley fens[5]. Vegetation and ecology are transitional between fen and bog, and surface conditions can range from acid bog to base-rich fen. They are often associated with level, static open waters with a characteristic high-water table. Floating mats of vegetation may form around the edge of the open water which are very unstable – giving rise to the term 'quaking bog' (Figure 15). If the mat encloses the entire water surface it may be known as a *schwingmoor.* Well-developed examples will exhibit large, bryophyte-dominated, ombrotrophic hummocks, and hollows with minerotrophic dominated species, which give rise to the transitional bog hydrochemistry. Where the vegetation mat overlies water, the bog will rise and fall with fluctuating water levels, whereas if it overlies peat vertical movement will be limited. Transitional and quaking mires can be found in the Scottish Highlands, Perth and Kinross, and Scottish Borders (Wheeler and Proctor, 2000; Joint Nature Conservation Committee, 2002a; McBride et al., 2011; Kimberley and Coxon, 2013; European Commission: DG Environment, 2013; SNIFFER, 2014; Lindsay, 2016;).

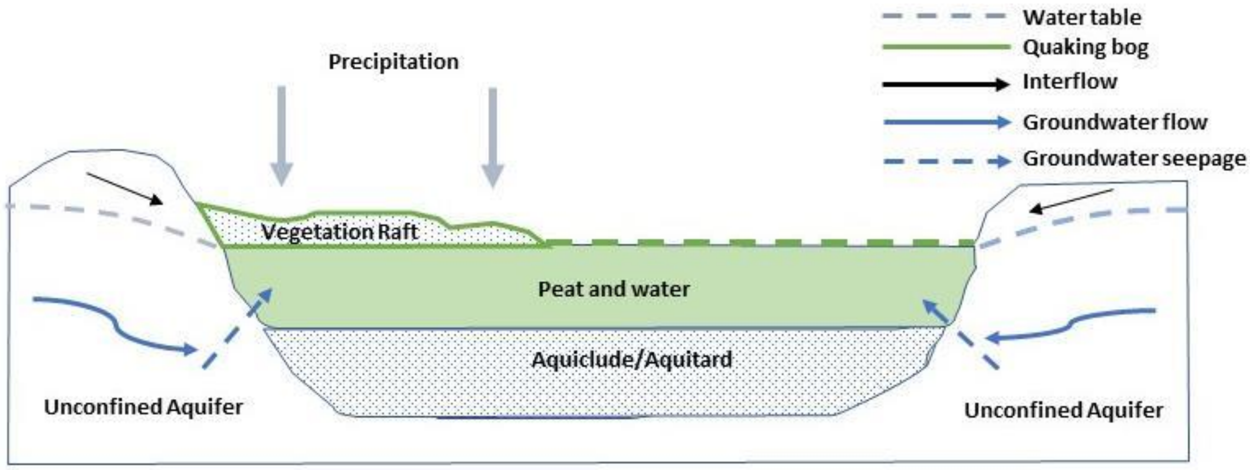


Figure 15. Conceptual model of a quaking bog (based on SNIFFER, 2014).

Land uses found on transition mires and quaking bogs

Quaking bogs may often be managed as part of a wider management unit, thus management outside the extent of this particular wetland may affect it. For example, where it is unmanaged, livestock may graze the drier edges.

Habitat conversion trajectories

Transition mire and quaking bog habitat may be negatively affected by lowered water tables, excessive grazing, increased nutrient levels, and increased acidity. This can result in changes in species composition towards fen, swamp, open water, peat bog, poor fen, or rich fen (Table 4). Quaking bog

[4] Expert opinion from PSG member D. Spray, 22 September, 2021.

[5] Expert opinion from PSG member D. Spray, 22 September, 2021.

is the dominant habitat in the Insh marshes, which is most likely strongly influenced by summer groundwater flooding (Grieve, Gilvear and Bryant, 1995; SNIFFER, 2014).

Table 4. Possible trajectories for transition mires and quaking bogs in the event of lowered water tables, insufficient or excessive grazing, raised water tables, or increased nutrition. Adapted from (SNIFFER, 2014).

	Cause					
	• Lowered water table	• Excessive grazing	• Increased nutrients	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition
Resulting habitat conversion	• Loss of floating rafts • Other wet woodland	• Fen	• Fen	• Swamp • Open water	• Peat bog • Poor Fen	• Rich Fen

2.5.2 Open-water transition fens

Characteristics

Open-water transition fens develop where the groundwater table creates level and relatively static open water bodies such as lakes, oxbow lakes, pools and reservoirs (Figure 16). They are widespread in Britain. Open-water transition fens and basin fens are similar but differ in that the proportion of water in open-water transition fens is greater than that of basin fens. Peat-forming vegetation may establish on the fringes of the water body and gradually infill the basin. Upland open-water transition fens are generally base-poor, while those in lower catchments may be base-rich, depending on the underlying bedrock and mineral base (Joint Nature Conservation Committee, 1989; Wheeler, 1984; SNIFFER, 2014; Lindsay, 2016).

Figure 16. An open water transition fen Kilconquhar Loch, Fife (Andrew McBride).

Land uses found on transition fens

Drained open-water transition fens may be used for agriculture – primarily grazing for animals.

Habitat conversion trajectories

Open-water transition fen habitat may be negatively affected by changes in water level, and eutrophication caused by nutrient enrichment. Water abstraction may either lead to a) lowered water tables thereby causing inflow from other water sources thereby causing acidification or eutrophication, or b) desiccation and oxidation of the peat. This can result in changes in species composition to marshy grassland, wet woodland, degraded fen, poor fen to rich fen, swamp or reedbed, or open water (Table 5; Šefferová, Šeffer and Janák, 2008; McBride et al., 2011).

Table 5. Possible trajectories for open-water fens in the event of lowered water tables, poor or excessive grazing, raised water tables, increased acidity or increased nutrition. Adapted from SNIFFER (2014).

	Cause					
	• Lowered water table	• Poor grazing management • No grazing • Excessive grazing	• Increased nutrition	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition

Resulting habitat conversion	• Marshy grassland • Other wet woodland	• Other wet woodland • Degraded Fen	• Poor Fen to Rich Fen	• Swamp or Reedbed • Open water	• Rich Fen to Poor Fen • Marshy Grassland • Wet Heath	• Marshy Grassland • Other wet woodland

2.5.3 Reedbeds

Characteristics

Natural reedbeds require standing water and can be found next to or near streams, lochs, floodplains, canals, basins and valley bottoms, often in swamp-like settings. The dominant species is the common reed *Phragmites australis.* Where reedbeds are adjacent to rivers or lochs, surface water is the dominant water source, and may be inundated during high river or loch levels. The dominant water source for reedbeds situated in basins or valley bottoms is groundwater and overland flow and the water table is less likely to remain near the surface compared to reedbeds supplied by loch or river water sources (Figure 17). Reed growth requires a stable water regime and are therefore uncommon in aquatic environments which are subject to erratic variation in water levels. Reedbeds provide a hydromorphological function by absorbing wave energy, thereby protecting the banks of rivers and lochs from erosion (Natural England, 2008; McBride et al., 2011; SNIFFER, 2014).

Figure 17. Reedbed at Kilconquhar Loch, Fife (Andrew McBride).

Land uses found on reedbeds

The main land uses of reedbeds include cutting for commercial thatching, basketwork and biofuels, as well as for grazing. Constructed reedbeds are used for filtering farm effluent and pollution (SNIFFER, 2014).

Habitat conversion trajectories

Reedbed habitat may be negatively affected by lowered water tables, heavy grazing, raised water tables, increased nutrition levels arising from drainage, engineering works, changes in farm management, and pollution. This can result in changes in species composition to fen, aquatic habitat, eutrophic swamp, tall-herb fen, rich or poor fen, and marshy grassland (Table 6; SNIFFER, 2014).

Table 6. Possible trajectories for reed beds in the event of lowered water tables, heavy grazing, raised water tables, or increased nutrition. Adapted from SNIFFER (2014).

	Cause					
	• Lowered water table	• Heavy grazing	• Increased nutrient inputs	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrient inputs
Resulting habitat conversion	• Fen	• Aquatic habitat	• Eutrophic Swamp • Tall-herb Fen	• Swamp • Aquatic habitat	• Poor Fen • Marshy Grassland	• Rich Fen • Marshy Grassland

2.5.4 Swamps

Characteristics

Lowland swamps (< 350 mAOD) are found in flat to gently sloping topography, mostly along stream or loch locations, as fringes along open water or in estuarine/coastal settings. They may also occur on the edges of fens and saltmarshes, basins, valley bottoms, as well as within dune slack and machair habitat (Figure 18). Upland swamps are restricted to narrow margins surrounding lochs and lochans. The dominant water source for swamps on loch shores and floodplains is from adjacent water bodies during flooding, which can occur throughout the year. Where there is no directly adjacent waterbody, groundwater is an important source. Water table levels tend to be above ground most of the year, including summer, although large fluctuations are possible, particularly where swamps are fed by surface water. Swamps near open water (loch, river or estuary) are dominated by the respective bodies water levels leading to periodic inundation. High groundwater tables may also lead to inundation of swamps in low lying areas. Depending on geomorphological setting, there may be a significant depth of standing water, providing permanently waterlogged conditions. Brackish swamps may be found in areas subject to seawater flooding upon dune and machair, and where there is a mixing of fresh and saline water (Scottish Natural Heritage, 2010; SNIFFER, 2014).

Figure 18. Swamp habitat at Logierait Mires, Perth and Kinross (Andrew McBride).

Land uses found on swamps

The main land uses of reedbeds include cutting for commercial thatching, basketwork and biofuels, as well as for grazing. Constructed reedbeds are used for filtering or attenuating farm effluent and pollution (SNIFFER, 2014). SNIFFER (2014) notes that direct management of inland and coastal swamps in Scotland is minimal as management is usually undertaken on the adjacent water body or land. Chief management pressures are grazing, water abstraction and changing nutrient levels. The exception is those swamps used for sustainable drainage systems (SuDS), which require vegetation cutting and silt removal. Artificial swamps may also be used for effluent and pollution treatment (SNIFFER, 2014).

Habitat conversion trajectories

Swamp habitat may be negatively affected by raised or lowered water tables, preferential grazing, and increased nutrient levels. This can result in changes in species composition towards rich fen or poor fen, marshy grassland, and aquatic habitat (Table 7). Nutrient enrichment from agriculture has caused eutrophication of many Scottish lowland swamps, while upland swamps remain relatively natural. Grazing and cutting will influence species composition and, if carried out regularly, can prevent rank species from replacing those less able to compete. The presence of sheep and cattle along unfenced river banks and loch shores may lead to denuding and poaching of the wet edge, thereby damaging roots and rhizomes (SNIFFER, 2014).

Table 7. Possible trajectories for swamps in the event of lowered water tables, increased acidity, preferential grazing, raised water tables, or increased nutrition. Adapted from (SNIFFER, 2014).

	Cause					
	• Lowered water table	• Preferential grazing	• Increased nutrient levels	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrient levels
Resulting habitat conversion	• Fen • Marshy Grassland	• Change in Swamp NVC • Loss of Swamp	• Change in Swamp NVC	• Change in Swamp NVC • Aquatic habitat	• Poor Fen • Marshy Grassland	• Rich Fen • Marshy Grassland

2.6 Lowland wetlands: Groundwater depression

2.6.1 Basin fens

Characteristics

Basin fens may form in kettle holes, the swales between beach ridges, and the embayments of seas or lakes that have been isolated by beach ridges. They are often small and usually waterlogged, receive water from a range of sources including rainfall, surface runoff, groundwater and influent streams. They are usually found in southern Scotland on suitable slopes. They may be located in lowland and upland settings and may benefit from high precipitation levels, lower temperatures and higher levels of cloud cover associated with hilly ground or montane regions. In some cases they may be succeeded by raised bogs. Groundwater inflow is normally nutrient deficient but may range from base-rich to base-poor. The variety of vegetation is determined by a mix of water supply mechanisms, vegetational succession and management. Vegetation may, in time, form a floating mat (*schwingmoor*[6]; Figure 19) which may eventually cover the water body (Wheeler, 1984; Joint Nature Conservation Committee, 2004; Rydin and Jeglum, 2013; Lindsay, 2016).

[6] Wheeler & Proctor (2000) suggest that the term *schwingmoor* is used only where the mat covers the whole site

Figure 19. Basin fen, at Whitlaw Mosses, Scottish Borders (Andrew McBride).

Land uses found on basin fens

Drainage, afforestation and grazing are the most common types of land management which affect lowland fens in Scotland (McBride et al., 2011).

Habitat conversion trajectories

Basin fen habitat may be negatively affected by raised or lowered water tables, excessive or no grazing, increased nutrition levels, and increased acidity. This can result in changes in species composition towards marshy grassland, wet woodland, degraded fen, rich fen or poor fen, swamp or reedbed, open water, or wet heath (Table 8) (McBride et al., 2011; Natural England and RSPB, 2014; SNIFFER, 2014).

Table 8. Possible trajectories for basin fens in the event of lowered water tables, poor or excessive grazing, raised water tables, increased acidity, or increased nutrition. Adapted from (SNIFFER, 2014).

	Cause					
	• Lowered water table	• Poor grazing management • No grazing • Excessive grazing	• Increased nutrition	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition

Resulting habitat conversion	• Marshy grassland • Other wet woodland	• Other wet woodland • Degraded Fen	• Poor Fen to Rich Fen	• Swamp / Reedbed • Open water	• Rich Fen to Poor Fen • Marshy Grassland • Wet Heath	• Marshy Grassland • Other wet woodland

2.7 Lowland wetlands: Floodplain

2.7.1 Floodplain fens

Characteristics

Floodplain fens develop on waterlogged, periodically inundated floodplains adjacent to streams and rivers (Figure 20). Riverbank levee prevents or limits the flow of floodwater back into the river, which then continues to move slowly downstream thereby causing waterlogged, peat-forming conditions. Flood-plain fens may also form on flat valley bottoms where the watercourse is small and overbank flooding is not substantial. Groundwater may be a significant water supply source. Floodplain fens are some of the largest fen complexes in the UK often supporting shallow lakes and pools within the surrounding fen. Areas of anaerobic stagnant water favour the development of peat-forming species (e.g. *Sphagnum* spp.) which, aided by the high humidity on the floodplain and regular precipitation, may develop large ombrotrophic raised-bog domes. Floodplain fens in Scotland, such as the Insh Marshes, are generally base-poor (Wheeler, 1984; McBride et al., 2011; Lindsay, 2016; Thom et al., 2019).

Figure 20. A floodplain fen on Speyside, Highland (Andrew McBride).

Land uses found on floodplain fens

The chief land use of floodplain fens is agriculture.

Habitat conversion trajectories

Floodplain fen habitat may be negatively affected by raised or lowered water tables, excessive or no grazing, increased nutrition levels, and increased acidity. Habitat may also be affected both by direct drainage and by reduced connection with the river due to construction of flood banks. This can result in changes in species composition towards marshy grassland, other wet woodland, degraded fen, rich or poor fen, swamp or reedbed, open water, or wet heath (Table 9). Floodplain fens have a medium to high risk of enrichment from floodwaters and groundwater, particularly in intensively farmed landscapes (Wheeler, 1984; McBride et al., 2011).

Table 9. Possible trajectories for flood-plain fens in the event of lowered water tables, poor or excessive grazing, raised water tables, increased acidity or increased nutrition. Adapted from (SNIFFER, 2014).

	Cause					
	• Lowered water table	• Poor grazing management • No grazing • Excessive grazing	• Increased nutrition	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition
Resulting habitat conversion	• Marshy grassland • Other wet woodland	• Other wet woodland • Degraded Fen	• Poor Fen to Rich Fen	• Swamp / Reedbed • Open water	• Rich Fen to Poor Fen • Marsh Grassland • Wet Heath	• Marshy Grassland • Other wet woodland

2.8 Wet woodlands: Groundwater depression

2.8.1 Fen woodland

Characteristics

Also known as fen-carr, fen woodlands are mainly found on topogenous sites throughout the lowlands - floodplain fens, open water transition fens and basin fens, as well as in isolated woodland stands, and may extend into open fen areas (Figures 21 and 22). Vegetation is dominated by *Salix spp.*, *Alnus glutinosa, Betula spp.*, and rarer fen species such as *Rhamnus catharticus and Frangula alnus.* Large sedge tussocks grow in the water body (Joint Nature Conservation Committee, 1989; McBride et al., 2011). Wheeler (1984) notes the development of fen woodlands occurs in the following steps:

- Initial lake muds under a shallow depth of open water
- Colonisation by a semi-floating reed swamp, dominated largely by *Typha angustifolia*
- Development into a wet, *Phragmites australis* dominated "early fen"
- Subsequent colonisation by tussocks of *Car ex paniculate,* forming a secondary swamp
- Colonisation of the tussock-tops by trees (alder and willow) causing depression and degeneration of the fen raft, leading to the development of a swamp-carr
- Gradual stabilisation into mature fen woodland

Figure 21. Fen woodland at Blackpool Moss, Scottish Borders. (Andrew McBride).

Land uses found on fen woodland

Fen woodland has value as a source of timber.

Habitat conversion trajectories

The loss of a healthy fen woodland habitat can be observed in increases to woodland density, indicating internal enrichment and, or drying out of the fen (McBride et al., 2011). This could lead to transition to established deciduous forest cover.

2.9 Wet woodlands: Groundwater slope / Floodplain

2.9.1 Alder woodland

Characteristics

Alder woodlands form part of wet woodlands characterised by alder *Alnus glutinosa* and willow *Salix* spp. on floodplains in a range of situations ranging from islands in river channels to low-lying wetlands (Figure 22). The habitat consists typically of base-rich, poorly drained or seasonally flooded soils, such as in fens and bogs, pond and lakesides, river banks, and flushed hillsides (Peterken, 1981; Lake et al., 2015; The Wildlife Trusts, 2020).

Figure 22. An alder dominated woodland, the Quithel Wood (SSSI) in the riparian zone of the mainstem River Dee in Aberdeenshire (S. Addy).

Land uses found on alder woodland

Alder woodland have been extensively drained for agriculture and has limited value for timber production.

Habitat conversion trajectories

Riverine woodland clearance has eliminated most true alluvial forests in the UK and converted them to farmland (Lake et al., 2015). In some cases however, wet woodland has expanded due to lack of management by grazing/cutting[7].

2.10 Wet woodlands: Surface water slope

2.10.1 Bog woodland

Characteristics

Bog woodland consists of mature Scots Pine scattered across an ombrotrophic (rain fed) bog surface, without loss to other bog species (Figure 24; SNIFFER, 2009b). Bog woodland is a conservation priority habitat type under the EU Habitats Directive and is rare in the UK, maintaining a fine balance between tree growth and bog development (Bruneau and Johnson, 2014). It is usually located on topographies ranging from wet hollows on gentle slopes to valley bogs in the highlands. They are found in the Cairngorms and a few other places in Scotland, typically located at altitudes from 0 to 600 m, where rainfall is high. However, drying out of upper peat layers during dry summer periods may be necessary

[7] Expert opinion from PSG member D. Spray, 22 September, 2021.

for the establishment of tree roots. Peat depths can vary (> 0.5 m; SNIFFER, 2014). SNIFFER (2014) citing O'Sullivan, 1977, Watson, 1983, and Dargie & Briggs, 1991), suggests that the rarity of bog woodland is probably the result of long-term loss of native pine woodland, an expansion of blanket bog, forest clearance, and grazing pressure.

Figure 24. Bog woodland at Abernethy, Highland (Andrew McBride).

Land uses found on bog woodland

Land use on bog woodland include grazing, forestry, peat cutting and tree harvesting. Many of the degraded UK raised bogs have succeeded to closed-canopy pinewood or birchwood (SNIFFER, 2014).

Habitat conversion trajectories

Bog woodland habitat may be negatively affected by burning, drainage, pollution, poaching, peat extraction and tree harvesting. This can result in changes in species composition towards dry woodland, degraded bog woodland, bog, and degraded bog (Table 10). Increased rainfall under climate change could lead to extensive waterlogging and a reversion to blanket bog. A decrease in rainfall could allow the bog woodland to dry out, leading to encroachment by more trees, resulting in a closed canopy woodland (SNIFFER, 2014).

Table 10. Possible trajectories for bog woodland in the event of lowered water tables, insufficient or excessive grazing, raised water tables, or increased nutrition. Adapted from (SNIFFER, 2014).

	Cause					
	• Lowered water table	• Increased grazing pressure	• Increased nutrition	• Raised water table	• Lowered water table and increased acidity	• Lowered water table and increased nutrition
Resulting habitat conversion	• Dry woodland	• Degraded bog • Woodland / Bog	• Degraded bog Woodland / Dry woodland	• Bog	• Degraded bog Woodland / Dry woodland	• Dry Woodland

2.11 Wet grassland / floodplain meadow: Groundwater slope / Floodplain

2.11.1 Fen meadow

Characteristics

In the UK, fen meadows, rush pasture and associated mires are restricted to moist, seasonally waterlogged and slowly permeable soils (e.g., Stagnogley soils, Stagnohumic gley (humose) soils or Stagnohumic (peaty) soils; (Figure 25). Stagnohumic gley soils are the soil type most commonly associated with this wetland type. Middleton et al. (2006) note that in Europe fen meadows are classified as ground or surface water-fed mown grassland that is not peat forming as they were formed after partial drainage of a fen or developed on moist soil. Consequently, fens and fen meadows are considered to be different ecosystems. Fen meadows are associated with lowland fens but occur on drained or drier soils. In the past natural fens with a sufficient supply of base-rich groundwater was able to stabilise the nutrient poor fen vegetation over many centuries. However, since the middle ages, many fens have been partially drained, forming (fen) meadows requiring management of some form and then used as unfertilised grasslands, thereby creating species rich vegetation. In Scotland *Juncus acutiflorus* and *J. articulatus* are the main rushes found in fen meadows, together with sedges and a wide variety of forbs. A slow groundwater flow is required to maintain the high biodiversity, prevent erosion and stabilise nutrient recycling (Wheeler, 1984; Middleton et al., 2006; Grootjans and Van Diggelen, 2009; Scottish Natural Heritage, 2010; Tallowin, 2011; Natural England, 2014; Lake et al., 2015).

Figure 25. Fen Meadow, Lauder, Scottish Borders (Andrew McBride).

Land uses found on fen meadows

After 1946 agriculture became increasingly mechanised and there was no longer a need to use fens for pasture. Consequently, mowing of fen meadows ceased, causing a shift from shorter, diverse, vegetation to taller and woody herbaceous vegetation (Middleton et al., 2006).

Habitat conversion trajectories

Fen meadow habitat may be negatively affected by hydrological changes, eutrophication, fragmentation, sedimentation, cessation of grazing and climate change (Grootjans et al., 2006; Middleton et al., 2006; Tallowin, 2011; McBride et al., 2011). This can result in changes in species composition towards rank species.

2.12 Wet grassland / floodplain meadow: Floodplain

2.12.1 Wet meadows / marshy grassland

Characteristics

Marsh grasslands occur on relatively level, seasonally saturated, areas of mineral soils, lacking the perennial high-water tables of fens or the large water table fluctuations of marshes, and generally do not form deep peat soils (Figure 26). The Joint Nature Conservation Committee (2010) habitat survey describes marshy grassland as a broad category covering certain purple moor grass grasslands; grasslands with a high proportion of rush, sedge or meadowsweet species; and wet meadows supporting communities of marsh marigold and valerian, with a predominance of broadleaved herbs rather than grasses. Marsh grasslands provide a broad range of provisioning, regulating and cultural services. They are often created by the partial reclamation of natural floodplain wetlands. The vegetation is generally the result of agricultural treatments, control of the flooding regime, long-term mowing and, or grazing, often on degraded land (Joint Nature Conservation Committee, 2010; Acreman and Mountford, 2010; Cooper and Merritt, 2012; SNIFFER, 2014; Mainstone, Hall and Diack, 2016)

Figure 26. Marshy grassland dominated by rushes and *Molinia* species on the Allanmore floodplain of the River Dee, near Braemar in Aberdeenshire. (S. Addy).

Land uses found on wet meadows

Wet meadows are often used for livestock forage and hay production.

Habitat conversion trajectories

Wet meadows and marshy grassland habitat may be negatively affected by excessive drainage, nutrient input, and a lack of management for example under-grazing. This can result in changes in species composition towards rank species.

2.12.2 Transition grasslands

Literature on transition grasslands is lacking as are clear definitions. However, their vegetation and hydrology are likely to be intermediate between wet meadows/marshy grasslands described above and drier, rough grassland.

2.12.3 Transition saltmarsh

Knowledge on transition saltmarshes (Figure 27) is sparse. They occur in association with true saltmarshes but have a lower inundation regime (Webb et al., 2018). Vegetation communities that occur in transition saltmarshes are intermediate between true saltmarshes and those vegetation communities that are adapted to saline environments (e.g. reedbeds; Webb et al., 2018).

Figure 27. A transition saltmarsh at St Margaret's Marsh, Fife (Andrew McBride).

3. Knowledge gaps

The following wetlands had very little literature associated with them on their general character:

- Transition grasslands
- Transition marshlands

There was a lack of knowledge on the change trajectory of the following wetland types:

- base-rich/alkaline fens
- raised bogs
- fen woodland
- alder woodland
- Fen meadow
- depressions on peat substrates of the *Rhynchosporion*

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2. Appendix II: Water Holding Capacity of Wetlands

by Stephen Addy

0.1 Research questions

The key research questions that this appendix sought to answer were:

- What are the different types of water holding features that naturally functioning (undisturbed) wetlands provide?
- What are the spatial and temporal controls on water holding capacity?
- How does the water holding capacity of different wetlands vary?

0.2 Objective

To produce a literature review of information on the water holding capacity of each type of wetland and how it relates to characteristics such as soil profile, evapo-transpiration or other criteria.

0.3 Approach

This review begins with a summary (Section 1) of general water holding concepts in relation to wetlands. The rest of the review (Section 2) is structured according to the same wetland habitat typology presented in Appendix I. The literature research has used search engines (Google Scholar, WOS etc.) and collated/summarised the scientific literature as well as the SEPA-commissioned report on water supply mechanisms (SNIFFER, 2014). It also reviewed grey, non-peer reviewed research.

1. General concepts in water holding capacity

1.1 Defining water holding capacity

As covered in Appendix I, the storage of water held in a wetland reflects its water balance (McCartney and Acreman, 2009). The water holding capacity of a wetland can be divided into two types: used water storage and available free storage with the balance between the two varying (Figure 1). When all available storage is used, compared to other terrestrial landscape features, wetlands have the potential to hold considerable quantities of water.

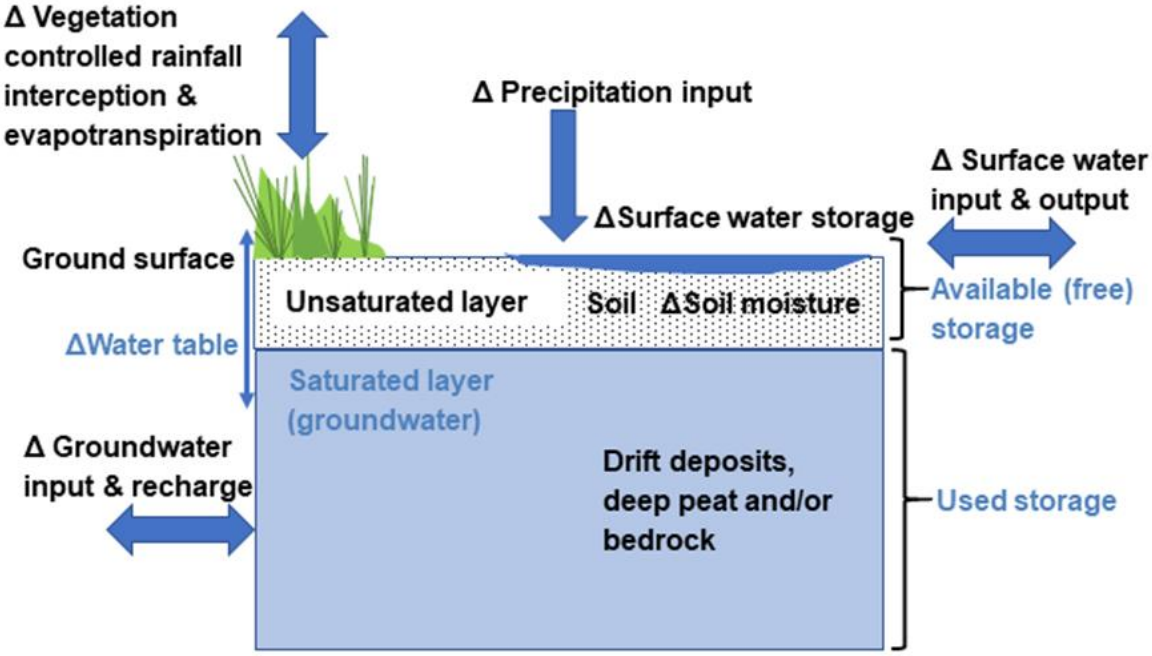

Figure 1. Conceptual summary of wetland water holding characteristics. Note not all wetlands are connected to groundwater or surface water and the combinations of input and outputs are not universal.

Water within a wetland is stored both at and beneath the ground surface (Figure 1). Above the ground surface water is stored as open water where it collects in hollows and channels. Beneath the ground surface, water is stored or flows through the soil (i.e., throughflow) in the unsaturated zone between soil pores or at depth within the saturated zone as groundwater (i.e., saturated zone beneath the level of the water table). The saturated zone is not static with the water table varying spatio-temporally in height and potentially spans the soil, and permeable soil parent material of bedrock or superficial drift (e.g., sedimentary deposits overlying the bedrock) layers. Moreover, soil moisture levels also vary depending on pedological characteristics and nature of overlying vegetation.

Several metrics are calculated to assess the water holding characteristics of a wetland (Table 1). Frequently, the water table is used to characterises the hydrology and to give a metric of the nature of water storage in a wetland (Gilvear and Bradley, 2000; see Table 1). Water tables can also be readily measured using manual measurements taken from a dipwell or piezometer instruments over long time to give an understanding of spatiotemporal variability of wetland hydrology (Gilvear and Bradley, 2000; SNIFFER, 2014). Ideally water tables should be measured over several years to account for interannual and seasonal variability. Other less commonly used metrics to characterise the hydraulic properties and retention of water in wetlands include soil hydraulic conductivity, specific yield and the extent of surface water inundation (Table 1).

Table 1. Summary of metrics used to characterise the water holding characteristics of wetlands.

Metric	Definition	Method examples	Application and metrics	References
Water table	Synonymous with water level. The fluctuating boundary between unsaturated conditions above and saturated conditions below (groundwater). When a wetland is saturated, water table level is at or above the surface.	Measured using manual measurements in dip-wells or automatically with electronic piezometric instruments.	Allows understanding of maximum and minimum ranges of water table for different wetland types over annual, summer and winter periods. Percentage exceedance curves and percentiles values (e.g. medians, 5% percentile, 95% percentile) can be produced (e.g. SNIFFER, 2014).	Duval and Waddington, (2018); Bradley et al., (2010); Grieve et al., (1995)
Hydraulic conductivity	Describes the rate of water movement through a material.	Measured using water table level recovery tests in dipwells and boreholes. Error from this technique can be large so multiple measurements are needed. Can also be measured using infiltration ring tests or lab analysis of saturated and dry soil cores.	Allows understanding of hydraulic conductivity of a material. This gives information on the rate of water movement and ability to retain moisture in the soil under saturated and unsaturated conditions.	Duval and Waddington (2018); Gilvear and Bradley (2000)
Specific yield	Measure of the quantity of water movement to or from storage (associated with movement up or down of the water table).	Lab analysis of saturated and dry soil cores. Field investigation with theta probes.	Gives an indication of water retention capabilities of a soil.	Duval and Waddington (2018); Baggaley et al., (2009)

Soil moisture	Measure pore water content or pressure.	Neutron probe (Pore water content) Tensiometer (pore water pressure) Cosmic Ray Neutron Sensors.	Give an indication of soil water storage characteristics.	Dimitrova-Petrova et al., (2020); Marshall et al., (2014); Bradley et al., (2010)
Areal extent of surface water	Area of wetland surface submerged by water.	Mapping using field techniques or remote sensing.	Gives an indication of surface water storage. When combined with information on water depth and underlying topography, volumetric calculations of water storage are possible.	Baker et al., (2009); Gilvear and Bradley (2000)

Measurement of water tables can be used to give an indication of the whole surface water balance of peat mires (Bragg, 2002). It also gives an indication of the amount of used saturated water storage and free, available storage in the unsaturated zone above. Wetlands are defined by an excess of inflow over outflow for a given period but seasonal and longer-term changes to water balance can occur (Gilvear and Bradley, 2000). Over a given period of time, a hydrological feature is said to be in storage deficit if it has a negative balance whereby outputs from the wetland exceed inputs. This condition as indicated by a relatively low water table and reduced extent of surface water inundation during dry conditions. In contrast during wetter periods, a storage surplus situation occurs where inputs exceed outputs and there is no additional unsaturated storage available. These conditions occur when the water table has risen to above the surface leading to a relatively deeper and wider extent of surface inundation.

1.2 Controls on water holding capacity

The different combinations and regimes of in and out-flows that determine water balance as outlined in Appendix I, is an important control on wetland type and in turn potentially water holding capacity (Baker et al 2009). For example, ombrotrophic (i.e. rain-fed) raised peat mires are not connected to groundwater or external surface water inputs but are affected by inflow via precipitation and outflow via evapotranspiration and potentially surface water runoff. As explored further in Section 2.1.2, such wetlands where undisturbed, tend to be fully saturated to a level close to or at the ground surface all year round thus having limited available free water storage. In contrast to peat mires, a floodplain wetland that is also controlled by surface water input from an adjacent river that seasonally floods and potentially other sources of inflow, may show a greater variation of water balance and level of saturation through the year (Gilvear and Bradley, 2000). Thus, floodplain wetlands may more often have available free water storage.

The volume of water that is stored and nature of its storage (i.e., duration, storage type: on the surface, in the soil as moisture or as groundwater) however may vary temporally and spatially depending on hydrological processes both operating within the wetland and the wider adjacent catchment area (Figure 2). Within a wetland, the nature of the topography is amongst the most important controls on how much water is stored and moves on the surface or is absorbed in the sub-surface through infiltration. Hollows, dips and channels can catch and maintain water storage received from multiple sources (Acreman and Holden, 2013).

The hydrological connection of a wetland to the adjacent landscape is also an important control. For example, if a wetland is sloping or has an outlet channel then it's holding capacity may be limited compared to an isolated, topographical basin with no connection to a surface water outlet. Another connectivity aspect that determines differences in storage of water throughout a year for a given wetland type is its size relative to the contribution area (Baker et al., 2009). For example, a receiving wetland with a large upland contributing area relative to its size would have a larger surface inflow component relative to a larger wetland with a smaller contributing area.

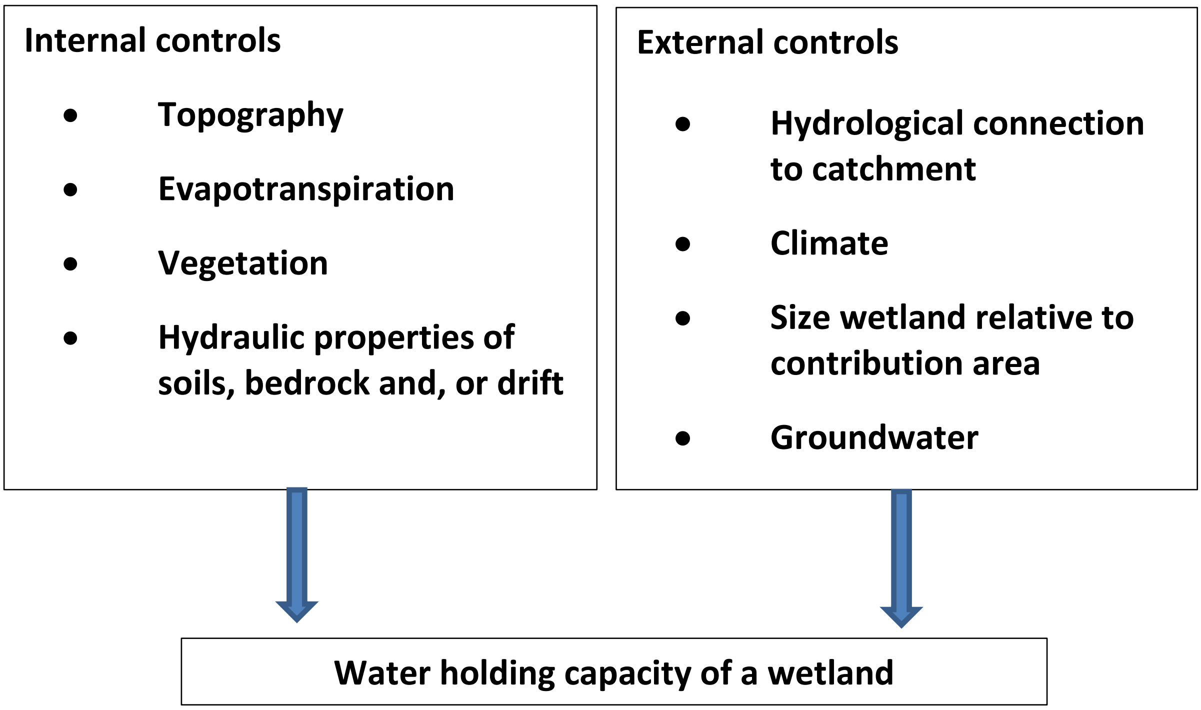

Figure 2. Summary of hydrological controls on the spatial and temporal variability of water holding capacity of wetlands. Internal controls refer to factors operating within the wetland and external controls refers to factors outside the area of the wetland.

The evapotranspiration of water to the atmosphere is a key temporal control on the duration, extent and depth of surface water storage. Evapotranspiration is one of the most important outflows from a wetland and accounts for the greatest loss of water from most wetlands (Mitsch and Gooselink, 2000). The evapotranspiration rate depends on the climate and vegetation and is strongly linked to seasonality with greater rates occurring during the summer months. Evapotranspiration also depends on where the water is stored; surface standing water is more prone to loss than water stored beneath the surface. The effects of vegetation upon evapotranspiration rates from wetlands however varies depending on the vegetation type and coverage (Baker et al., 2009).

The nature of the vegetation can determine the canopy interception and temporary moisture storage. Thus, overlying vegetation can provide a potentially considerable type of indirect water storage in wetlands. For example, interception rates as high as 50% have been observed in open (i.e. no tree cover) fens (Gilman and Newson, 1983). Moreover, vegetation creates surface roughness and irregularities that in turn can aid the slowing of flood waves and capture surface water (Thomas and Nisbet, 2007; Shuttleworth et al., 2019). Wetland vegetation communities are sensitive to changes in hydrology (Appendix VII) and changes in community composition can lead to shifts in their hydrological influence on a wetland. For example, where both surface- and groundwater inputs are present, an increase in surface water flooding could lead to a change in the vegetation types present - with a loss of those that are dependent on ground water. This could in turn alter evapotranspiration, interception, and roughness attributes of the wetland.

The hydraulic properties of the underlying material also influence surface water storage regime. The soil hydraulic conductivity determines the sub-surface absorption of water from above and in turn the volume and duration of water stored on the surface (Baker et al., 2009). Hydraulic conductivity depends on the nature of the underlying soil (stratigraphy, grain size and organic content), bedrock or drift deposits (e.g. sand and gravel glacial deposits) beneath the surface, characteristics that vary greatly over a catchment.

Often, the soils underlying wetlands are poorly draining, with low hydraulic conductivity (e.g., peats, clays and gleys) and high-water tables meaning there is limited potential free storage within the soil. However, seasonally wet wetlands, for example those underlain by soils with better drainage characteristics (e.g., alluvial mineral soils) with lower water tables may have additional water storage at certain times compared to wetlands that are permanently saturated to a shallower depth.

The groundwater regime of a wetland is a particularly important control on wetland water storage for certain wetland types. More commonly, the groundwater regime is an independent control on wetland hydrology producing groundwater fed and groundwater dependant wetlands (McCartney and Acreman, 2009). In rarer cases however, depending on the wetland type, climate and season, wetlands can lose surface water storage to an aquifer through infiltration and recharge groundwater stores (McCartney and Acreman, 2009; Gilvear and Bradley, 2009). In such cases, groundwater acts as an additional water store to the surface water store of the wetland. Alluvial valley fills in river valleys potentially represent a major store of groundwater (alluvial aquifer) that can be recharged following surface water inundation during floods (e.g. Macdonald et al., 2014).

2. Water holding capacity of different wetland types

2.1 Upland wetlands

Surface water slope

Blanket bog

By nature of their extent (Appendix I), blanket bogs represent a major hydrological component of headwaters in many catchments and are well studied. The water holding capacity of peat is dependent on its hydraulic conductivity which can vary depending on peat type, extent of decomposition and depth (Holden and Burt, 2003; Gilvear and Bradley, 2009). It also depends on the extent to which the blanket bog has been damaged or drained which can reduce the storage capacity of a bog (Appendix III). In blanket bogs, the existence of two hydraulically distinctive layers represents an important control on their hydrology. Peatlands consist of two layers: the upper acrotelm layer and the lower catotelm layer. The permeable (relatively high hydraulic conductivity although it can vary between sites; Holden and Burt, 2003) acrotelm layer which is typically 5-70 cm in depth, defines the zone in which the water table fluctuates (Clymo, 2004). In contrast the catotelm layer lies underneath the water table and is permanently saturated with a relatively low hydraulic conductivity (Gilvear and Bradley, 2009). In addition to these factors, the existence of sub-surface macro-pores and pipe networks in peat can also strongly affect the movement of and residence time of water; such features can account for up to 10-14% of river discharge (Holden and Burt, 2002).

Blanket bogs are typically saturated from their base to a shallow depth within the acrotelm, beneath the surface all year round. The water table of ombrotrophic peatlands typically occur within the topmost <0.1 m layer beneath the surface (Bragg, 2002). However, there can be variations between sites. In the English Pennines, water tables have been observed within 0.4 m of the surface 80% of a year (Holden and Burt, 2003) and within 0.05 m of the surface 93% of the time (Evans et al., 1999). In Scotland, water tables have been observed typically to range between -0.01 and -0.3 m (SNIFFER, 2014) and less than -0.05 m on average (Scheliga et al., 2018). Typically, water tables fluctuate only slightly through the year with perennial saturation within the catotelm layer and fluctuations of 0.1 to 0.2 m have been observed (Gilman, 1994). Rare summer droughts can lead an even greater shift of water tables than normal in a given year. Observations during the summer drought of 2018 from the Bruntland Burn catchment in north-east Scotland showed that groundwater levels and soil moisture were significantly lower than normal conditions; three boreholes located in valley bottom peaty soils showed water levels were 0.15 – 0.4 m lower than normal (Soulsby et al., 2021).

Blanket bogs reach depths on average of 0.5 to 3 m (Bragg and Tallis, 2001). Considering the dominance of a near complete saturation throughout the year, typical peat depths and blanket bog extent (Appendix I, Appendix VIII), this presents a considerable volume of all year-round water storage in upland environments. For example, in the Bruntland Burn, electric resistivity tomography surveys were used to assess the extent of drift deposits and peat to estimate the water storage across the 3.2 km^2 catchment (Soulsby et al., 2016). It was estimated that in areas of valley bottom blanket bog which extended up to 4 m in depth, up to 10,000 mm of precipitation equivalent of water storage was held. Given the typically high-water table levels of peat soils, the availability of free capacity (i.e. a storage deficit) to store additional water inputs during rainfall or snowmelt events within the acotelm layer is limited however (Bragg, 2002).

An additional form of water storage in blanket bogs but on a comparatively smaller scale to the subsurface, is that offered by the overlying *Sphagnum* cover. *Sphagnum* moss occurs in three different forms in peatlands that have their own distinctive micro-topography and range of *Sphagnum* species. These three types have different positions relative to the water table which are in descending order: hummock, lawn and hollow (McCarter and Price, 2014). Hummock *Sphagnum* species are most common in blanket bogs and are distinctive for having higher water retention capacity than species in lawn and hummock settings (Campbell, 2014; McCarter and Price, 2014). The position of the water table exerts a strong influence on the moisture regime and in turn survival of *Sphagnum* cover although these characteristics also depend on the underlying soil moisture and water pressure (Ketcheson and Price, 2014). Therefore, the soil hydrology and the overall health of the blanket bog are important controls on the condition of the *Sphagnum* cover, its storage capacity and the hydraulic roughness it offers. In contrast, the control that direct rainfall has on the moisture regime of *Sphagnum* is weaker and its retention within the moss is limited (Ketcheson and Price, 2014)

Wet heath

Wet heaths like blanket bogs have a persistently high-water table that is rarely deeper than 0.2 m below the surface and periods of surface water inundation during the winter (SNIFFER, 2014; Wildlife Trusts, 2018). Soil types underlying heaths tend to be poorly draining mineral soils (e.g. gleys or peaty gleys) and shallow (<0.5 m) peats (Hampton, 2008). Observational studies from wet heaths are limited (SNIFFER, 2014). However, given the poor drainage characteristics, wet heaths have a limited capacity to store excess water especially during the winter when water levels are at or close to the surface.

Surface water depression

Depressions of peat substrates

Runoff from peatlands tends to be rapid. However, the movement and storage of water on the surface during saturated conditions that promote overland flow, depends on the surface roughness as determined by the vegetation and the ground topography. On blanket bogs topographical variation produced by surface erosion and variable peat development can produce hollows and dips that provide storage of surface water in pools. Depressions can also occur on peat substrates of the *Rhynchosporion* sometimes in association with *Narthecium ossifragum – Sphagnum papillosum* mire providing additional surface water storage (Stalleggar, 2008).

Micro-topographic variation can create marked differences in hydrology over small (<10 m) scales. In a study in the Bruntland Burn catchment in the north-east Scotland, riparian groundwater fed hollows were generally associated with higher water tables (~0.2-0.4 m below surface) and more frequent inundation during precipitation events compared to the neighbouring hummocks that remained relatively drier (Scheliga et al., 2019). The topography of hollows and hummocks can also vary through time as a result of hydrological variation with changes in water table and soil moisture resulting in fluctuation of the ground surface (Alshammari et al., 2018). These changes could affect the small-scale surface hydrology as a result through changing runoff pathways and the availability of storage.

Groundwater slope

Base-rich fens, alkaline fens

Base-rich or alkaline fens, are groundwater fed and often found in association with springs or flushes on mid-slopes or where there are breaks in slope or changes in geology occur. Groundwater fed wetlands tend to exhibit stable, near constant surface water discharge thus annual water tables are at or close to the surface (SNIFFER, 2014). However, elevated water levels of up to +0.15 m can occur over brief periods (SNIFFER, 2014) although given the sloping nature of such sites, surface storage opportunities tend to be limited.

2.2 Lowland wetlands

Surface water depression

Raised bogs

Similar to blanket bogs, raised bogs feature similar hydrological characteristics reflecting the hydrological properties of the acrotelm and catotelm layers within the peat. Typical water table levels are also like blanket bogs with the water table at the height of the acrotelm between -0.22 and 0.03 m relative to the surface (Wheeler and Shaw, 2010) with surface water inundation occurring during wetter conditions and within hollows and seasonally inundated pools (SNIFFER, 2014).

Like blanket bogs, raised bogs generally have low storage deficits and thus free capacity for storing additional water in responses to hydrological events is limited. However, the ability of a raised bog to store water and its subsequent contribution to run-off can vary temporally. Studies on the Dun Moss, a raised mire in the Grampian foothills of eastern Scotland, showed that peak run-off response to rainfall was delayed by 22 hours following a dry summer that created a storage deficit (Bragg, 2002). In contrast under 0 storage deficit conditions, reflecting wetter conditions, the runoff response delay was reduced by 3 to 6 hours. The runoff response of raised bogs is also potentially dependant on the surface runoff slowing effect (Shuttleworth et al., 2019) and water holding capacity of the overlying *Sphagnum* moss. Observations from the restored Blawthorn Moss in West Lothian showed that four different *Sphagnum* species distributed over the 109ha site could hold 0.012m^3/m^2 of water or the equivalent of eight commonwealth swimming pools (Campbell, 2014).

As raised bogs can reach considerable depths (e.g. up to 7 m; Clymo, 2004) that can exceed that of blanket bogs, they have the potential to store water to a considerable depth. However, compared to the extent of blanket bogs, raised bogs are less common and more localised in extent (SNIFFER, 2014) thus their cumulative contribution to catchment scale water storage may be limited compared to blanket bogs. It is also important to place raised bogs within their landscape context. Lagg fens are often associated with the margins of raised bogs (Bragg, 2002) and potentially sympathetic management beyond the extent of a raised bog may help to restore and sustain these associated wetlands. As further explored in Appendix IV, such management to enlarge the extent of wetlands, could help to increase overall storage capacity and hydrological resilience of raised bogs and surrounding associated wetlands.

Groundwater slope

Transition mires, open water transition fens and quaking bogs

Knowledge on the hydrology of transition mires, open water transition fens and quaking bogs is limited but some monitoring data from Scottish sites exists. These wetland types are characterised by flat surfaces (SNIFFER, 2014) thus lack topographical heterogeneity for enhancing surface storage and their hydrology is controlled by fluctuations of the adjacent standing waterbody. Water table levels are usually close to the surface and surface water inundation often occurs. An example of a quaking bog was monitored over two years on Uist and exhibited water levels above the surface for nearly the whole duration although there were data reliability problems (SNIFFER, 2014). These observations suggest the capacity of such wetlands to provide additional free water storage is limited. However, groundwater fed transition mires may maintain more variable storage availability with longer periods of water table below the surface. Available, surface storage may increase during dry periods which could help to provide storage during summer rainfall events. For example, in the Insh Marshes of the upper Spey Valley, groundwater fed transition mires occur which are prone to groundwater flooding during the summer months (Grieve et al., 1995). The potential for additional storage also depends on the landscape context for example the particular assemblage of wetland types in a given area and the nature of the transitions between adjacent wetlands.

Base-rich fens

Base-rich fens in lowland areas may exhibit a similar hydrological regime to upland examples being groundwater fed by underlying aquifers consisting of base-rich rocks (McBride et al., 2011). However, in lowland settings, controls on water balance can vary over short distances depending on topography and landscape position (Duval and Waddington, 2018). In a study of a calcareous fen complex in Ontario Canada (Duval and Waddington, 2018), it was found that the riparian fen was dominated by surface water inputs from a stream and the high retention of this water varied little throughout the year (i.e. the potential for additional storage was limited). In contrast the trough fen and basin fen were more influenced by evapotranspiration and precipitation with the basin fen receiving greater groundwater inputs. Thus, the availability of free storage was more variable through the seasons.

Reedbeds and swamps

Reedbeds and swamps are characterised by permanent or frequent, deep inundation supplied by surface water bodies (nearby loch or river) and, or groundwater inputs (SNIFFER, 2014). Generally compared to other wetland types, swamps or reedbeds exhibit very high annual mean water depths and ranges of water depth that are comparable to lakes (Weller, 1994).

However, differences in surface storage regime are shown by swamps depending on the source of water supply. Swamps fed by surface water tend to exhibit greater fluctuations of water levels compared to groundwater fed systems which are more stable (SNIFFER, 2014). Based on five monitoring sites from Scotland, median annual water levels typical of swamps or reedbeds are +0.02

m above the ground surface and as high as +2 m during wet periods (SNIFFER, 2014). Swamps can thus hold large volumes of open surface water all year round compared to other wetland types where the water table is at or below the ground surface. Thus, swamps can offer potentially useful free capacity for water storage.

Groundwater depression

Basin fens

Basin fens are mainly sustained by groundwater and possibly surface water inputs and their low-lying topographies give rise to groundwater discharge and the accumulation of surface water at or near the surface. Basin fens that are groundwater fed tend to have less variable water levels than surface water fed floodplain fens that fluctuate more rapidly and over a greater range (SNIFFER, 2014).

Monitoring case studies of basin fens are limited in number but data from the Whitlaw alkaline fen in southern Scotland, provides useful information on their main hydrological characteristics (SNIFFER, 2014). Situated in a topographic basin, surface water inundation occurred 75% of the time in winter and 50% of the time in summer. In contrast, in adjacent surface water fens, surface water inundation occurred <5% of the time during either winter or summer. The Newham Bog in Northumberland is another example of a groundwater fed fen supplied by an underlying aquifer and nearby esker that bounds the site (Large et al. 2007). Based on long term monitoring of water table of levels between 1983 and 2002, the naturally functioning period of the wetland following recovery, the hydrology was characterised by regular winter inundation and average water levels of +0.1 to -0.3 m relative to the ground surface. Both examples suggest some capacity for additional water storage especially during summer and dry periods however potentially sympathetic management and restoration outside the current wetland area, could increase wetland extent and water storage capacity as further explored in Appendix IV.

Floodplains

Floodplain fens

Floodplain fens are affected by occasional or seasonal inundation from a nearby watercourse during flood events and can also be affected by upwelling groundwater inputs for example at the foot of hillslopes along valley margins (Grieve et al., 1995). As such, floodplain wetlands in general tend to have a variable hydrology (Gilvear and Bradley, 2000). Floodplain fens specifically tend to exhibit water tables that fluctuate more than mainly groundwater fed fens (SNIFFER, 2014). Usually, water table levels in fens fed by surface water flows are close to the surface all year round with times of surface water inundation when the presence of ponds and depressions aid surface water storage (Šefferová Stanová et al., 2008). In contrast during dry periods, the lower water table and greater potential surface water storage, means floodplain fens may receive water from the nearby watercourse (Gilvear and Watson, 1995) thus helping to recharge the wetland. However, despite these seasonal patterns, based on observations from 12 Scottish sites, the majority of which were mainly surface water fed, annual median water tables were -0.03 m indicating that the capacity for additional sub-surface water storage of fens is typically minimal (SNIFFER, 2014).

Floodplain fens occur close to other wetland habitat types that naturally functioning floodplain systems are comprised of. In the Insh Marshes for example, localised base poor fens, which are synonymous with transition mire and quaking bog wetlands (SNIFFER, 2014), occur within the wide floodplain amongst adjacent areas of swamp, basin mire, scrub, marsh and open water (RSPB, 2007). Valley aquifers composed of alluvial and glacial sediments that can be extensive and deep in many river systems are connected to wetlands (Macdonald et al., 2014; O Dochertaigh et al., 2018). The seasonal recharge of floodplains and the wetlands they contain through flooding, could help to sustain long term groundwater stores.

2.3 Wet woodlands

Groundwater depression; Groundwater slope; Floodplain

Fen and alder woodland

Other types of wet woodland (fen and alder woodland) exist which like bog woodland, remain understudied. These wet woodlands occur in groundwater depressions, groundwater slopes and floodplains although specific knowledge to differentiate their functioning in relation to wetland hydrology type is limited. Like bog woodland, the interaction between the water table, soil type and evapotranspiration regime dictate the effects of trees on the wetland hydrology and vice versa. The presence of trees in otherwise open floodplain fen and groundwater fed wetlands can be indicative of the change to drier conditions in the wetland (McBride et al., 2011). Thus, development of tree cover may indicate water table lowering due to climatic or land use change factors and in turn the presence of trees may further modify the water table through altering the evapotranspiration regime. This may lead to improved provision of available water storage in the unsaturated soil layer compared to the previous, more saturated wetland condition. However, this could in turn lead to a loss of the characteristic wetland vegetation species. Hydrological monitoring is needed to ensure sufficient water levels are available to maintain the characteristic vegetation.

The hydrology of stable, naturally functioning wood covered wetlands may be broadly similar to that of their open examples. Limited monitoring of two contrasting Scottish sites (one surface water fed site and one groundwater fed site) give indications of the range of water table conditions associated with tree covered wetlands (SNIFFER, 2014). Over two wet years with flooding, the median water table level was at 0 but site-specific differences were apparent. At the groundwater fed site (alder tree cover; Whitlaw site) water table levels changed little through the year with a range of +0.3 and -0.3 m relative to the ground surface reflecting the stable groundwater discharge regime. In contrast at the Loch Lubnaig site (willow tree cover), water levels ranged from +0.7 to -0.6 m reflecting the inundation and drawdown periods of the nearby loch. The presence of trees, deadwood and shrub vegetation found in these types of wetland, may also aid the attenuation and capture of surface water runoff through increased roughness (Thomas and Nisbet, 2007).

Surface water depression

Bog woodland

Since bog woodland characterised by infrequent birch and Scots pine trees is associated with ombrotrophic raised bogs (SNIFFER, 2014), the hydrology of this wetland type is broadly similar to raised bogs lacking tree vegetation but there can be important differences. Although relevant studies are limited, high water tables at or near the surface are a feature of these wetlands with water tables showing a seasonal pattern (highest during the winter months and lower in summer; Bragg, 2002; SNIFFER, 2014). However, the presence of the trees can increase evapotranspiration rates leading to lowering of water tables both in the summer and winter (Bragg, 2002; SNIFFER, 2014). Progressive changes in water table level linked to climate or land management could affect the suitability of conditions for tree growth; a feedback that could in turn further influence the soil moisture and water table regimes of the wetland (SNIFFER, 2014). Depending on their effect on interception, evaporation and transpiration conditions, an increase in tree cover could free up more capacity for water storage in the unsaturated zone (acrotelm) compared to open raised bogs with infrequent tree cover. The presence of trees and deadwood may also aid the attenuation of surface water runoff through increased roughness (Thomas and Nisbet, 2007). However, these changes could result in the transition of the bog woodland to a scrub or forest habitat and the loss of the characteristic eco-hydrological features of this wetland type.

2.4 Wet grassland and floodplain meadows

Groundwater slope; Floodplain

Fen meadows, wet meadows and marshy grassland

Marsh grasslands and wet meadows (including fen meadow vegetation classification; SNIFFER, 2014) are characterised by water table levels just below the surface. Based on the monitoring of surface water fed sites in Scotland (Loch Lubnaig), the median annual water table was -0.06 m relative to the ground surface with a clear seasonal pattern; flooding up to +0.5 m occurred 10% of the time during winter and the water table lowered to as low as nearly -0.4 m in summer (SNIFFER, 2014). Hydrological monitoring of Oxley Mead a floodplain meadow in Southern England managed through traditional hay cutting, showed a similar seasonal pattern and a high total range of water levels (Rothero et al., 2016). Between 2009 and 2013, the water level at one dipwell ranged from +0.3 m to -0.6 m. These observations suggest that that the capacity to store additional water is low during the winter months when the soil is saturated but can be relatively high during the summer months.

Bradley et al., (2010) monitored the soil water pressure at 30 and 60 cm depths of a headwater floodplain wetland dominated by *Molinia* species and rush vegetation in Wales. The study showed that the soil responded rapidly to rainfall by infiltration and was also strongly influenced by river stage. However, soil moisture varied across the site depending on the sedimentology of the floodplain.

Other types

Transition grassland

Knowledge on the hydrology of transition grasslands is lacking but it is likely to be similar to floodplain meadows and wet meadows described above with widely ranging, seasonally controlled water tables. Thus, available free storage is most likely during the summer months when water table drawdown occurs.

Transition saltmarsh

Specific literature on the hydrology of transition saltmarshes is lacking. However, there may be some similarities with adjacent true saltmarshes that are regularly fully inundated by tidal seawater. The hydrology of saltmarshes are complicated reflecting the wide range of factors that determine their water balance and also remain understudied (SNIFFER, 2014). In a hydrological study of the Bay of Fundy Nova Scotia, eastern Canada, it was found that geomorphology, rainfall and soil type were more important controls on hydrology than the tidal height regime (Byers & Chmura, 2014). Water tables are typically at shallow depths; based on observations from Balranard in the Outer Hebrides, annual median water table levels were -0.04 m but levels fell in the summer months to -0.09 m for half of the time.

3. Knowledge gaps

Based on the review of literature sources outlined above, the following wetland types appear to be under studied in terms of their water holding capacity:

- Depressions on peat substances
- Base-rich fens
- Transition mires and quaking bogs
- Open water transition fens
- Basin fens
- Bog woodland
- Transition grassland
- Transition saltmarsh

In general, there is a lack of empirical field-based studies that assess water holding capacity of the wetland types considered. There is a particular need for water balance-based studies that robustly quantify changes in wetland net storage, inflows and outflows over different seasons.

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3. Appendix III: Buffering Mechanisms

by Stephen Addy

0.1 Research questions

The key research questions that this section sought to answer were:

- *How do a broad range of wetlands in Scotland buffer extremes of water availability, focusing on both low and high flows?*
- *What are the mechanisms for this and their relative importance?*
- *How is this buffering capability compromised when wetlands are degraded due to land use conversion or climate change?*

0.2 Objective

The objective was to produce a literature review of the mechanisms by which wetlands in Scotland buffer extremes of water availability, both in terms of water scarcity and flooding (high flows and low flows). The review defines each mechanism in turn, their relative importance and how these mechanisms are affected when the wetland is not in a healthy condition.

0.3 Approach

The first half of this review introduces concepts on buffering capacity and the potential impacts that climate change and land use change can have. The second half of the review has been structured according to the wetland typology specified in Appendix I and the different mechanisms (e.g. sub-surface storage, climate, vegetation and surface roughness) by which wetland buffer hydrological extremes. The literature research used the following search engines (Google Scholar, WOS etc.) and collated/summarised the scientific literature as well as the SEPA-commissioned report on water supply mechanisms (SNIFFER, 2014). It also reviewed grey, non-peer reviewed research.

1. Introduction

1.1 Hydrological extremes and effects of climate and land use changes

Hydrological changes caused by climatic and land use changes have potentially significant implications for the condition and functioning of wetlands.

Climate change

The occurrence of hydrological extremes of flooding and drought are expected to increase through climate change (Guerreiro et al., 2018). This has implications for understanding and managing wetlands in the future both in terms of how the hydrological processes within wetlands are affected and their ability to buffer extremes that result in high or low flows.

Although projections are inherently varied and uncertain, in Scotland the following hydrological impacts of climate change are likely:

- Milder and wetter winters with more extreme precipitation events leading to higher flood frequency (Werritty, 2002; Hiller et al. 2019).
- Decreased annual snow cover and depth from the 2030s in upland areas (Rivington et al., 2019) leading to increased winter flows and decline of spring flows as snowmelt reduces (Capell et al., 2013).
- Average summer precipitation is expected to decrease but extreme rainfall events are expected to become more intense (Chan et al, 2018).
- Increased temperatures are expected to result in more summer droughts leading to increased periods of low river flow, reduced groundwater recharge (Cuthbert et al., 2019; Rivington et al., 2020) and depletion of groundwater storage (Fennell et al., 2020).
- Changing seasonality of precipitation patterns altering the temporal patterns of groundwater recharge and droughts (Rivington et al., 2020).
- Accentuation of the east to west difference in climate with the west becoming wetter and east becoming drier (Rivington et al., 2020).
- Projected sea level rises of 15-61 cm for Edinburgh in 2100 under a medium emissions scenario (5^{th} to 95^{th} percentile values; Fung et al., 2018).

Land use change

Changes in land use are varied thus there are a range of potential effects on wetlands. Changes in land use can occur within and, or adjacent to a wetland resulting often in profound direct or indirect changes in wetland hydrological processes. Examples of land use changes both within wetlands and in the catchment of wetlands that can have hydrological impacts include:

- Alterations of floodplain hydrology through the construction of flood embankments and dredging and straightening of watercourses which disconnects the natural exchange of water, nutrients, seeds, and sediment (Ward and Stanford, 1995; Kondolf et al. 2006).
- Afforestation of blanket bog including drainage ditching leading to changes in vegetation and accelerated runoff especially following clear felling (Joosten, 2009).
- Overgrazing and moorland burning which can reduce water infiltration of soils and accelerate runoff (Holden et al., 2014; Murphy et al., 2021).
- Drainage and cultivation for increasing agricultural productivity leading to complete transformation of a wetland to a different type of land use, soils and vegetation (Cook et al., 2009). Drainage can also accelerate runoff downstream and exacerbate flood peaks (Czicova et al., 2013).
- Urban expansion leading to increased coverage of impermeable surfaces that reduce infiltration and accelerate surface runoff leading to heightened flood peaks downstream (Miller et al., 2014).

- Another anthropogenic pressure, but localised in nature that can affect wetlands, is through the over-abstraction of surface and groundwater at the site of a wetland or within the catchment area for drinking, agriculture or industry. This can lead to a lowering of the water table and wider effects of reduced river base-flow (McCartney and Acreman, 2009) and depletion of groundwater reserves (Fennell et al., 2020).

Changes in catchment hydrology and wetlands

Whilst a range of hydrological effects can result from climate and land use change, the effects will vary depending on the nature of the catchment. For example, the combinations of land use, topography, geology, soil cover and vegetation are catchment specific and can result in differences in catchment response to projected changes in climate (Capell et al., 2013).

In relation to wetlands, these wider changes in catchment hydrology have the potential to alter their water balance (Appendix I) and inherent hydrological character. It has been predicted that more intense droughts will have the greatest impact on wetlands in general and cause wider water level fluctuations (Cizkova et al., 2013). However, the style and magnitude will depend on the capacity of the wetland type to absorb change. For example, rain-fed wetland vegetation communities are expected to be impacted by climate change more than wetlands sustained by river flow (Acreman et al., 2009) or groundwater (Winter, 2000). In some cases, changes in hydrology could lead to the loss of wetlands; a trend that has taken place since the 1970s with an estimated global loss of 31% (Dixon et al., 2016). An even greater global historic loss of possibly as high as 87% since 1700 AD has been estimated (Davidson, 2014). The potential change in wetland functioning thus has wider implications. Changes to their character can alter the movement, routing and storage of water downstream throughout catchments. As wetlands constitute one part of a catchment hydrological system, their potential to mediate or buffer the wider effects of hydrological extremes at local to catchment scales could change in response to changes in their hydrological functioning.

1.2 Buffering of hydrological extremes

High flows

Downstream flooding can be mitigated via the delay of flood peaks, attenuation of flood peak discharge or through reduced volume of runoff. The capacity of a wetland to buffer the effects of flooding is commonly highlighted as a service that naturally functioning wetlands offer. Key spatial controls include wetland location within a catchment, its size and the distance from a receptor (e.g. downstream urban community; Larson, 2009). However, certain wetlands may have the opposite effect by functioning as net contributors to flooding (Bullock and Acreman, 2003) whereas some wetlands may have no effect on flood generation and moderation as a result of being isolated from stream networks (Larson, 2009). In temperate regions, generally, wetlands hydrologically connected to headwater streams in upland areas tend to be flood generating as soils are often saturated due to high rainfall input and poor drainage leading to rapid saturation excess overland runoff (Acreman and Holden, 2013; Scheliga et al., 2018). In contrast, floodplain wetlands adjacent to higher order rivers downstream, are larger and have more permeable soils thus offering greater capacity to attenuate flood peaks (Bullock and Acreman, 2003). Aside from these catchment position controls, the inherent roughness, topography, soil characteristics and vegetation of a floodplain wetland, as explored further below, present further controls on the precise response to a flood wave in a wetland. Generally, extensive floodplains with numerous channels, hollows and rough vegetation have a greater capacity to slow flood waves, store excess surface water and slowly release water following cessation of a flood event (Acreman and Holden, 2013).

Low flows

Some wetlands also have the potential to buffer the effects of dry periods and low flows through sustaining groundwater outflows that in turn maintain baseflows in watercourses. However, most wetlands compared to other habitat types, tend to reduce streamflow during dry periods by reducing inputs to baseflow (Bullock and Acreman, 2003). This reflects the retention of water and through loss to the atmosphere through evapotranspiration. The ability to buffer the effects of dry periods is nonetheless dependant on the wetland type. For example, floodplains, and the wetlands they potentially support, have water tables strongly coupled to the level of water flow within the adjacent stream or river (e.g. Burt et al., 2002; Addy and Wilkinson, 2021). During periods of low river flow, a hydraulic gradient between the floodplain and adjacent watercourse tends to exist. This directs groundwater into the watercourse thus helping to sustain the baseflow of that watercourse during dry periods (Burt et al., 2002). Floodplain deposits represent a potentially large store of groundwater and major source of baseflow in the headwaters of large catchments (Tetzlaff and Soulsby, 2008). Peatlands (blanket bog and raised bogs) represent a potentially large store of groundwater in upland catchments as already summarised in Appendix II. In a typical large catchment, compared to other wetlands they can cover a larger proportion of the areas of a catchment. Their contribution towards sustaining river baseflows has been observed to be limited on account of their low hydraulic conductivity (Evans et al., 1999) but restoration of degraded peatlands could improve water holding capacity, aid groundwater recharge and potentially provision of baseflows (Wilson et al., 2011; Fennell et al., 2020).

1.3 Controls on capacity of wetlands to buffer hydrological extremes

The arrangement and extent of wetlands

The arrangement and extent of wetlands also represent major controls on the hydrological buffering capacity of wetlands. Hydrological models have been used to explore the possible catchment scale effects of climate change on wetland functioning. For example, based on modelling of a Canadian catchment with a dry continental climate, wetlands positioned close to water courses were predicted to play an important role in attenuating high flows that was disproportionate to the number of, and size of wetlands (Ameli and Creed, 2019). In contrast, with increasing distance from watercourses, the attenuation function through storing excess surface water, declined. In the same study, it was found that loss of wetlands led to predicted increased peak flows and generated flooding downstream. Loss of wetlands has also been predicted in another Canadian study to compromise the baseflow contribution they provide during dry periods, but responses are catchment specific (Fossey and Rousseau, 2016). The size of wetlands also determines their vulnerability to future changes and wider hydrological effects; small, hydrologically isolated wetlands are less resilient to human or natural change compared to larger wetlands that are well connected (Acreman and Macartney, 2009). Thus, loss or further shrinkage of such vulnerable wetlands may reduce the potential for catchments to buffer future hydrological extremes. Expanding the number and size of wetlands through restoration, creation and appropriate management that improves their connectivity to sources of water supply (Appendix IV), has the potential to improve the buffering capacity of isolated, small wetlands.

Vegetation

Changes in vegetation through land use or climatic changes have the potential to affect the hydrological character of a wetland through altering the evapotranspiration regime, roughness, soil water infiltration and canopy storage. In the UK, it is anticipated that reduced summer rainfall and increased summer evapotranspiration will put additional stress on plant communities within wetlands in the late summer and autumn months especially in the south and east (Acreman et al., 2009). Reduced vegetation cover through overgrazing or deforestation can lead to decreased infiltration (thus reducing soil moisture storage and potentially groundwater recharge) and lower the surface roughness leading to increased surface runoff (Marshall et al., 2014). Changes in vegetation type could also alter patterns of water loss through evapotranspiration. In addition to these aspects, increased frequency of hydrological extremes predicted under climate change is a further factor. Extreme droughts or floods could lead to crossing of hydrological thresholds for the vegetation communities characteristic of a particular wetland type leading to disappearance of certain species, changes in wetland community type and prevention of any recovery (Acreman et al., 2009; Appendix VII). These changes in vegetation could in turn alter the characteristic hydrology of a given wetland type and the buffering capacity.

Groundwater

In Scotland, groundwater contributes to at least 30% of the flow in most rivers (Ó Dochartaigh et al., 2015). Groundwater is an important reserve of water because of its potentially large volume within a catchment and its role in supplying rivers with continuous water input when seasonally dry periods reduce rainfall and surface water runoff and storage (McCartney and Acreman, 2009). However, relatively small changes in temperature and rainfall regime could result in large impacts on groundwater recharge and in turn the condition of aquifers. Lowering of water tables due to climate change is expected to be an effect in many wetlands (Freeman et al., 1993). An indirect effect of climate change could be increased human use of aquifers through groundwater abstraction as other sources of water supply become less reliable. This could result in depleted groundwater reserves that in in turn lower water tables that affect wetland (Acreman and McCartney, 2009) and wider catchment hydrology.

Soils

Wetland soils have an important role in retaining excess water and hence flood regulation (Cook et al., 2009). Soils could change in nature under climate change but predicting change is difficult due to the inaccuracy of global circulation models and the short-term nature of experiments (Cook et al., 2009) but it has been predicted that soils during summer months generally will become drier for longer (Appendix VI; Acreman et al., 2009). A recent study from a Scottish headwater catchment with peaty soils has shown the cumulative effect of a dry winter followed by a dry summer led to abnormally low soil moisture; such changes could make the soil more prone to fire risk and degradation (Soulsby et al., 2021). Moreover, more frequent drought episodes could make certain soils hydrophobic thus leading to increased surface runoff during storm events. However, the precise hydrological response will vary depending on the soil type and landscape position within a catchment; some wetlands may have greater capacity to store water during the summer months. Factors such as the depth, organic matter content, particle size distribution and presence or not of macropores and cracks are important determinants of the storage capacity of soils.

Evapotranspiration

As all wetlands are affected by evapotranspiration, it represents an important control on water balance. With climate change, evapotranspiration rates are expected to increase as atmospheric temperatures increase. In general, wetlands evaporate more water than other types of land cover (Bullock and Acreman, 2003) thus evapotranspiration changes could significantly alter the hydrology of wetlands (e.g. Thompson et al., 2017). The effect of changing evapotranspiration however will vary depending on the wetland type. In open-water dominated wetlands, evapotranspiration is not limited by water availability compared to wetlands where the water table is frequently below the surface where vegetation controls the evapotranspiration regime (McCartney and Acreman, 2009). Evaporation from wetlands where the water table is below surface may be less than cases where surface and/or open water dominates and may be correlated with the water table depth (Acreman et al., 2003). Thus, wetlands with open-water storage may be particularly vulnerable to the effects of future droughts.

Timescales

It is important to note that hydrological functioning and thus buffering capacity of wetlands varies temporally over a variety of time scales. Long term (e.g. decadal), seasonal and event scale temporal factors result in important changes to used and available storage of water within a wetland At the event scale, for example a high rainfall or snowmelt event or period of drought over a longer timescale, the antecedent hydrological condition of the wetland in part determines the response.

For example, a floodplain wetland already saturated with a high water table during winter, is unlikely to provide as much of a flood attenuation service in response to a rainfall event as the same wetland during summer conditions with a lower water table.

2. Buffering capacity of different wetland types

2.1 Upland wetlands

Surface water slope

Blanket bog

Healthy blanket bogs tend to be dominated by high water tables all year round (Appendix II) and rapid saturation excess overland flow with high event runoff coefficients of around 0.6 (i.e. the proportion of rainfall that runs off; Tetzlaff et al., 2007). Generally, such areas have little capacity to reduce flooding. This characteristic is broadly true of upland wetlands in general that have little spare capacity to store additional rainfall and thus mitigate floods (Acreman and Holden, 2013).

Given the projected increases in winter rainfall and decreased snow cover, winter is likely to be the most dominant period of heightened flood generating conditions. Observations in the Bruntland Burn catchment, north-east Scotland, give hydrological insights into a catchment with valley bottom blanket bog during the exceptionally wet winter of 2015/2016 (Scheliga et al., 2018). During the very wettest periods, the catchment was almost fully saturated with no spare capacity following previous snowmelt and rainfall events. As a result of these antecedent conditions, riparian peat soils were almost fully saturated and over large areas that connected to the stream resulting in exceptionally high stream flows that contributed to the > 1 in 200 year 'Storm Frank' flood event in this catchment (Scheliga et al., 2018).

In contrast to these hydrological responses during very wet periods, in dry summer conditions when water tables are lower in blanket peat, there can be available water storage. A study from the peatlands in Minnesota, USA, showed that for two storms of similar volume and intensity, responses in the peatland varied between the spring in summer. In response to the summer event, the lower water table prior to the event compared to the spring, meant the available storage was not exceeded, resulting in reduced surface runoff (Boeler and Verry, 1997). This suggests that during dry periods provided the blanket peat is healthy, there may be improved capacity in the short term to mitigate flooding prior to re-saturation of the peat when the peat loses its high flow buffering capacity.

Degradation of blanket bog caused by climate change or land use change can further alter the ability of such wetlands to buffer floods. Degradation results in more frequent piping and cracking (Appendix I and II; Section 1.1) that can accelerate runoff (Holden, 2005). Areas with high soil moisture deficits may also enhance surface runoff during the summer. Sometimes after dry periods or wildfires, peat soils dry out and become hydrophobic so even if there is capacity for water storage within the soil it is not readily absorbed leading to infiltration excess overland (Hortonian) flow (Holden et al., 2014). Increased drying out of peat due to climate change, drainage, increasing incidence of deliberate or wild-fires, or increased groundwater abstraction, may as a consequence, accelerate runoff responses during dry periods leading to heightened flood peaks downstream (Acreman and Holden, 2013). Moreover, long-term drying out of peat could affect their ability to retain water by altering their physical structure (Huesco et al., 2012). Restoration through drain blocking can help to improve the flood buffering capacity of degraded blanket bog by increasing surface pooling (Wilson et al., 2011) although complete recovery may take years (Holden, et al., 2011).

Changes in peatland vegetation could also affect the potential for flooding. The water retention capacity of healthy, undegraded peatland ecosystems is slightly improved during the summer growing season when evapotranspiration is higher than in winter because of the periodic lowering of the water table (Kolmanova et al., 1999). One consequence of climate change or overgrazing may be increased erosion of sloping peat reducing vegetation cover (Heathwaite, 1993). This could result in more and larger extents of bare, exposed peat which is more prone to surface runoff than vegetated surfaces with higher roughness, leading to increased flood risk (Shuttleworth et al., 2019). Small blanket bog catchments (<0.01 km^2) restored with *Sphagnum* planting and drain blocking, reduced peak flows by 27% and increased lag times by 106% compared to bare peat control sites Furthermore, the loss of *Sphagnum* cover characteristic of healthy blanket bog, either directly or indirectly, could reduce the water storage capacity it potentially offers (Appendix II).

Deep peat bogs in headwater areas can be extensive (Appendix I) and are a contributor to the baseflow of streams that have their source in such areas. However, when compared to other soil units at the catchment scale, peaty soils generally tend to contribute less groundwater towards sustaining baseflows and are characterised by low Baseflow Indices (BFI < 0.3; Tetzlaff et al., 2007). In catchments in the Cairngorms dominated by hydrologically responsive peat soils, groundwater contributions towards total runoff have been observed to be less than 35% with short residence times (less than 0.5 year) compared to those dominated by more freely draining soils (e.g. alluvial soils), where runoff contributions of older groundwater were greater than 40% (residence times greater than 1 year; Soulsby et al., 2006). The contribution of groundwater towards sustaining baseflows in very dry periods may be further compromised when soil moisture and water tables become depressed. In the Bruntland Burn during the exceptional drought of summer 2018, soil moisture storage across the catchment was less than half the summer average and groundwater levels were 0.5 m lower than average resulting in a large catchment storage deficit (Soulsby et al., 2021). Over May to September, very low stream flows equivalent to a total of 100 mm of precipitation (mean annual precipitation: ~1000 mm), were supplied almost completely by groundwater. The study of Evans et al. (1999) showed the baseflow contribution of peatlands during the dry summer of 1995 in the northern Pennines was limited despite near record rainfall during the preceding winter and water tables being never lower than 42 cm. For example, flows in August of that year in the Troutbeck catchment (11.4 km^2) were less than 5% of the mean daily flow for the three-year period (0.49 m^3/s). The implication they suggested was that higher rainfall projected during the winter months due to climate change would be lost as excess runoff and not contribute to sustaining summer baseflows. In boreal peatlands where blanket bog had been degraded due to drainage, water table levels were lower than natural examples (Haapalehto et al. 2014) and so compromised groundwater contributions towards sustaining baseflows.

Wet heath

Specific information on the buffering capacity of undisturbed wet heaths is limited but as outlined in Appendix I and Appendix II, their hydrological characteristics are broadly similar to that of blanket bog. As a result, similar sensitivity to wider hydrological changes and capacity to mitigate hydrological aspects would be expected. As wet heath is a semi-natural habitat influenced by the management of grazing and drainage, it is thus sensitive to land management changes including tree planting (SNIFFER, 2014). Vegetation communities characteristic of wet heath require periodically high water tables in the winter and are vulnerable to dry conditions (Elkington et al., 2001). Thus, change to dry tolerant vegetation communities (potentially succession to tree cover) and in turn altered hydrology, may result from the drying out of wet heaths due to land drainage or climate change. Wet heaths can occur both in basins and gentle slopes (SNIFFER, 2014). Wet heaths that are isolated, (e.g., occur in topographical basins) are less likely to buffer the downstream effects of hydrological change on stream networks compared to those that occur on sloping ground. Restoration that seeks to increase the area, condition where degraded, and number of wet heath habitats could increase the buffering capacity of such wetlands (Appendix IV).

Surface water depression

Depressions of peat substrates

Occurring adjacent to or within areas of blanket bog and raised bog, it would be expected that depressions on peat substances have similar characteristics. However, the small and isolated nature of such features (Stalleger, 2008) makes the characteristic vegetation communities both vulnerable to change and unlikely to have a major role in buffering hydrological extremes. Reduction in the underlying water table and soil moisture is an effect of peat drying through drainage or droughts that results in surface subsidence (Alshammari et al., 2018). This could in turn alter the depth and extent of surface micro-scale hollows that enhance surface water storage and roughness but knowledge is lacking on the nature of such potential changes.

Groundwater slope

Base-rich fens, alkaline fens

Fens that are separate from rivers and therefore don't receive surface water inputs, have the capacity to store water and create surface runoff but they tend to hydrologically respond to longer wet and dry phases than short term rainfall (Acreman and Holden, 2013). There is a dearth of information on how these types of wetland may influence floods at larger catchment scales (Acreman and Holden, 2013). However, given their small and isolated nature and near constant groundwater discharge, their ability to buffer floods is likely to be limited.

Fens may play an important role in maintaining baseflows in upland catchments during dry periods through their connection to shallow or deeper aquifers within drift materials and fractured bedrock. Studies of the geochemistry of alkaline springs and groundwater seeps in the Girnock Burn in north-east Scotland, showed that such sources were important for sustaining baseflows in contrast to water sourced from soil (Soulsby et al., 2007). Extended droughts, abstraction or land drainage and afforestation could reduce the ability of fens to sustain baseflows by reducing aquifer recharge.

2.2 Lowland wetlands

Surface water depression

Raised bogs

As raised bogs are dominated by peat soils, their ability to buffer hydrological extremes is likely to be limited as it is for blanket bogs previously detailed. Furthermore, nearly all raised bogs are degraded (Appendix I). However, there may be some important differences in their hydrological functioning and potential changes under climate change compared to blanket bog. Firstly, raised bogs are scattered in their distribution and tend to be isolated which may make them more vulnerable to change. Further shrinkage in their number and size and condition could reduce their groundwater contribution to sustaining baseflows. Raised bogs in good health and their association with intact lagg fens are important aspects to consider. Such raised bogs are likely to have a greater potential to buffer floods in the summer months when available storage is higher (Appendix II; Bragg, 2002). Restoration of degraded raised bogs that includes restoring their associated lagg fens may help to improve their ability to buffer floods in summer (Appendix IV). Secondly, it has been suggested that higher temperatures and longer dry periods could result in the invasion of uncharacteristic vegetation communities. (Niedermair, 2007 from Stallegger et al., 2008). Depending on the nature of vegetation community change, this could further lower water tables especially during dry periods that could improve spare capacity for water storage assuming hydrophobic soil conditions don't develop. Thirdly, it has also been suggested that increased rainfall may lead to the expansion of peat at lower elevations (Heathwaite, 1993). Expansion of raised bogs could in turn alter the effect of raised bogs on wider catchment hydrology.

Groundwater slope

Transition mires, open water transition fens and quaking bogs

With the exception of groundwater fed transition fens that exhibit variable water tables, transition mires, open water transition fens and quaking bogs are characterised by high water tables throughout the year and often experience periods of surface water inundation (Appendix II). Their spare capacity for storing excess floodwater is therefore limited. The projected increase of winter rainfall and associated river flows or higher loch levels, would be expected to increase the saturation levels during the winter given the hydrological connection to such waterbodies. This could further impede the ability of these wetlands to mitigate flood events and lead to the increased incidence of localised flooding. However, as these wetlands are often restricted by adjacent land use or drained (Appendix I), allowing them to expand and naturally fluctuate in response to rainfall could help to improve their flood buffering capacity (Appendix IV).

The increased frequency of water supply during the winter, may in turn increase the duration of saturated water storage and help to aid the maintenance of baseflows during dry conditions. The rise in water tables could lead to the conversion to swamp wetlands characterised by deeper and more permanent standing water features (SNIFFER, 2014). However, the likelihood of this would be checked by projected increases in summer evapotranspiration that could lower water tables and increase the availability of spare water storage capacity during storm events. In the case of quaking bogs, this could lead to the loss of the characteristic floating vegetation rafts if they become anchored to the substrate during dry periods (SNIFFER, 2014).

Base-rich fens

The capacity of base-rich fens to mitigate flooding will vary depending on the topographical setting. Base-rich, riparian fens connected to watercourses may have limited capacity throughout a typical year for storing excess floodwater compared to those situated in troughs and basins that have more variable free storage (Appendix II; Duvall and Waddington, 2018). Thus, trough and basins may have slightly more capacity to store water during floods resulting in localised flooding in these areas.

Being mainly sustained by groundwater and usually smaller contributions of rainfall and surface water, base-rich fens may play an important role in sustaining baseflows during droughts. Like their upland counterparts, provision of this function is vulnerable to any changes in the water supply regime as a result of climate change, land use changes, or groundwater abstraction.

Reedbeds and swamps

As reedbeds and swamps occur in topographical hollows and basins they may provide local flood risk mitigation, although information on the services they provide in general is limited (SNIFFER, 2014). As they are often hydrologically linked to nearby water courses or lochs (Appendix II), their water levels can fluctuate. This results in variable spare capacity for water storage during flood events with the amount of surface storage determined by the size and number of hollows, which can be considerable for example in intact floodplains containing oxbow lakes and relict channels. The accumulation of surface water in turn facilitates loss through evapotranspiration. The tall and dense vegetation that can occur in reedbeds or swamps would be expected to offer greater hydraulic roughness than grassland (Chow, 1959). Thus, increased surface roughness of such wetlands would be expected to slow surface flows and attenuate flood peaks during floodplain inundation events more effectively than wetlands with shorter vegetation.

As the presence of large areas of surface standing water is a feature of swamps and reedbeds, they may be particularly vulnerable to water loss through evapotranspiration during periods of drought or through drainage. This could in turn impair contribution towards sustaining baseflows.

Groundwater depression

Basin fens
By definition, as these wetlands are isolated and have poor outflow surface water connectivity, it is likely they can have a downstream impact on catchment scale flooding. As basin fens are characterised by more variable water levels than fens supplied by watercourses and lochs (Duvall and Waddington, 2018; Appendix II), they may at times have more capacity to store water during summer flood events than their floodplain counterparts, resulting in localised flooding within the basin fen.

Given the hydrological disconnection from water courses and their isolated nature, it is likely that basin fens provide a more limited role in sustaining baseflows during dry periods than other wetlands that are hydrologically better connected.

Floodplains

Floodplain fens
Floodplain systems and the variety of wetland types they support, provide capacity for floodwater storage primarily within the soil and ground surface in hollows. The flood regulating service that naturally functioning floodplain systems provide is well recognised. For example, the semi-natural Insh Marshes on upper River Spey which contains base poor fens and other wetland habitat types, provide an estimated average annual saving of £83,000 in avoided downstream flood damage (Davis, 2004). Controls on the capacity of floodplains to attenuate floods include the degree of connectivity between the river and its floodplain (i.e. extent and height of flood embankments), the roughness of the floodplain as determined by the vegetation and extent of topographical low points that collect water (Acreman and Holden, 2013; Czikova et al., 2013). Climate change could lead to increased seasonality of flood buffering capacity. With anticipated increases in winter flooding frequency, the availability of spare capacity is likely to be more limited during the winter compared to the summer months.

As outlined in Appendix II, floodplain fens together with other floodplain wetlands represent a potentially significant source of groundwater that could help to mitigate the effects of droughts on baseflows. Floodplain fens however are often degraded through drainage for agriculture (Appendix I) resulting in changes that compromise their hydrological functioning (Kondolf et al., 2006). For example, drainage of fenlands in the River Ouse catchment in eastern England, led to loss of peat soils and lowering of the land surface by several metres. This has left remaining undisturbed fens isolated and more vulnerable to the impacts of further drainage and groundwater extraction (Lock et al., 1997). This could in turn further limit the ability of such wetlands to buffer hydrological extremes in future. The expansion of the area of floodplain fens through restoring drained areas and restoring hydrological connectivity to the adjacent watercourse, could help to reinstate their buffering capacity.

2.3 Wet woodlands

Groundwater depression; Groundwater slope; Floodplain

Fen and alder woodland
As outlined Appendix II, forest covered wetlands have temporally variable water tables and soil moisture capacity depending on tree water usage, evapotranspiration and thus variable spare capacity to store floodwater. The conditions of the trees (density, age, size and phenology) and other vegetation also affects surface roughness and in turn further influence the attenuation of high flows through reducing floodplain conveyance (Thomas and Nisbet, 2007).

Fen woodland may increase in extent if water tables in open fens drop as a result of climate change or land drainage. Depending on the density and maturity of the trees, this could thus increase the spare soil capacity available for floodwater storage through increasing atmospheric loss through transpiration. Such a change however could negatively affect groundwater contributions towards sustaining baseflows during dry periods and lead to the loss of the characteristic vegetation community.

Surface water depression

Bog woodland

It has been suggested bog woodland provides a flood regulating service (SNIFFER, 2014) however their capacity may be limited as it is for open raised bogs and blanket bogs with seasonal variations of water table dictating availability of spare capacity (Appendix II). Flood regulation is also dependent on any longer temporal changes in the nature of the trees and the water balance of the surrounding bog. Increasingly dry summers may result in the lowering of the water table and invasion of uncharacteristic invasive vegetation that could in turn affect the flood regulating service (SNIFFER, 2014). Conversely, if conditions become wetter, trees may decline, and the bog could change to an open raised bog (SNIFFER, 2014). As bog woodlands are isolated and have limited extents where they do occur, they may be especially vulnerable to such changes.

As explained earlier (Section 2.1), the baseflow contributions of peatlands and raised bogs and in turn the capacity to buffer the effects of dry periods in general is limited. A similar and perhaps even more limited role given the tree water usage, would be expected in the case of bog woodlands.

2.4 Wet grassland and floodplain meadows

Groundwater slope; Floodplain

Fen meadows, wet meadows and marshy grassland

Marshy grassland, fen meadows or wet meadows that occur on floodplains provide a number of ecosystem services including flood mitigation (SNIFFER, 2014). Reflecting the seasonality of water tables (Section 2), capacity to mitigate floods in such wetlands is most likely to occur during the summer months. As these wetland types have water tables that are strongly controlled by the adjacent water course, increased winter flood frequency predicted due to climate change, could lead to changes in vegetation communities as predicted for the River Shannon in Ireland (Maher et al., 2015). Wetter conditions could result in conversion to swamp and inundation grassland wetlands (Rothero et al., 2016). Conversely, floodplain wet grasslands have been predicted to exhibit greater seasonality of water tables but become drier overall under climate change in the south-east of England leading to changes in vegetation community (Thompson et al., 2017). These possible changes in vegetation community under different scenarios, may in turn alter the vegetation water usage patterns and surface roughness characteristics thus influencing the flood mitigation role of such wetlands. Marshy grassland supplied by groundwater seepage are unlikely to have a substantial flood mitigation role given their upland locations, small size and typically stable groundwater discharge regimes.

Fen meadows, wet meadows and grassland are likely to play a role in recharging floodplain aquifers and thus sustaining baseflows during dry periods. Moreover, groundwater dominated marshy grassland is likely to represent an important source of baseflow during dry periods through their groundwater contribution. Nonetheless baseflow provision is vulnerable to long term changes in climate and land use or groundwater abstraction that could alter the characteristic water balances.

Other types

Transition grasslands

Where they occur within floodplains, transition grasslands are likely to have broadly similar flood mitigation and baseflow contribution services to that of floodplain fen meadows and wet meadows described above with seasonally variable water tables.

Transition saltmarsh
Salt marshes provide a wide range of ecosystem services including attenuating wave height and storm energy (SNIFFER, 2014). Transition saltmarshes would be expected to play a similar role but their capacity to mitigate storms may alter through climate change related sea level rise. Sea level rises of up to 61 cm in Scotland have been predicted (Fung et al., 2018) and storm surge extremes may increase in the North Sea region (Woth et al., 2006). This could lead to alterations in the eco-geomorphology of saltmarshes and transition saltmarshes. In some cases, inundation due to chronic sea level rise could result in the complete loss of such wetlands and thus the services they provide (Kirwan et al., 2010). However, salt marshes have capacity to adjust to changing sea levels through inland migration if there is an adjacent natural transition wetland present (SNIFFER, 2014). Thus, transition saltmarshes may convert to true salt marshes due to climate change. Moreover, through feedbacks of vegetation growth, sediment deposition and organic matter accretion, salt marshes have the ability to adapt to slower rates of sea level change (Kirwan et al., 2010).

3. Knowledge gaps

Based on the review of literature sources outlined above, the following wetland types appear to be under studied in terms of buffering capacity:

- Depressions on peat substances
- Base-rich fens
- Transition mires and quaking bogs
- Open water transition fens
- Basin fens
- Bog woodland
- Transition grassland
- Transition saltmarsh

In general, there is a lack of empirical field-based studies that assess the role of wetlands during dry and wet periods in influencing streamflow generation.

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4. Appendix IV: Wetland Health

by Andrew McBride and Gillian Donaldson-Selby

0.1 Research questions

The key research questions that this section sought to answer were:

- *What is meant by wetland health?*
- *What do Site Condition Monitoring results indicate in terms of wetland condition?*
- *Does Site Condition Monitoring measure wetland health?*
- *What is the condition of the whole wetland resource?*

0.2 Objectives

- Estimation of wetland health.
- Use knowledge from literature on designated sites to provide qualitative estimates as to the proportion of healthy wetland in designated sites and other sites.
- Provide qualitative estimates of wetland health.

0.3 Approach

This review included a definition of wetland health and condition, a review of current data, assessment of the total area occupied for each of the described habitat types, the proportion that is under designation, and used grey literature searches to identify any further evidence for non-designated sites. We then extrapolated from this data to estimate the condition across the full area for each wetland type in Scotland.

1. Introduction to Wetland Health: What does this mean?

1.1 Definition

A review of the literature on wetlands, specifically, provides several notable guides and indicators of health and degradation, including the water balance, that could be used for assessing wetland health. However, faced with the complexity of a wetland system it is often difficult to define the state of health. Due to the huge diversity of wetland types, there is no one clear definition that describes a healthy wetland. A reasonable way to describe wetland health is the comparison of the wetland of interest with similar sites that are considered fully functional. This is clearly subjective and relies on there being sites in good health to make that comparison that could provide an idea of comparative health from the benchmark. The hydrological requirements of each wetland type could be clearly defined in terms of acceptable levels and range, but this is not currently available. Measuring attributes over time as in Site Condition Monitoring (SCM) provides a method for measuring aspects of wetland health but depends on the scope and frequency of the attribution measurement. Depending on those attributes, if the wetland's structure and function no longer measure up to the potential benchmark of healthiness, it could be termed unhealthy.

Costanza (1992, p248) defines ecosystem health "*as a comprehensive, multiscale, dynamic, hierarchical measure of system resilience, organization, and vigour*". Mountford (2018) notes, for example, that the chief purpose of biological wetland assessment is the quantitative and qualitative description and enumeration of the species, communities, and habitats present; and that to achieve, this an inventory is needed, which should include:

- Wetland attributes
    - physical properties like extent and features within the site
    - species composition
    - structure
- Soil
- Water chemistry
- Hydrological characteristics

According to Karr et al. (1986), "*a biological system ... can be considered healthy when its inherent potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support for management is needed*.''

In some cases, definitions of wetland health are strongly anthropogenic and see the wetland function in the terms of floodwater and sediment retention, recreation, biomass production, carrying capacity and water purification.

Rapport et al. (1985) popularized the word "ecosystem health", as a form of biological system dependability and maintainability, which has the capacity for keeping up its organisational structure as well as natural regulating and recuperation capacity after resilience. Das et al.(2020), produced an excellent summary of the range of approaches to evaluate wetland health. The evaluation of wetland environment wellbeing is done by using qualitative assessment methods and techniques to combine quantitative and qualitative assessments. Patience and Klemas (1993) provide a good outline noting Ecosystem health evaluation involves: 1) the identification· of systematic indicators of ecosystem structural and functional integrity, 2) the measurement of ecological sustainability and 3) the detection of potential symptoms of ecosystem disease or stress (Rapport, 1989). Four types of indicators may be distinguished (Leibowitz et al., 1991): 1) response indicators, which provide a metric of biological condition (e.g., vegetation community composition); 2) exposure indicators, which assess the occurrence and magnitude of contact with a physical, chemical, or biological stressor (e.g., nutrient concentrations); 3) habitat indicators, which characterize the natural physical, chemical, and biological conditions necessary to support an organism, a population, or a community (e.g., wetland hydrology); and 4) stressor indicators, which quantify natural processes, environmental hazards, or management actions that result in changes in exposure or habitat (e.g., changes in land use). Indicator selection must be parsimonious, including only those that most effectively define wetland condition.

Researchers, practitioners, and catchment managers have used water, soil, vegetation, and other related indicators for determining the health conditions of wetlands. Until recently wetland health measurements have used field observation data and models to assess the wetland ecology. Péron et al., (2013) observed water birds as an indicator of wetland health. Albert and Minc (2004) indicated plants as regional indicators of lake ecosystem health. Shil and Singh (2017) used water quality data for determining the health condition of a wetland. Field observation data cannot map and predict the spatial and temporal scenarios of wetland ecosystem health. However, with high efficiency and multi-phase information, remote sensing is increasingly used to determine and observe the ecosystem health over extensive areas and through a regular time series. However, field observations are required to validate the remote output.

Clearly the definition of wetland health is as complex as the wetland systems it seeks to assess. Although the terms condition and health are often interchangeably used, there is a distinction. Wetland health is a holistic concept that not only includes the assessment of condition, through the identification of relevant indicators, but also assessment of potential stressors and the ability of the wetland system to resist and also affect some form of internal self-repair once stressors have been removed. Wetland health can be considered similar to human health; for example, a doctor could assess the condition of a patient from an external examination and by inference from indicators have an insight to the patient health. However, to understand the whole-body health further examination and testing would probably be required and the results of which may require expert interpretation along with an assessment of the prognosis and management of the condition to resume good health through treatment and self-rejuvenation.

For the purposes of this study wetland condition is the measurement of indicators such as positive and negative vegetation indicators at a broad visual scale that generally relate to physical wetland structure at a specific juncture in time. Wetland health however, includes all condition indicators and goes further to include the hydrological functionality, water quality and ability of that wetland feature to perpetuate and sustain over time. The hydrological health underpins all the other condition aspects that are measured, and without hydrological health the wetland will not fully function. This requires both site-based monitoring over long time periods, the use of modelling and expert assessment.

1.2 Assessment of wetland health

1.2.1 Sources of information used

Site Condition Monitoring

Site Condition Monitoring (SCM) is the main data source for assessing the condition of wetlands in Scotland. The information is from only designated areas and freely available on Scotland's Environment web pages : https://www.environment.gov.scot/data/data-analysis/protected-nature-sites/. The SCM is run in 6-year cycles; Cycle 1: 1999 – 2005; Cycle 2: 2005 – 2012; Cycle 3: 2012 – 2018; Cycle 4: 2018 – 2024). With over 700 individual Upland and Lowland wetland features to be monitored it is unsurprising that not all features are monitored in every cycle. SCM has common standards for both upland and lowland wetlands. The monitoring covers specific attributes including habitat extent, structure, vegetation composition and indicators of negative change. The method relies very heavily on the vegetation and response to external inputs. Following the assessment, the feature is attributed a condition category. The uniform methodology and data collection make this a good resource for wetland health information.

Note: SCM is progressing to a 3-tiered monitoring approach, with Tier 1 being a brief Site Check, Tier 2 equates to SCM and Tier 3 that applies to wetlands includes the option for detailed commissioned studies on for example, hydrology or water quality, possibly beyond the site boundary.

State of the Environment Wetlands 2014

The State of the Environment (Wetlands) 2014 Report suggests that the state and trend for Scottish wetlands was Poor - high agreement, medium evidence and Trend: Stable/declining - high agreement, low evidence. The assessment was based on the level of agreement between the specialists involved, and the quality and quantity of the supporting evidence. Most of the supporting evidence relates to SCM data on designated sites.

Article 17 Reporting

Every six years, all EU Member States are required to report on the implementation of the EU Habitats Directive (under Article 17). Article 17 Reporting includes assessments of the condition of all Natura habitats, whether within or out with designated sites. In theory it should provide a reported insight into the condition of non-designated sites. The last Report was delivered in 2019. The reported data sheets suggest the following with regards to condition, in most cases best estimates are based on '*extrapolation from a limited amount of data'.* The assessments are generally based on the results of the most recent SCM which in some cases could predate the previous Article 17 Report.

1.2.2 Sources of information not used

Agri-environment Schemes

Agri-environment schemes (AES) are the main European policy response to biodiversity loss caused by agricultural intensification. Maximizing their effectiveness is a key policy challenge for the Scottish Government. Wetland management and creation are included in the scheme prescriptions. There is no specific wetland monitoring and research papers tend to focus on specific species and not the wetland health. By way of the scheme scoring system, activities are focussed on designated sites, and as such the expectation is that monitoring wetland health is recorded in SCM. Data and information from Scottish Government AES is difficult to access and tends to relate to specific prescriptive items rather than wetland health and so in this case was not requested.

Scottish Wetland Inventory

As part of the response to the Water Framework Directive, the Scottish Wetland Inventory started in 2010 and was developed by assimilating spatial data from NatureScot (SNH). The data relates to designated sites only and the whole country has not yet been surveyed and as a result the dataset only displays known wetlands. The wetland inventory database comprises a number of fields that include the main WFD95 wetland type which relates to water supply and levels. Through the WFD95 project, water level threshold requirements for surface water and ground water dependent wetlands were established for a limited number of sites/wetland types. These thresholds will inform the connection between water pressures and wetland impacts, but to date the range of sites has not been extended. The sites where information was collected was on designated sites so this could relate to SCM. Further details can be found at [Development of a Scottish Wetland Inventory (sepa.org.uk)]

The dataset has poor coverage of non-designated sites, but in the future could provide a good foundation to link wetland spatial data and wetland health.

NES BEC Northeast Scotland Wetland Inventory 2007 *(Amanda Biggins and Ian Francis (RSPB Scotland) unpublished)*

The Northeast Scotland wetland inventory examined the current wetland resources of Moray, Aberdeenshire and Aberdeen City, with the principal aim of identifying sites with potential for restoration, expansion or creation and as such the health or current condition was not specifically monitored.

Lowland Raised Bog Inventory 1994

Lowland raised bogs are the focus of this report, which brings to a close the National Peatland Resource Inventory (NPRI) lowland raised bog survey of Great Britain. It includes data supplied to the NPRI up to December 1994 and comments received up to January 1996. The Inventory lists all known existing or former lowland raised bog sites and provides an estimate of their presumed former extent as recorded by the British Geological Survey. The inventory base data does provide some indication of habitat condition of the whole lowland raised bog resource, but this information is no longer current to assess wetland health.

Development Environmental Impact Assessments/ Statements Phase 1 and 2 Surveys

Environmental Impact Assessment (EIA) is a process of evaluating the likely environmental impacts of a proposed project or development. Developers are expected to describe baseline information, but this does not include consideration or assessment of the ecosystem or habitat. EIA do usually map the different habitats present and could provide information on the wetland condition depending on the surveyor's assessment. These are often not made publicly available or are stored disparately and difficult to access as a whole resource.

1.3 Analysis of the usefulness of information sources

Site Condition Monitoring

The Joint Nature Conservation Committee (2009, 2004) define a broad range of attributes that should be part of the conservation objectives for any wetland site. These relate to the original selection and designation of the designated sites and include:

- Habitat extent: Total extent of the wetland vegetation.
- Habitat composition: On some sites only a single component wetland may be present, but in others there may be multiple components in an intimate or extensive mosaic.
- Habitat structure: Important structural elements such as surface patterning (hummocks, hollows, and pools), as well as exposed substrate.
- Vegetation composition: positive indicator species, e.g., floristic structure, focusing on plant community (NVC) level for topogenous and soligenous fens and at supra-NVC level for ombrogenous mires.
- Vegetation composition: indicators of negative change, including invasive and or non-native species, indicators of vegetation change which are inappropriate to the site interest.
- Vegetation composition: indicators of negative change (undesirable woody species), for example, the presence of wet woodland may a) indicate drying out of fens and bogs and b) perpetuate drying out with birch, pine, willow, and rhododendron as being species of concern. In previously forested peatlands/or forests adjacent to wetland sites, conifer regeneration is a problem.
- Indicators of local distinctiveness. Features that make a site special – e.g., rare or uncommon species, structural features, and habitat mosaics

When monitoring wetlands, the perspective is on condition at one point in time whereas wetland health which involves the functionality of the wetland system and not just the condition which is historical as it relies on vegetation proxy indicators. As far as possible these are tailored to the specific feature but unable to be too site/geographically specific to consider local variations as this would affect the ultimate analysis.

For monitoring purposes, it is the dependent biota which is taken as the prime indicator of wetland quality. The Common Standards Monitoring guidance for Lowland Wetland Habitats (Joint Nature Conservation Committee, 2004) and Common standards monitoring guidance for Upland Wetland Habitats (Joint Nature Conservation Committee, 2009) describe in some detail the attributes (particularly NVC communities) ascribed to healthy wetlands.

Does SCM measure wetland health? No, SCM assesses the wetland condition at a point in time by way of proxy condition measures which are often several years after an event or multiple events for example pollution incidents. In addition, SCM only reports on the notified wetland features whilst in many cases, there may be a range of other wetland types present on site which contribute to the overall biodiversity and resilience of the site.

Article 17 Reporting

Every six years, all EU Member States are required to report on the implementation of the EU Habitats Directive (under Article 17). Article 17 Reporting includes assessments of the condition of all Natura habitats, whether within or out with designated sites. It therefore should provide a reported insight into the condition of non-designated sites. This insight is not quantified as the assessment generally relies on SCM reporting of designated sites, where that information is available.

Survey of Wetland Specialists/Advisers in Scotland

Given the paucity of information on the condition of non-designated sites, a questionnaire (Survey Monkey) was sent to 5 wetland specialists within the Government Agencies and NGOs. The 10 questions covered the main wetland habitats and an overarching question on whether the health for all wetland types was better in designated sites than undesignated wetlands. In addition, 3 other specialists covering woodland and coastal habitats were approached for their opinions on the condition of the resource outside the designated series.

WETMECs (Wetland Water Supply Mechanisms)

WETMECs provide ecohydrological guidelines for different wetland types. This approach has been developed in England (Wheeler et al., 2004) but has been only partially taken up in Scotland (SNIFFER, 2007). The resultant project produced limited information from a few selected designated sites and was not continued or developed. Individual site reports were produced but not collated to form one reference. If developed, the method could provide a significant improvement in the understanding of wetland function.

1.4 Synthesis of SCM and other information sources

1.4.1 Site Condition Monitoring

Results from the last SCM round Cycle 3

Results of the last SCM round Cycle 3 (2012-18)[8] for reported condition are shown below in Table 1. Cycle 4, the most recent SCM cycle, was not analysed as to date only 6 features were recorded for the selected wetland features.

The overall analysis of the SCM condition returns is very positive with 68% of the wetland features in a "Favourable" condition and 14% moving towards "Favourable" condition and 19% in "Unfavourable" condition. The background reasons why all features are not all "Favourable" within the designated sites often relates to much larger issues than those that involve just management of the designated site. These can include water abstraction and nutrient input. Water abstraction need not be pumped water but also the effect of tree growth over many years. These aspects require extensive investigation and negotiation with adjacent landowners that may take many years to complete. In addition, some impacts on the wetland system are not immediately detected. For example, encroachment of reeds, responding to years of additional nutrient input into the wetland system. Thus, what appears to currently be in "Favourable" condition is sliding into "Unfavourable" but not being detected early enough to remedy the situation.

Table 1. Reported SCM Condition.

Reported SCM Cycle 3	Favourable	Unfavourable Recovering	Unfavourable	Total Features
Base-rich / Alkaline fens	12		3	15
Blanket Bog	46	8	13	67
Raised bogs	20	9	7	36
Depressions on Peat Substrates	6		3	9
Estuarine Raised Bogs	1			1

[8] Note: Raised Bogs: As all SAC and RAMSAR sites are underpinned by SSSI designation; Active and Degraded features were not analysed separately and only the SSSI Raised Bog feature data was used. In addition, the Degraded Bog feature could be considered spurious when this feature is in "Favourable" condition as it becomes the Active Bog feature at that point, but is unlikely to be renotified and so the classification remains Degraded Raised Bog.

Intermediate Raised Bogs Upland and Lowland	1	1	1	3
Transition mires and quaking bogs		1		1
Open-water transition fens	19	1	6	26
Swamps Very Wet Quaking Mire	8	1		9
Basin Fens	16	13	8	29
Valley Fen	10		1	11
Floodplain fens	11	1	1	13
Transition grasslands	1		1	2
Transition saltmarsh	2		1	3
Hydro morphological mire range	10		1	14
Springs including Flushes	8		1	9
Transition Open Fen	4		1	5
Transition Sand Dunes	1			1
Totals	176	35	48	254
Percentage Totals	68%	14%	19%	

Review of SCM Data from all Cycles

Of the 722 wetland features from all Cycles of SCM, nearly half have not been fully assessed since 2012 or earlier. Unassessed wetland features: Cycle 1: 104, Cycle 2: 248, Cycle 3: 364, Cycle 4: 6.

In terms of wetland health, the important part of the assessment is the Original Assessed condition as this is the true reflection of wetland health trend.

The reported condition for all features in the "Favourable" category was 482 features whilst the original assessed condition for "Favourable Maintained" and "Favourable Recovered" was 344 features. This is a major difference in the number of features in Favourable condition and highlights the difference between what is observed and reported. The difference is those sites in "Unfavourable Recovering" due to management, which may or may not be effective. This has a major effect on the assessment of wetland health. This difference relates partly to remedies and actions being taken after the recorded condition, moving the site into a more positive condition. However, despite those actions being taken, and for them to have a significant effect on wetland health, this may take many years. In effect it is therefore probably more accurate to use the recorded condition. In addition, to assess the progress of the health change, frequent monitoring would be required.

For those features assessed as "Unfavourable" or "Favourable Declining", the change is very significant with 239 reported in the "Unfavourable" category with the originally assessed condition being a much greater 378 features. As described above, the difference between recorded and reported is very significant and would suggest wetland condition and by inference wetland health, to be much poorer.

Change in condition between cycles

Table 2 shows all cycles and how condition has changed between the last and the current assessment. This reflects a similar stability of sites in "Favourable" condition at 66% of the total number of wetland features to that found in Cycle 3. At 88% of features showing no change between cycles, 4% “Improving” and 8% "Declining”, this would suggest a reasonably stable picture. However, the trend is one of decline with more features declining than improving. In addition, when looking into more detail from the SCM rounds, the most recent assessed cycle was Cycle 1 for over one third of the features and dates back to 1999 to 2005. The infrequency of SCM makes an overall assessment of ‘real time’ wetland feature health difficult and SCM should only be used as a broad indicator of wetland health.

In addition, “No Change” could mean a feature is declining. Further specific analysis is not helpful as the “No Change” category often relates to an original condition only monitored in Cycle 1 with no subsequent monitoring. In the period since 1999/2005, given the pressures on wetland health for example nutrient input and continued effects of drainage, it is highly likely in the subsequent two decades that wetland health has changed significantly.

Table 2. Change in Reported Condition since last assessment.

All Cycles SCM and change in Reported Condition					Condition change since last assessment		
Reported SCM	Favorable	Unfavorable Recovering	Unfavorable	Total number of Features	No Change	Decline	Improving
Base-rich / Alkaline fens	17	1	4	22	21	1	
Blanket Bog	101	8	57	167	167		
Raised bogs	31	9	20	60	40	11	2
Depressions on Peat Substrates	14	1	4	20	20		
Estuarine Raised Bogs	2			2	1		1
Intermediate Raised Bogs Upland and Lowland	1	3	1	5	4	1	
Laggs of raised bogs	1			1	1		
Transition mires and quaking bogs	12	2	2	16			
Open-water transition fens	46	3	9	60	47	11	2
Swamps Very Wet Quaking Mire	12	2	2	16	16	0	
Basin Fens	35	3	21	63	48	6	9

Valley Fen	21	2	4	27	23	1	3
Floodplain fens	13	2	3	18	15	3	
Fen woodland	2		1	3	2	1	
Transition grasslands	3	1	1	5	5		
Transition saltmarsh	4		1	5	4		1
Hydro morphological mire range	12		6	21	1		
Springs including Flushes	12	4	1	36	33	2	1
Transition ombrotrophic mire	1			1	1		
Transition Open Fen	5		1	7	4	1	2
Transition Sand Dunes	1			1	1		
Totals	346	41	138	556	414	38	21
Percentage Totals	66%	8%	26%		88%	8%	4%

1.5 Expert assessment of the relative health of wetlands inside and outside the designated areas

Although the instruction was for a general ‘gut feeling’, in most cases respondents were apprehensive to comment with a strong opinion due to a lack of information. Overall respondents considered that wetland health within the designated suite is better than in the wider countryside. However, there were a few exceptions where respondents were more confident in the response. For Lowland Raised Bogs, of the 6 respondents, 4 strongly agreed that condition was better in the designated series. Reedbeds, Floodplain Fens and Base Rich Fens were also considered in better health in the designated series. There was an interesting and clear ambivalence in the responses related to Upland springs and flushes and Depressions in Peat Substrate features with respondents at both the positive and negative extremes strongly showing a preference. This may reflect different personal experiences but may also reflect the remoteness of these features and that, unless drained, these features are relatively consistent and robust, and designation makes very little difference.

For the coastal communities, the Saltmarsh Survey of Scotland was specifically designed to incorporate the whole resource condition. However, this approach highlighted an anomaly related to the designation selection: 78% of the surveyed resource is designated. The undesignated saltmarsh was in better condition than designated. This was thought to be simply because the larger systems were most likely to be both designated and damaged. Where there is a greater amount of information (e.g. Uist), this suggests no difference between designated and the wider countryside habitat condition, but Uist is atypical for the habitats and so it is difficult to extrapolate to the rest of Scotland.

The perspective on wet woodlands and bog woodlands was that those outside the designated sites were in poorer condition but this was caveated by a lack of information to substantiate the conclusion apart from personal experience. Seral succession of wet habitats to drier habitats was highlighted as a particular issue that affected the health of this wetland habitat.

As designated sites are selected for their high quality and representativeness of that feature in an area of search, it should not come as a surprise that wetland health within the designated sites is considered better than out with, in many cases. The strongly positive responses for Lowland Raised Bogs, Reedbeds, Floodplain Fens and Base Rich Fens, probably reflects many years of focused positive management on these specific habitats through projects and agri-environment schemes mainly on the Designated wetland sites.

1.6 Article 17 Reporting

Article 17 provides an insight into the wider health of the Natura wetland resource including undesignated sites.

The assessments are generally based on the results of the most recent SCM which in some cases may predate the previous Article 17 Report, and do not provide an accurate current indication of wetland health. As Article 17 covers all Natura wetland types, and not just designated sites, expert opinion and experience is used to fill the knowledge gaps.

Table 3. Article 17 Reporting (2019).

Feature	Condition
Alkaline Fens	improvement
Blanket Bogs	stable
Depression in Peat Substrates	stable
Transition Mires	improvement
Raised Bogs (Active)	improvement
Raised Bogs (Degraded)	improvement

The overall assessment from Article 17 is that for the habitats considered, there is a positive general improvement with some habitats remaining stable. This result possibly reflects the known condition from SCM but also the expert's knowledge of activities on the ground that will improve condition. This does highlight the importance of having up to date information to report wetland health.

2. Qualitative Assessment of Wetland Health for the different wetland habitats

The characterised assessment was done utilising the information assimilated in this report and the personal knowledge of the lead author of Appendix IV. The categories for current and future health are presented in a basic categorisation of Good, Moderate and Poor.

The assessment of each wetland habitat type is according to four criteria. The first is:

- *Its most recent SCM observed condition* - this column shows the ratio of wetlands in *Favourable* and *Unfavourable* condition. As there is a very little current health information available, the SCM condition in these assessments is used as a partial proxy indicator to health. The condition of *Favourable*, used in these tables, relates to the SCM categories of *Favourable Recovering* and *Favourable Maintained*. *Favourable Declining* in the SCM is included as *Unfavourable* in this table, since the trajectory towards an *Unfavourable* condition is highly likely in most cases of *Favourable Declining* wetlands particularly with the additional issues created by climate change.

The assessment of the other three criteria was carried out utilising the personal expert knowledge of the lead author of Appendix IV; information from the 2014 State of the Environment briefing note on Wetlands and the Article 17 Habitat Directives Report (2019); and interviews with external experts. For each wetland habitat type, these criteria are:

- *its estimated current health* (good/moderate/poor)
- *its estimated future health* (good/moderate/poor) in the context of climate change, with or without remedial action
- its *resilience* or lack thereof.

Confidence levels of the assessment are not included as there is a very high level of variability within each wetland type, dependant on a wide range of external factors, including location, topography, and resilience. These factors in turn depend on the long term and sustained management of the wetland and vegetation dynamics and responses. If we then layer the extremes of drought and excess water, it becomes difficult to assess the confidence of the assessment. This is also exacerbated by the consideration that wetlands will have to endure both extremes not just one. The strongest confidence for resilience of all the wetland habitats is in floodplain fen, reedbeds and springs and flushes, all of which are well adapted to extreme fluctuations in water conditions. However, this is also caveated as these habitats are also very reliant on the whole catchment and management of that catchment.

Table 5a. A qualitative assessment of the health of upland wetlands.

Hydrological wetland type	Wetland habitat	Most recent SCM Observed Condition Favourable/ Unfavourable	Estimated Current Health	Estimated Future Health with 'Extreme' Climate Change impacts, with action/no action	Resilience
Surface water slope	Blanket bog	74/92	Moderate	Moderate/Poor	Large scale restoration investment is required, but risk of wildfires will escalate if more bogs are not rewetted. In general deer numbers still too high to ensure wetland health improvement. Scale of habitat very large and not easy to get agreement over whole area.

	Wet heath	10/30	Poor	Moderate/Poor	Strong likelihood that tree planting will reduce extent but may leave existing resource in good condition due to changes in burning regimes. Wildfire will become an increasing threat.
Surface water depression	Depressions on peat substances	12/7	Good	Good/Poor	Depressions on peat substrates tend to be relatively stable but depend on the health of the adjacent bog. Drought may cause cracking which leads to peat contraction and loss of water even after rewetting.
Groundwater slope	Base-rich fens, alkaline fens	12/15	Moderate	Moderate/Poor	These fens rely heavily on base-rich water inputs. The extremes of Climate Change could have a beneficial effect, through more flushing and more base rich water input. This will depend on the residency of water in the base rich strata.

Table 5b. A qualitative assessment of the health of lowland wetlands.

Hydrological wetland type	Wetland habitat	Most recent SCM Observed Condition Favourable/ Unfavourable	Estimated Current Health	Estimated Future Health with 'Extreme' Climate Change impacts, with action/no action	Resilience
Surface water depression	Raised bogs	12/48	Poor	Moderate/ Poor	Raised bogs in good health could be resilient to the extremes. Good health relies on hydrological integrity.
Groundwater slope	Transition Mires and quaking bogs	2/4	Poor	Moderate/ Poor	These mires are quite resilient to wide fluctuations in water levels. One issue is

					that persistent drought could lead to floating mats becoming rooted to substrate below. Increased flooding may assist with flushing and diluting nutrients in the system.
	Open water transition fens	40/18	Good	Moderate/ Poor	Resilient to a wide fluctuation in water tables.
	Base-rich fens	12/15	Moderate	Moderate/ Poor	These fens rely heavily on base rich water inputs. The extremes could have a beneficial effect, through more flushing and more base rich water input. This will depend on the residency of water in the base rich strata.
	Reedbeds and swamps		Good	Good/ Good	Reedbeds are very resilient to a wide range of water levels and may encroach on other wetland habitats as they dry out.
Groundwater depression	Basin fens	23/33	Poor	Moderate/ Poor	Basin fens often contain a range of wetland features and could be resilient to extreme changes. The impact of runoff nutrients from within the catchment could be countered by additional flushing due to heavier rain events.
Floodplain	Floodplain fens	12/6	Good	Good/ Good	A resilient wetland type. Low level of management required depending on situation and river morphology. Societal responses to flooding and agriculture, and hard river engineering, will all affect the connectedness and

					function of floodplain wetlands.

Table 5c. A qualitative assessment of the health of wet woodlands.

Hydrological wetland type	Wetland habitat	Most recent SCM Observed Condition Favourable/ Unfavourable	Estimated Current Health	Estimated Future Health with 'Extreme' Climate Change impacts, with action/no action	Resilience
Groundwater depression; Groundwater slope; Floodplain	Fen woodland	2/1	Moderate	Moderate/ Moderate	Resilient wetland that with maintenance of sufficient water levels can retain a regenerative dynamic.
	Alder woodland /Wet woodland	27/29	Moderate	Moderate/ Moderate	Resilient wetland that with maintenance of sufficient water levels can retain a regenerative dynamic.
Surface water slope	Bog woodland	0/2	Poor	Poor/Poor	This is a poorly mapped wetland habitat, vulnerable to mismanagement, but also the effects of drainage of the supporting bog habitat.

Table 5d. A qualitative assessment of the health of wet grassland/flood plain meadow.

Hydrological wetland type	Wetland habitat	Most recent SCM Observed Condition Favourable/ Unfavourable	Estimated Current Health	Estimated Future Health with 'Extreme' Climate Change impacts, with action/no action	Resilience
Groundwater slope; Floodplain	Fen meadow	15/14	Moderate	Moderate/ Poor	Relies heavily on appropriate management to maintain health. Connectedness to water supply and frequency of inundation important and much affected by societal responses.

Floodplain	Wet meadows, marshy grassland			Moderate/ Moderate	Generally, a resilient wetland habitat, with lower biodiversity interest but good flood retention potential. And affected by societal response to flooding
Other	Transition grasslands	0/2	Poor	Poor/ Poor	This habitat is more an artefact of SCM. The habitat is part of a dynamic wetland.
Other	Transition saltmarsh	3/2	Good	Poor/ Poor	Sea level rises, and extent to which this habitat can move is questionable. This is a SCM feature which formalises a dynamic wetland and is considered a natural component of a healthy salt marsh.

The above tables provide an indication of future wetland health. The trajectory of wetland health is highly dependent on the management of wetland sites. For many of the wetland types, management measures could mitigate the effects of climate change (Appendix VI). Inevitably, in some smaller sites, implementing management measures will be unviable due to the overall cost of the required management. A prioritisation process would be important to consider as some small sites are home to rare, immobile species that would warrant the additional expenditure.

The impact of ‘poor’ wetland health influences the buffering capacities of the different wetland types. In the case of peatlands, poor health in the form of a dysfunctional hydrology caused by drainage, affects the vegetation type and cover that protects the surface from the extremes of drought and flood. Once this protective cover is stressed, the water holding buffering capacity in the form of *Sphagnum* moss is lost. In addition, other factors like herbivore impacts will further exacerbate the poor health, after which a ‘tipping point’ is reached where the habitats become degraded and require extensive intervention to restore the hydrological health and replacement of the protective vegetation cover and restore the buffering capacity. The buffering capacity may not only benefit the wetland habitat but also society and the biodiversity that the habitat supports.

As individual entities, some wetland types such as floodplain fens, wet woodlands and reedbeds are robust and highly resilient to changes in water regimes. These wetlands have often developed in conditions where there are large seasonal fluctuations in water levels. Others through spatial constraint like basin fens or through large scale management interventions like blanket bog are highly vulnerable to the extremes of drought and flood. In the case of deeper peat wetlands such as blanket bog and, less so, lowland raised bog, the climate change extremes will potentially exacerbate degradation through extreme drying followed by heavy rain which will induce and enhance erosion of the habitats. Lowland raised bogs are often vulnerable as the edges of the site have been cut into removing the buffer of lagg fen making the smaller exposed peat mass more vulnerable to drying out. This highlights the need to consider wetlands as networks and the habitats within the wetlands as mosaics of different wetland communities. By restoring and creating wetlands within a catchment, this will provide a greater buffer to climatic extremes for the existing wetlands. Key to creating climate resilient wetlands in the future is the management of the individual wetlands to ensure good wetland health and to enhance appropriate buffering effects in each location. To improve wetland health future wetlands will require consideration on a spatial and temporal basis to allow more natural dynamic processes to occur.

3. Wetland Extent

The hydrological wetland typology is based on broad, landscape-scale hydrological features. Therefore, the landform types of the National Soil Map units were classified into hydrological wetland types using available descriptions of landform characteristics such as slope, relative landscape position and topography.

Wetlands occur where soils are permanently or seasonally wet due to climatic, topographical and soil hydrological conditions and characteristics (Appendix I and II) but many of the National Soil Map units contain a mixture of both dry and wet soils, whose exact location within the polygon is often unknown. The areas of wet soils were mapped by selecting soils assigned to HOST classes 7, 8, 9 and 10 (potentially wet or waterlogged alluvial soils), HOST class 12 (basin peat and some peaty gleys), HOST classes 14 and 24 (mainly noncalcareous gleys), HOST class 15 (peaty podzols, peaty gleyed podzols and peaty gleys), HOST classes 26 and 27 (peaty soils, mainly peaty rankers) and HOST classes 28 and 29 (upland blanket peats). By spatially overlaying wet soils from HOST DSM and selected habitat types, the total areal extent of unique HOST class and EUNIS habitat type combinations was calculated.

Table 5e. Total areas for the different wetland types/vegetation cover derived from HOST and EUNIS mapping (see Appendix VIII).

EUNIS	(km^2)	Ha
C Surface standing and running waters	97	9,700
D1 Raised and blanket bogs	12078	1,207,800
D2 Valley mires, poor fens and transition mires	351	35,100
D4 Base-rich fens and calcareous spring mires	12	1,200
E3 Seasonally wet and wet grasslands	4251	425,100
F4 Temperate shrub heathland	10185	1,018,500
F9 Riverine and fen scrub	4	400
G1 Broadleaved deciduous woodland	207	20,700
G3 Coniferous woodland	3704	370,400
G4 Mixed deciduous and coniferous woodland	209	20,900
Native pinewoods	120	12,000
Total Wetland Area		**3,121,800 ha**

Comparisons of extent for different types of wetlands are always fraught as there is no one standard categorisation of wetland types and the wetlands tend to be a mosaic of different types making it difficult to differentiate the extent of each type. In addition, many wetland types transition with other habitats. From the above table, the area for Raised and Blanket bog is considered low (1,207,800 ha), as the combined total for the two wetland types is thought to be 1,800,600 ha. (Bruneau and Johnson, 2014). The addition of F4 Temperate shrub heathland (1,018,500 ha) would take the figure beyond the current estimate for Blanket and Lowland Raised Bog. Peatlands are particularly difficult to define with some methods using peat soils and others considering peatland vegetation. By comparison all other wetland categories are relatively small in area but may have a very strong local influence on the buffering of extreme climate. At over 3 million ha, wetlands are a substantial component of Scotland's land cover and as such can influence many aspects related to climate change. Before this piece of work there has not been a concerted effort to map/calculate the area of wetlands in Scotland. Improved satellite technology and ground truthing with different research teams answering the question from different perspectives may start to fill some gaps. NatureScot are planning to commence a project to utilise remote sensing to identify wetlands. Ultimately to have accurate figures, similar exercises like the Scottish Native Woodland Inventory are required for wetlands.

4. Discussion

Information on wetland health is currently very sparse. The key information is gathered through SCM and focusses on designated wetlands only. SCM was not set up to measure wetland health in its entirety, but as a way to collect simple and robust information. However, SCM provides a good indication of condition on sites which are deemed to be the best examples of their type and also sites where management effort is focussed. From the 571 wetland features monitored in SCM (assessed condition), 34 had declined since the last assessment, whilst 19 had improved and no change on the remaining 518. This would suggest that for designated sites in most cases the *status quo* is maintained but the overall trend in wetland condition is slightly declining. However, of the 518 with no change, 219 of these sites were in the "Unfavourable" categories or "Favourable declining" category, thus 'maintaining' a large proportion of the wetland sites in poor health. Due to the long-time lag and many sites not being revisited, 'no change' could potentially mean further decline on some favourable sites. SCM therefore provides an indicator of historical wetland health but is not definitive. This has a value but does not allow for a quick response to poor health. If a quick Site Check method is used and shows an issue, a full SCM assessment is brought forward, but even a site check will only look at the condition and is not an in-depth assessment of health.

The Article 17 Reporting is interesting, as it uses expert opinion to fill in information gaps, but is limited to Natura features. Expert judgement which forms the extrapolation of the SCM assessments is limited to experience which is particularly relevant when considering wetland sites outside the designated areas. The poll of wetland experts confirmed that it is highly likely that wetland health is better within the designated sites than in the wider countryside. Outside the designated areas wetlands are generally under the same pressures as designated sites often with limited impetus to improve the condition or monitoring. Emphasis of agri-environment schemes focusses on management of designated sites, with the result that the undesignated wetland resource is not appropriately managed. There are some exceptions to this for example the Tweed Forum who champion wetland management in the Borders on all wetlands.

Whilst wetland health is important to monitor particularly in the context of rare habitats and species, the overall dynamic of wetland health must also be considered. Historically the wetland classifications shown above were part of an extensive dynamic network of wetland types that would move according to prevailing conditions. Within this dynamic process there would be losses and gains and rejuvenation of the individual wetland and transitional habitats. In many cases today, wetlands are isolated and no longer part of a dynamic rejuvenating network. Those which come closest to this dynamic, for example the Insh Marshes, are extensively modified and only have a partially functional dynamic. Extensive wetlands like blanket bog still maintain a dynamic but this has often been pushed into a degraded state by drainage, herbivore management and burning. Smaller lowland wetland types like basin fens and lowland raised bogs are artefacts of a much larger area of wetland. Inevitably there will be losses of certain wetland types due to the extremes of drought and flood. This is where multifaceted prioritisation of all wetlands is required to account for the multiple benefits expected from wetlands in the future and include the concept of Natural Capital accounting.

5. Recommendations

The analysis highlights the need for more relevant and contemporary information gathering across all wetlands. Some of this can be obtained by remote sensing but by necessity a considerable amount will come from basic sample collection and analysis. It is of concern that from the available condition monitoring, the trend is one of decline with more features declining than improving. However, for many sites the current condition and by implication wetland health, are unknown.

The following recommendations to improve the characterisation and management of wetlands are proposed:

- Complete the Scottish Wetland Inventory. The Water Framework Directive includes all wetlands within its remit. Assessment of Scotland's wetlands is restricted by the incomplete Scottish Wetland Inventory, which primarily only covers designated wetland sites. The completed inventory could underpin all future strategy and decision making in relation to the impacts of Climate Change. This is a major undertaking but shown to be clearly possible by the completion of the native woodlands and salt marshes inventories. Wetlands require a similar level of detail and probably more to account for the hydrological functionality. Given the variability of wetlands, remote sensing alone is insufficient and frequent ground truthing to measure condition and health will make future modelling more accurate.
- Mapping of wetland features within the designated series to allow accurate reporting and understanding of the wetland vegetation dynamics. Whilst it is appreciated this is difficult, the combination of remote sensing and ground truthing would provide a basis for better wetland vegetation dynamics at a time of great changes in the climate system. The historical records and surveys from designated sites would provide good baseline information to which further hydrological information and current mapping could be added to create a full picture of wetland health.
- The inclusion of the WETMECS system as a compulsory aspect of SCM would provide a much clearer understanding of the hydrology and provide information relevant to wetland health. Within SCM there is a strong emphasis on wetland condition and not health. This is understandable as wetland health is costly to ascertain over a large number of wetlands. Using the WETMECs system would add hydrological characterisation of wetlands in the SCM system. In addition, including water quality and microbial monitoring would improve SCM.
- Explore the potential of remote sensing to assess wetland health through variation in foliage colour. WETMECS Wetland health is closely aligned to water quantity, quality, periodicity, and dynamics. WETMECS provides a considered and consistent approach to include this functionality into an assessment. Current protocols for SCM are valid but reconsider some less relevant attributes to focus on ecosystem function and context. Devising a methodology that addresses this deficit will be challenging but would create a more accurate health assessment. Wetland health monitoring should include more sensitive proxy measures like microbial analysis, diatom analysis. Repeat a revised wetland SCM at no more than 5 yearly intervals.
- The wetland extremes of drought and flood will demand a very high degree of adaptive management and necessitate rapid decision making in some cases. To make these decisions effectively requires regular monitoring of changes that are occurring within the wetland and monitoring of changes in vegetation condition. Key aspects are water supply and quality information. This would be costly, but a focused well-funded network of more detailed monitoring sites would provide information to respond to the threat of climate change and provide the confidence for extrapolation. A catchment-based approach is advised to mesh with other expectations within the catchment.
- Fully engage land managers and owners as wetland managers to monitor and maintain wetland health.

- Through wetland creation and expansion, create a network of wetlands and supporting habitats in all catchments to provide resilience to water extremes and multiple benefits for a prioritised group of wetlands for example protected areas.
- Prioritisation. At some stage key decisions are required on wetland health and the financial inputs required to maintain a 'good' level of health that is sustainable. Consideration should be given to the prioritisation of wetlands in a changed climate and a society looking for different wetland functions. This would align well with WFD objectives. The current designated site series may require a 'downgrade' of some sites but would allow a refocus on what is important in terms of wetland health for the future, and not a historical concept of wetland protection.
- Use experience from other countries that are actively measuring wetland health like California and also already experiencing the extremes of drought and flood to ascertain the response of wetland communities to these extremes.

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5. Appendix V: Key Aspects of Biodiversity (Species, Habitats and Communities) Intrinsic to Wetlands

by Robin Pakeman

0.1 Research questions

The key research question that this appendix sought to answer was:

- *What is the nature of wetland biodiversity that might be impacted by extremes of water availability?*

0.2 Objective

To produce a review of the key aspects of biodiversity (habitat and communities) intrinsic to wetlands in the designated sites**.**

This work builds on Appendix I which explored the potential change trajectories and causes of change for the habitat attributes of different wetland types.

0.3 Approach

To get an overall picture of what species, plant communities and habitats are associated with or make up wetlands, three data sources were explored.

- The number of protected sites within Scotland with wetland "features" (the reason for designation and can be either species or habitat) was summarised by type of protection. The condition of wetland features across Scotland was also summarised.
- The National Vegetation Classification lists of rare species associated with each plant community in the community descriptions.
- Species on the Scottish Biodiversity List as either "Conservation action needed" and "Avoid negative impacts" and associated with wetlands.

1. Introduction

Many species are obligatorily associated with various wetland habitats. However, to create this linkage between biodiversity and wetland type, a correspondence table between different wetland classifications is necessary. Starting from Bullock & Acreman's (2003) classification of wetland hydrological systems, the guidelines for selection of SSSIs (https://jncc.gov.uk/our-work/guidelines-for-selection-of-sssis/#part-2-habitat-chapters) and the manual of terrestrial EUNIS habitats in Scotland (Strachan, 2017) were used to match up hydrology, habitat and vegetation types (Table 1). Note that vegetation type repeat in the final column as plants respond to local conditions rather than to landform.

Table 1. Correspondence between wetland types, EUNIS habitat types and National Vegetation Classification (NVC) communities for Scotland. Names of NVC communities, e.g., M1, can be found in Table 10. Habitats Directive Annex 1 habitat numbers are given in square brackets, e.g. [H7110].

Type	Wetland type	Features	Supplied habitat list	EUNIS
Headwater (not fed by significant stream systems)	Surface water depression	No hydraulic connectivity with groundwater. Outlet has no direct connectivity with river system.	Raised bogs: (all types - raised, active, degraded, intermediate and estuarine SSSI features) Depressions on peat substrates (*Rhynchospora*)	D1.1 Raised bogs D1.11 Active, relatively undamaged raised bogs (M18, M19, M1, M2) [H7110] D1.12 Damaged, inactive bogs D1.12 Degraded raised bogs still capable of natural regeneration (M3, M15, M16, M17, M18, M19, M20, M25) [H7120] D1.12x Damaged, inactive bogs not capable of restoration within 30 years (various)
	Surface water slope	No hydraulic connectivity with groundwater. Outlet has direct connectivity with river system.	Blanket bog: (all types - blanket bog, intermediate blanket bog, saddle mire)	D1.2 Blanket bogs (includes D1.21, D1.22, D1.24) [H7130] D1.21 Hyperoceanic low-altitude blanket bogs, typically with dominant *Trichophorum* (M1, M2, M3, M15, M17, M18, M25) [H7130] D1.22 Montane blanket bogs, *Calluna* and *Eriophorum vaginatum* often dominant (M1, M2, M3, M15, M19, M20) [H7130] D1.24 Wet bare peat and peat haggs on blanket bogs [H7130]

			Wet heath – wet heath with Erica tetralix and sub-alpine wet heath Bog woodland	F4.1 Wet heaths F4.11 Northern wet heaths (M15, M16) [H4010] F4.13 *Molinia caerulea* wet heaths (M25) G1.5 Broadleaved swamp woodland on acid peat G1.51 *Sphagnum Betula* woods G1.51 Birch bog woodland (W4, M17, M18) [H91D0] G1.51x Other *Sphagnum Betula* woods (W4) G1.52 *Alnus* swamp woods on acid peat (W4) G3.D Boreal bog conifer woodland G3.D1 Boreal *Pinus sylvestris* bog woods (W18, M18, M19) [H91D0] G3.D1 Bog woodland (W4, W18, M17, M18, M19, other) (includes G1.51, G3.D1) [H91D0]
	Groundwater depression	Hydraulic connectivity (permanent or periodic) with groundwater. Outlet has no direct connectivity with river system.	Basin fens (can include floating Schwingmoor vegetation - see also above transition mire/quaking bog - and valley fens)	C3.2 Reedbeds and tall helophytes C3.26 *Phalaris arundinacea* beds (S28) [H3150] C3.29 Large sedge swamp communities (S3, S6, S7, S9, S11) [H3130, H3140, H3150, H3160, H3260] D2.3 Transition mires and quaking bogs D2.32 *Carex diandra* quaking mires (M9) [H7140] D4.1 Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks D4.1C *Carex rostrata* alkaline fens (M9) [H7230]

			Fen woodland, alder woodland, wet woodland	E3.5 Moist or wet oligotrophic grassland E3.51 *Molinia caerulea* meadows and related communities E3.511 Calcicline purple moorgrass meadows (M26) [H6410] F9.2 Salix carr and fen scrub F9.21 Grey willow carrs (W1, W3) F9.22 *Sphagnum* willow carrs (W4) F9.23 Bay willow carrs (W3) G1.4 Broadleaved swamp woodland not on acid peat G1.41 *Alnus* swamp woods not on acid peat (W3, W6, W7)
	Groundwater slope	Hydraulic connectivity (permanent or periodic) with groundwater. Outlet has direct connectivity with river system.	Reedbeds and swamps (on designated sites these are likely to be included within open water transition fen features, basin fen or floodplain fen features) Open water transition fens (can include fen meadow, fen, swamp, reedbed),	C3.2 Reedbeds and tall helophytes C3.21 *Phragmites australis* beds (S4) [H3110, H3130, H3140, H3150] C3.22 *Schoenoplectus lacustris* beds (S8) [H3130, H3160] C3.23 Typha beds (S12) [H3130, H3150] C3.24 Medium-tall non-graminoid swamp communities (S10 S14 S19) [H3130, H3150, H3160, H3260] C3.25 *Glyceria maxima* beds (S5) [H3150] C3.26 *Phalaris arundinacea* beds (S28) [H3150] C3.27 Halophile *Scirpus, Bolboschoenus* and *Schoenoplectus* beds (S21) C3.29 Large sedge swamp communities (S3, S6, S7, S9, S11) [H3130, H3140, H3150, H3160, H3260]

				D2.2 Poor fens and soft-water spring mires D2.22 *Carex nigra, Carex canescens, Carex echinata* fens (M6, M7)
			Transition mires and quaking bogs (very wet mires/quaking bogs and some laggs of raised bogs)	D2.3 Transition mires and quaking bogs D2.31 *Carex lasiocarpa* swards (M4, M5, M9) [H7140] D2.32 *Carex diandra* quaking mires (M9) [H7140] D2.33 *Carex rostrata* quaking mires (M4, M5, M8 M9) [H7140] D2.33 Transition mires and quaking bogs (Annex I) (includes D2.31-33, D2.39, D2.3) [H7140] D2.37 *Rhynchospora alba* quaking bogs (M1, M2) [H7150] D2.39 *Menyanthes trifoliata* and *Potentilla palustris* rafts (S27 non-NVC) [H7140] D2.3 *Hypericum elodes-Potamogeton polygonifolius* soakway (M29) [H7140]
			Fens: Base-rich fens, alkaline fens	D4.1 Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks D4.12 *Schoenus ferrugineus* fens (M10) [H7230] D4.15 *Carex dioica, Carex pulicaris* and *Carex flava* fens (M10) [H7230] D4.15 Alkaline fens (includes D4.12, D4.15, D4.19, D4.1C) [H7230] D4.17 *Carex saxatilis* fens (M12) [H7240] D4.19 British *Carex demissa - Saxifraga*

				aizoides flushes (M11) [H7230] D4.1C *Carex rostrata* alkaline fens (M9) [H7230]
			Fen meadow	E3.4 Moist or wet eutrophic and mesotrophic grassland E3.41 Atlantic and sub-Atlantic humid meadows (M22 M23b MG8 MG9) E3.42 *Juncus acutiflorus* meadows (M23a) E3.44 Flood swards and related communities
			Fen woodland, alder woodland, wet woodland	G1.4 Broadleaved swamp woodland not on acid peat G1.41 *Alnus* swamp woods not on acid peat (W3, W6, W7)
Floodplain	Floodplain	Inputs are dominantly upstream river flows	Floodplain fens	C3.2 Reedbeds and tall helophytes C3.21 *Phragmites australis* beds (S4, S26) [H3110, H3130, H3140, H3150] C3.25 *Glyceria maxima* beds (S5) [H3150] C3.26 *Phalaris arundinacea* beds (S28) [H3150] C3.29 Large sedge swamp communities (S3, S6, S7, S9, S11) [H3130, H3140, H3150, H3160, H3260] D2.3 Transition mires and quaking bogs D2.31 *Carex lasiocarpa* swards (M4, M5, M9) [H7140] D2.33 *Carex rostrata* quaking mires (M4, M5, M8 M9) [H7140] D4.1 Rich fens, including eutrophic tall-herb fens and calcareous flushes and soaks
			Wet meadows, marshy grassland, Fen meadow, transition grasslands	E3.4 Moist or wet eutrophic and mesotrophic grassland

				E3.41 Atlantic and sub-Atlantic humid meadows (M22, M23b, MG8, MG9) E3.42 *Juncus acutiflorus* meadows (M23a) E3.44 Flood swards and related communities (MG10, MG11, MG12, MG13, OV28) E3.5 Moist or wet oligotrophic grassland E3.51 *Molinia caerulea* meadows and related communities E3.511 Calcicline purple moorgrass meadows (M26) [H6410] E3.512 Acidocline purple moorgrass meadows (M25)
			Fen woodland, alder woodland, wet woodland	G1.1 Riparian and gallery woodland, with dominant *Alnus, Betula, Populus* or *Salix* G1.11 Riverine *Salix* woodland (W6) [H91E0] G1.2 Mixed riparian floodplain and gallery woodland G1.21 Riverine *Fraxinus - Alnus* woodland, wet at high but not at low water (W6, W7) [H91E0] G1.21 Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (Alno-Padion, Alnion incanae, Salicion albae) (W6, W7) (includes G1.11, G1.21) [H91E0]

2. Designated sites

Data on the numbers and condition of protected sites was taken from Scotland's Environment Web, specifically Ecosystem Health Indicator 2 – Protected Nature Sites (https://www.environment.gov.scot/data/data-analysis/ecosystem-health-indicators/?indicator=Protected_nature_sites).

A range of levels of protection cover Scotland, but this analysis specifically covers just Sites of Special Scientific Interest (SSSI), Special Areas of Conservation (SAC), Special Protection Areas (SPA) and Ramsar sites.

There is an overlap between SSSIs and the other categories and between Ramsar sites and the other categories, as sites often have multiple designations. Hence these protection types have been treated separately.

Roughly a third of SSSIs and Ramsar sites have wetland features, more than half of SACs, but only 15 % of SPAs (Table 2).

Table 2. The number of protected sites in Scotland with wetland habitats and/or species according to the type of designation. It should be noted that there are overlaps between the categories as sites may have multiple designations.

Type of protection	Number of sites with wetland habitats and/or species	Percentage of total designated sites	Total number of designated sites
SSSI	483	34.0	1422
SAC	140	57.6	243
SPA	25	15.4	162
Ramsar	16	31.4	51

The data in Tables 3 to 9 show the overall number of designated features and species under each type of designation. Features, as a term, is equivalent to habitat and can be related to vegetation communities via Table 1. Data are presented in terms of their condition; ”Favourable” where the designated feature(s) within a unit are being adequately conserved, “Recovering” where features are not yet fully conserved but the necessary management mechanisms are in place so that the feature will reach favourable condition, “Unfavourable” where the feature is not being conserved and will not reach favourable condition unless there are changes to the site management or external pressures (https://designatedsites.naturalengland.org.uk/SSSIGlossary.aspx).

Condition can be seen as one dimension of wetland health, but one that is solely focussed on the vegetation and any designated species. Assessing condition does take into account hydrology in an implicit way, but it assumes that monitoring vegetation composition can be used as an indicator of wetland quality (JNCC 2004).

From Table 3, it can be seen that large numbers of SSSIs contain basin fens, blanket bogs, fen meadows, open water transition fens, raised bogs and wet woodland. A high proportion of features with unfavourable condition are evident for basin fen and wet woodland. This is indicative that many of these basin fens and wet woodlands are in poor health.

Table 3. The number of each wetland habitat feature within the SSSI network, the numbers in each condition category and the percentage of total in unfavourable condition.

Feature	Favourable	Recovering	Unfavourable	Percent unfavourable	Total
Alkaline fen	4	1			5
Alpine flush	1	1			2

Basin fen	34	8	14	25.0	56
Basin fen - Schwingmoor type	4	1			5
Blanket bog	76	19	13	12.0	108
Estuarine raised bog	2				2
Fen meadow	25	3	5	14.7	34*
Fen woodland	2	1			3
Flood-plain fen	13	3	1	5.9	17
Intermediate bog (blanket)	1	1			2
Intermediate bog (raised)	1	1	1	33.3	3
Laggs of raised bog	1				1
Lowland wet heath	9	1	2	16.7	12
Open water transition fen	41	5	11	19.3	57
Raised bog	34	15	11	18.3	60
Saddle mire	2				2
Spring fen	4	1			5
Spring-head, rill and flush	2	2			4
Springs (including flushes)	14	2	2	10.5	19†
Subalpine flushes	6				6
Subalpine wet heath	3	3			6
Transition ombrotrophic mire	1				1
Transition open fen	6		1	14.3	7
Valley fen	23	2	2	7.4	27
Wet woodland	27	3	16	34.8	46
Total	336	73	79	16.1	490

*Includes 1 fen meadow to be denotified. †Includes one feature not assessed.

Fewer SSSI have been designated for species or their species assemblages (Table 4). Notable numbers of SSSIs have been notified for their dragonfly assemblages, dunlin, golden plover, greenshank and hen harriers. What is also highlighted is that all SSSIs notified for whimbrel have these populations in unfavourable condition and that high numbers of populations for dunlin, golden plover and marsh fritillary are also in unfavourable condition.

Table 4. The number of each wetland species and assemblage features within the SSSI network, the numbers in each condition category (favourable, recovering, unfavourable) and the percentage of total in unfavourable condition.

	Favourable	Recovering	Unfavourable	Percent unfavourable	Total
Amphibian assemblage	2	1			3
Bearded tit (*Panurus biarmicus*), breeding	1				1
Beetle (*Oreodytes alpinus*)	1				1
Blue aeshna dragonfly (*Aeshna caerulea*)	1				1

Bog orchid (*Hammarbya paludosa*)	1				1
Brown bog-rush (*Schoenus ferrugineus*)	1				1
Club sedge (*Carex buxbaumii*)	2				2
Corncrake (*Crex crex*), breeding	2				2
Cranefly (*Lipsothrix ecucullata*)	2				2
Dragonfly assemblage	22				22
Dunlin (*Calidris alpina schinzii*), breeding	10		5	33.3	15
Golden plover (*Pluvialis apricaria*), breeding	12		4	25.0	16
Great crested newt (*Triturus cristatus*)	1	1	1	33.3	3
Greenshank (*Tringa nebularia*), breeding	15		2	11.8	17
Green-winged orchid (*Orchis morio*)	1				1
Hen harrier (*Circus cyaneus*), breeding	10		3	23.1	13
Marsh fritillary butterfly (*Euphydryas aurinia*)	3		3	50.0	6
Marsh harrier (*Circus aeruginosus*), breeding	1				1
Marsh saxifrage (*Saxifraga hirculus*)	1	1			2
Narrow-mouthed whorl snail (*Vertigo angustior*)	1				1
Northern blue damselfly (*Coenagrion hastulatum*)	1				1
Northern emerald dragonfly (*Somatochlora arctica*)	2				2
Otter (*Lutra lutra*)	6		1	14.3	7
Oystercatcher (*Haematopus ostralegus*), breeding	1				1
Redshank (*Tringa totanus*), breeding			1	100.0	1
Scottish dock (*Rumex aquaticus*)	2				2
String sedge (*Carex chordorrhiza*)	1				1
Varnished hook-moss (*Hamatocaulis vernicosus*)	1				1
Water rail (*Rallus aquaticus*), breeding	1				1
Whimbrel (*Numenius phaeopus*), breeding			6	100.0	6
Total	105	3	26	19.4	134

The SAC network has been designated using a standard list of habitats listed within Annex 1 of the Habitats Directive (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043), so there is a more restricted habitat list (Table 5). As for the SSSI network, many sites contain blanket bog and raised bogs. In contrast, many sites contain wet heathland which is rarely used as a feature to notify SSSIs. What is noticeable is the high proportion of alder woodland on floodplains, blanket bogs and wet heathland that are in unfavourable condition.

Table 5. The number of each wetland habitat feature within the SAC network, the numbers in each condition category (favourable, recovering, unfavourable) and the percentage of total in unfavourable condition.

	Favourable	Recovering	Unfavourable	Percent unfavourable	Total
Active raised bog	20	5			25
Alder woodland on floodplains	3		7	70.0	10
Base-rich fens	17	1	4	18.2	22
Blanket bog	30	7	14	27.5	51
Bog woodland	6	1			7

Degraded raised bog	11	5	2	11.1	18
Depressions on peat substrates	14	2	4	20.0	20
Very wet mires often identified by an unstable 'quaking' surface	13	2	1	6.3	16
Wet heathland with cross-leaved heath	12	6	12	40.0	30
Total	126	29	44	22.1	199

As for SSSIs, fewer species compared to habitats have been used as a reason for designation (Table 6), but this is also a consequence of the relatively short list of species in Annex 2, 4 and 5 of the Habitats Directive. More than two thirds of the species features used to notify sites are from a single species, the otter.

Table 6. The number of each wetland species features within the SAC network, the numbers in each condition category (favourable, recovering, unfavourable) and the percentage of total in unfavourable condition.

	Favourable	Recovering	Unfavourable	Percent unfavourable	Total
Geyer's whorl snail (*Vertigo geyeri*)	2		1	33.3	3
Great crested newt (*Triturus cristatus*)	1	1	1	33.3	3
Marsh fritillary butterfly (*Euphydryas aurinia*)	5				5
Marsh saxifrage (*Saxifraga hirculus*)	2	1			3
Narrow-mouthed whorl snail (*Vertigo angustior*)	1				1
Otter (*Lutra lutra*)	39		5	11.4	44
Round-mouthed whorl snail (*Vertigo genesii*)	2				2
Slender green feather-moss (*Hamatocaulis vernicosus*)	1	1			2
Total	53	3	7	11.1	63

The SPA network was designated for the protection of bird species listed in the Birds Directive (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147). Notable species include corncrake and hen harrier (Table 7). The relatively small numbers of sites and features makes it difficult to generalise about which species are notable for the proportion of sites in unfavourable condition.

Table 7. The number of each wetland species features within the SPA network, the numbers in eachcondition category and the percentage of total in unfavourable condition.

	Favourable	Unfavourable	Percent unfavourable	Total
Corncrake (*Crex crex*), breeding	9	1	10.0	10
Dunlin (*Calidris alpina schinzii*), breeding	5	1	16.7	6
Golden plover (*Pluvialis apricaria*), breeding	1	2	66.7	3
Greenshank (*Tringa nebularia*), breeding	2			2
Hen harrier (*Circus cyaneus*), breeding	8	3	27.3	11

Marsh harrier (*Circus aeruginosus*), breeding	1			1
Oystercatcher (*Haematopus ostralegus*), breeding	3			3
Redshank (*Tringa totanus*), breeding	2	1	33.3	3
Spotted crake (*Porzana porzana*), breeding	1			1
Whimbrel (*Numenius phaeopus*), breeding	1			1
Total	33	8	19.5	41

There are relatively small numbers of Ramsar sites (https://www.ramsar.org/) in Scotland compared to the other designations. Notable are the number of designations for blanket bog and the relatively high proportion of them in unfavourable condition (Table 8).

Table 8. The number of each wetland habitat feature within the Ramsar site network, the numbers in each condition category and the percentage of total in unfavourable condition.

	Favourable	Recovering	Unfavourable	Percent unfavourable	Total
Blanket bog	3	2	3	37.5	8
Flood-plain fen	1				1
Open water transition fen	3				3
Wet woodland			2	100.0	2
Total	7	2	5	35.7	14

Similarly, relatively few Ramsar sites in Scotland are designated for their wetland species (Table 9). Dunlin are the main species used for designation.

Table 9. The number of each wetland species features within the Ramsar site network, the numbers in each condition category and the percentage of total in unfavourable condition.

	Favourable	Not Assessed	Unfavourable	Percent unfavourable	Total
Dunlin (*Calidris alpina schinzii*), breeding	4		1	20.0	5
Otter (*Lutra lutra*)		1			1
Oystercatcher (*Haematopus ostralegus*), breeding	1				1
Redshank (*Tringa totanus*), breeding			1	100.0	1
Total	5	1	2	25.0	8

3. National Vegetation Classification rare species

The National Vegetation Classification (Rodwell 1991a, 1991b, 1992, 1995, 2000) lists rare species associated with each plant community in the community descriptions (Table 10). This assessment was restricted to non-coastal wetlands. The table can be used to identify habitat types that are rich in rare species and those, generally the more widespread one, which rarely contain notable plant species.

Large numbers of rare species in a habitat are a particular feature of mires receiving more calcareous drainage water in the oceanic part of the country such as the M9 *Carex rostrata-Calliergon cuspidatum/giganteum* and M10 *Carex dioica-Pinguicula vulgaris* mires or upland flushed wth calcareous inputs such as the M11 *Carex demissa-Saxifraga aizoides* and M12 *Carex saxatilis* mires. More common communities such as the widely distributed M17 *Scirpus cespitosus-Eriophorum vaginatum* blanket mire and M25 *Molinia caerulea-Potentilla erecta* mire tend to have few rare species associated with them.

Table 10. Rare species listed in wetland communities in the National Vegetation classification where both the community and the species occur in Scotland (Rodwell 1991a, 1991b, 1992, 1995, 2000).

Supplied habitat list	National Vegetation community	Rare plant species
	Mires	
Raised bog/Depressions on peat/Blanket bog	M1 *Sphagnum auriculatum* bog pool community	*Hammarbya paludosa, Rhynchospora fusca, Scheuchzeria palustris, Utricularia intermedia, Sphagnum pulchrum*
Raised bog/Depressions on peat/Blanket bog	M2 *Sphagnum cuspidatum/recurvum* bog pool community	*Andromeda polifolia, Carex magellanica, Sphagnum pulchrum*
Raised bog/Depressions on peat/Blanket bog	M3 *Eriophorum angustifolium* bog pool community	-
Transition mires and quaking bogs/Floodplain fens	M4 *Carex rostrata-Sphagnum recurvum* mire	*Carex chordorrhiza, Lysimachia thrysifolia*
Transition mires and quaking bogs/Floodplain fens	M5 *Carex rostrata-Sphagnum squarrosum* mire	-
Reedbeds and swamps/ Open water transition fens	M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire	-
Reedbeds and swamps/ Open water transition fens	M7 *Carex curta-Sphagnum russowii* mire	*Carex aquatilis, Carex rarifolia, Sphagnum lindbergii, Sphagnum riparium*
Transition mires and quaking bogs	M8 *Carex rostrata-Sphagnum warnstorfii* mire	*Tomentypnum (Homalothecium) nitens, Sphagnum subsecundum*
Transition mires and quaking bogs	M9 *Carex rostrata-Calliergon cuspidatum/giganteum* mire	*Carex approprinquata, Carex daindra, Cicuta virosa, Dactylorhiza traunsteinerioides (traunsteineri), Potamogeton coloratus, Pyrola rotundifolia, Utricularia intermedia, Cinclidium stygium*
Fens: Base-rich fens, alkaline fens	M10 *Carex dioica-Pinguicula vulgaris* mire	*Bartsia alpina, Carex capillaris, Equisetum variegatum, Juncus alpinus, Kobresia simplisciuscula, Minuartia verna, Primula farinosa, Schoenus ferrugineus, Sesleria albicans*
Fens: Base-rich fens, alkaline fens	M11 *Carex demissa-Saxifraga aizoides* mire	*Alchemilla filicaulis ssp. filicaulis, Carex atrofusca, Carex microglochin, Carex vaginata, Equisetum variegatum, Juncus alpinus, Juncus biglumis, Juncus castaneus, Kobresia*

		simpliciuscula, Salix reticulata, Schoenus ferrugineus, Calliergon trifarium, Meesia uliginosa
Fens: Base-rich fens, alkaline fens	M12 *Carex saxatilis* mire	*Alchemilla filicaulis ssp. filicaulis, Carex atrofusca, Carex microglochin, Carex saxatilis, Carex vaginata, Juncus biglumis, Juncus castaneus, Kobresia simpliciuscula*
Raised bog/Depressions on peat/Blanket bog/Wet heath	M15 *Scirpus cespitosus-Erica tetralix* wet heath	*Campylopus atrovirens var falcatus, Campylopus setifolius*
Raised bog/Depressions on peat/Wet heath	M16 *Erica tetralix-Sphagnum compactum* wet heath	*Lycopodiella inundata, Rhynchospora fusca*
Raised bog/Depressions on peat/Blanket bog/Wet heath/Bog woodland	M17 *Scirpus cespitosus-Eriophorum vaginatum* blanket mire	*Campylopus atrovirens var falcatus, Campylopus setifolius, Campylopus shawii, Sphagnum imbricatum, Sphagnum strictum*
Raised bog/Depressions on peat/Blanket bog/Wet heath/Bog woodland	M18 *Erica tetralix-Sphagnum papillosum* raised and blanket mire	*Andromeda polifolia, Sphagnum imbricatum*
Raised bog/Depressions on peat/Blanket bog/Wet heath	M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire	*Arctostaphylos alpinus, Betula nana, Vaccinium microcarpon, Kiaeria stakei*
Raised bog/Depressions on peat/Blanket bog	M20 *Eriophorum vaginatum* blanket and raised mire	-
Fen meadow	M22 *Juncus subnodulosus-Cirsium palustre* fen-meadow	*Thyselium (Peucedanum palustre), Tomentypnum (Homalothecium) nitens*
Fen meadow	M23 *Juncus effusus/acutiflorus-Galium palustre* rush-pasture	-
Raised bog/Depressions in peat/Blanket bog/Wet heaths/ Wet meadows, marshy grassland, Fen meadow	M25 *Molinia caerulea-Potentilla erecta* mire	-
Basin fen	M26 *Molinia caerulea-Crepis paludosa* mire	*Primula farinosa*
Transition mires and quaking bogs	M29 *Hypericum elodes-Potamogeton polygonifolius* soakway	*Pilularia globulifera*
	<u>Mesotrophic grasslands</u>	

Fen meadow	MG8 *Cynosurus cristatus-Caltha palustris* grassland	-
Fen meadow	MG9 *Holcus lanatus-Deschampsia cespitosa* grassland	-
Wet meadows, marshy grassland, Fen meadow	MG10 *Holcus lanatus-Juncus effusus* rush-pasture	-
Wet meadows, marshy grassland, Fen meadow	MG11 *Festuca rubra-Agrostis stolonifera-Potentilla anserina* grassland	-
Wet meadows, marshy grassland, Fen meadow	MG12 *Festuca arundinacea* grassland	-
Wet meadows, marshy grassland, Fen meadow	MG13 *Agrostis stolonifera-Alopecurus geniculatus* grassland	-
	Other vegetation	
Wet meadows, marshy grassland, Fen meadow	OV28 *Agrostis stolonifera-Ranunculus repens* community	-
	Swamps	
Basin fens/ Reedbeds and swamps/Open water transition fens/Floodplain fens	S3 *Carex paniculata* swamp	-
Reedbeds and swamps/Open water transition fens/Floodplain fens	S4 *Phragmites australis* swamp and reed-beds	*Cicuta virosa, Utricularia intermedia*
Reedbeds and swamps/Open water transition fens/Floodplain fens	S5 *Glyceria maxima* swamp	-
Basin fens/ Reedbeds and swamps/Open water transition fens/Floodplain fens	S9 *Carex rostrata* swamp	*Eriocaulon septangulare*
Reedbeds and swamps/Open water transition fens	S10 *Equisetum fluviatile* swamp	*Calamagrostis stricta, Lysimachia thrysifolia*

Basin fens/Reedbeds and swamps/Open water transition fens/Floodplain fens	S11 *Carex vesicaria* swamp	*Carex aquatilis*
Reedbeds and swamps/Open water transition fens	S12 *Typha latifolia* swamp	*Cicuta virosa*
Reedbeds and swamps/Open water transition fens	S14 *Sparganium erectum* swamp	*Butomus umbellatus, Wolffia arrhiza*
Reedbeds and swamps/Open water transition fens	S19 *Eleocharis palustris* swamp	-
Floodplain fens	S26 *Phragmites australis-Urtica dioica* tall-herb fen	-
Basin fens/Reedbeds and swamps/Open water transition fens/Floodplain fens	S28 *Phalaris arundinacea* tall-herb fen	-
	<u>Woodland</u>	
Fen woodland, alder woodland, wet woodland	W1 *Salix cinerea-Galium palustre* woodland	*Lysimachia thyrsiflora*
Fen woodland, alder woodland, wet woodland	W3 *Salix pentandra-Carex rostrata* woodland	*Salix myrsinifolia (nigricans), Carex approprinquata, Carex diandra, Corallorhiza trifida, Lysimachia thyrsifolia, Pyrola rotundifolia*
Bog woodland/ Fen woodland, alder woodland, wet woodland	W4 *Betula pubescens-Molinia caerulea* woodland	*Dryopteris cristata*
Fen woodland, alder woodland, wet woodland	W6 *Alnus glutinosa-Urtica dioica* woodland	-
Fen woodland, alder woodland, wet woodland	W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland	-
Bog woodland	W18 *Pinus sylvestris-Hylocomium splendens* woodland	*Orthilia secunda, Pyrola rotundifolia*

4. Scottish Biodiversity List species

The Scottish Biodiversity List (SBL) "is a list of animals, plants and habitats that Scottish Ministers consider to be of principal importance for biodiversity conservation in Scotland" (https://www.nature.scot/scotlands-biodiversity/scottish-biodiversity-strategy/scottish-biodiversity-list). These species were categorised as to whether they were associated with wetlands.

A number of data sources were used in this categorisation: Bryophytes (Hill et al. 2007), Fish (https://www.fishbase.de), Fungi (except lichens, http://fungi.myspecies.info/, r600_part_1.pdf, SSSI-Guidelines-14-Non-lichenisedfungi-2018a.pdf, https://www.bioinfo.org.uk/), Invertebrates (Webb et al. 2017), Lichens (Britton et al. unpublished), Mammals (Harris & Yalden 2008), Stoneworts (https://freshwaterhabitats.org.uk/wp-content/uploads/2013/09/Stonewort_V2-Feb15.pdf) and Vascular Plants (Clapham et al. 1987). Other groups and species not covered by these sources were categorised individually from a range of data sources.

The need to do this categorisation *de novo* indicates that there is a lack of structured data sources to do an assessment that links species conservation status to habitat conservation status. The current data structures really only allow for analysis of habitats and species separately.

Species on the SBL primarily associated with wetlands total 98 out of 700 across the categories "Conservation action needed" and "Avoid negative impacts" (Table 11). Notable are the 24 associated with blanket bogs (and often with raised bogs), 15 associated with base-rich and alkaline fens and 14 with wet meadows. A significant number of generalist wetland species are also on the list (15).

Table 11. Wetland species numbers in the Scottish Biodiversity List in the categories "Conservation action needed" and "Avoid negative impacts". Please note that the species are listed by their primary wetland habitat and a number will occur in different wetlands habitats, for example a species listed under Blanket Bog may also occur in Raised Bogs.

	Number of species
Wetland habitats	
Blanket bog	24
Fen meadow	3
Fen woodland, alder woodland, wet woodland	7
Fens: Base-rich fens, alkaline fens	15
General wetlands	15
Open water transition fens	1
Reedbeds and swamps	6
Transition mires and quaking bogs	8
Wet heath	5
Wet meadows, marshy grassland	14
Non-wetland habitats	
Aquatic	81
Dry habitats, including coastal	521
Grand Total	**700**

The 98 species (14 %) on the SBL are distributed across many taxa (Table 12). In line with the SBL as a whole, the dominant taxa in the list are birds and vascular plants.

Table 12. Wetland species in the Scottish Biodiversity List and their primary wetland habitat. A few species have had name changes from the time since the list was put together and old names appear in parentheses. Data sorted by Wetland type.

Main group	Taxon group	Scientific Name	Common name	Wetland type
Aquatic invertebrates	insect - dragonfly (Odonata)	*Coenagrion hastulatum*	Northern Damselfly	Blanket bog
Aquatic invertebrates	insect - beetle (Coleoptera)	*Helophorus (Cyphelophorus) tuberculatus*	a water beetle	Blanket bog
Aquatic invertebrates	insect - beetle (Coleoptera)	*Hydroporus elongatulus*	a water beetle	Blanket bog
Aquatic invertebrates	insect - beetle (Coleoptera)	*Hydroporus glabriusculus*	a water beetle	Blanket bog
Aquatic invertebrates	insect - beetle (Coleoptera)	*Hydroporus rufifrons*	Oxbow Diving Beetle	Blanket bog
Aquatic invertebrates	insect - beetle (Coleoptera)	*Ilybius wasastjernae*	a water beetle	Blanket bog
Birds	bird	*Pluvialis apricaria*	Golden Plover	Blanket bog
Fungi	lichen	*Acarospora rhizobola*	a lichen	Blanket bog
Fungi	lichen	*Cladonia stygia*	a Lichen	Blanket bog
Fungi	lichen	*Cladonia uncialis subsp. uncialis*	a Lichen	Blanket bog
Fungi	lichen	*Lecanora epibryon*	a Lichen	Blanket bog
Non-vascular plants	moss	*Aplodon wormskjoldii*	Carrion-moss	Blanket bog
Non-vascular plants	moss	*Dicranum bergeri*	Waved Fork-moss	Blanket bog
Non-vascular plants	moss	*Sphagnum balticum*	Baltic Bog-moss	Blanket bog
Non-vascular plants	moss	*Sphagnum majus*	Olive Bog-moss	Blanket bog
Terrestrial invertebrates	insect - spider (Araneae)	*Centromerus levitarsis*	a money spider	Blanket bog
Terrestrial invertebrates	insect - butterfly	*Coenonympha tullia*	Large Heath	Blanket bog
Terrestrial invertebrates	insect - spider (Araneae)	*Erigone welchi*	Welch's Money-spider	Blanket bog
Terrestrial invertebrates	Insect - trichopteran	*Hagenella clathrata*	Window Winged Sedge	Blanket bog
Terrestrial invertebrates	insect - spider (Araneae)	*Notioscopus sarcinatus*	Swamp Lookout Spider	Blanket bog
Terrestrial invertebrates	insect - true fly (Diptera)	*Prionocera pubescens*	a cranefly	Blanket bog
Vascular plants	flowering plant	*Calamagrostis scotica*	Scottish Small-reed	Blanket bog
Vascular plants	flowering plant	*Calamagrostis stricta*	Narrow Small-reed	Blanket bog
Vascular plants	flowering plant	*Carex microglochin*	Bristle Sedge	Blanket bog
Birds	bird	*Limosa limosa*	Black-tailed Godwit	Fen meadow
Birds	bird	*Porzana porzana*	Spotted Crake	Fen meadow
Terrestrial invertebrates	insect - true fly (Diptera)	*Rymosia speyae*	a fungus gnat	Fen meadow

Birds	bird	*Poecile montanus*	Willow Tit	Fen woodland, alder woodland, wet woodland
Fungi	lichen	*Biatora veteranorum (Catillaria alba)*	a Lichen	Fen woodland, alder woodland, wet woodland
Fungi	fungus	*Cytidia salicina*	Scarlet Splash	Fen woodland, alder woodland, wet woodland
Fungi	fungus	*Entoloma aethiops*	Black Pinkgill	Fen woodland, alder woodland, wet woodland
Fungi	lichen	*Polychidium dendriscum*	a Lichen	Fen woodland, alder woodland, wet woodland
Fungi	fungus	*Stagnicola perplexa*	Puzzling Rootshank	Fen woodland, alder woodland, wet woodland
Vascular plants	flowering plant	*Rumex aquaticus*	Scottish Dock	Fen woodland, alder woodland, wet woodland
Non-vascular plants	moss	*Dicranella grevilleana*	Greville's Forklet-moss	Fens: Base-rich fens, alkaline fens
Non-vascular plants	moss	*Hamatocaulis vernicosus*	Varnished Hook-moss	Fens: Base-rich fens, alkaline fens
Non-vascular plants	liverwort	*Leiocolea rutheana var. rutheana*	Fen Notchwort	Fens: Base-rich fens, alkaline fens
Non-vascular plants	moss	*Tayloria lingulata*	Tongue-leaved Gland-moss	Fens: Base-rich fens, alkaline fens
Terrestrial invertebrates	insect - true fly (Diptera)	*Stratiomys chamaeleon*	a soldier fly	Fens: Base-rich fens, alkaline fens
Terrestrial invertebrates	mollusc	*Vertigo (Vertigo) genesii*	Round-mouthed Whorl Snail	Fens: Base-rich fens, alkaline fens
Terrestrial invertebrates	mollusc	*Vertigo (Vertigo) geyeri*	Geyer's Whorl Snail	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Carex atrofusca*	Scorched Alpine-sedge	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Carex buxbaumii*	Club Sedge	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Cochlearia officinalis subsp. scotica*	Scottish Scurvygrass	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Dactylorhiza ebudensis*	Hebridean Marsh-orchid	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Oenanthe fistulosa*	Tubular Water-dropwort	Fens: Base-rich fens, alkaline fens
Vascular plants	flowering plant	*Saxifraga hirculus*	Marsh Saxifrage	Fens: Base-rich fens, alkaline fens

Vascular plants	flowering plant	*Sesleria caerulea*	Blue Moor-grass	Fens: Base-rich fens, alkaline fens
Vascular plants	fern	*Thelypteris palustris*	Marsh Fern	Fens: Base-rich fens, alkaline fens
Aquatic invertebrates	insect - beetle (Coleoptera)	*Donacia aquatica*	Zircon Reed Beetle	General wetlands
Aquatic invertebrates	insect - beetle (Coleoptera)	*Gyrinus suffriani*	a water beetle	General wetlands
Aquatic invertebrates	annelid	*Hirudo medicinalis*	Medicinal Leech	General wetlands
Birds	bird	*Circus aeruginosus*	Marsh Harrier	General wetlands
Birds	bird	*Circus cyaneus*	Hen Harrier	General wetlands
Mammals	land mammal	*Arvicola amphibius*	Water Vole	General wetlands
Mammals	land mammal	*Lutra lutra*	Otter	General wetlands
Mammals	land mammal	*Myotis daubentonii*	Daubenton's Bat	General wetlands
Non-vascular plants	liverwort	*Barbilophozia kunzeana*	Bog Pawwort	General wetlands
Non-vascular plants	liverwort	*Jamesoniella undulifolia*	Marsh Flapwort	General wetlands
Reptiles & amphibians	amphibian	*Bufo bufo*	Common Toad	General wetlands
Reptiles & amphibians	amphibian	*Triturus cristatus*	Great Crested Newt	General wetlands
Terrestrial invertebrates	insect - true fly (Diptera)	*Wiedemannia simplex*	a dance fly	General wetlands
Vascular plants	flowering plant	*Platanthera bifolia*	Lesser Butterfly-orchid	General wetlands
Vascular plants	flowering plant	*Stellaria palustris*	Marsh Stitchwort	General wetlands
Birds	bird	*Pandion haliaetus*	Osprey	Open water transition fens
Birds	bird	*Acrocephalus scirpaceus*	Reed Warbler	Reedbeds and swamps
Birds	bird	*Botaurus stellaris*	Bittern	Reedbeds and swamps
Birds	bird	*Panurus biarmicus*	Bearded Tit	Reedbeds and swamps
Birds	bird	*Tringa glareola*	Wood Sandpiper	Reedbeds and swamps
Fungi	fungus	*Armillaria ectypa*	Marsh Honey Fungus	Reedbeds and swamps
Terrestrial invertebrates	insect - moth	*Rhizedra lutosa*	Large Wainscot	Reedbeds and swamps
Non-vascular plants	moss	*Bryum schleicheri var. latifolium*	Schleicher's Thread-moss	Transition mires and quaking bogs
Non-vascular plants	liverwort	*Lophozia wenzelii*	Wenzel's Notchwort	Transition mires and quaking bogs
Non-vascular plants	moss	*Pohlia obtusifolia*	Blunt-leaved Thread-moss	Transition mires and quaking bogs

Non-vascular plants	moss	*Scorpidium turgescens*	Turgid Scorpion-moss	Transition mires and quaking bogs
Non-vascular plants	moss	*Splachnum vasculosum*	Rugged Collar-moss	Transition mires and quaking bogs
Non-vascular plants	moss	*Tayloria tenuis*	Slender Gland-moss	Transition mires and quaking bogs
Vascular plants	flowering plant	*Sagina saginoides*	Alpine Pearlwort	Transition mires and quaking bogs
Vascular plants	flowering plant	*Saxifraga hypnoides*	Mossy Saxifrage	Transition mires and quaking bogs
Birds	bird	*Asio flammeus*	Short-eared Owl	Wet heath
Fungi	fungus	*Puccinia clintonii*	Lousewort Rust	Wet heath
Fungi	fungus	*Puccinia eriophori*	Deer Grass Rust	Wet heath
Fungi	fungus	*Puccinia moliniae*	Purple Moorgrass Rust	Wet heath
Vascular plants	flowering plant	*Wahlenbergia hederacea*	Ivy-leaved Bellflower	Wet heath
Birds	bird	*Anas querquedula*	Garganey	Wet meadows, marshy grassland
Birds	bird	*Calidris alpina*	Dunlin	Wet meadows, marshy grassland
Birds	bird	*Motacilla flava*	Yellow Wagtail	Wet meadows, marshy grassland
Birds	bird	*Numenius arquata*	Curlew	Wet meadows, marshy grassland
Birds	bird	*Vanellus vanellus*	Northern Lapwing	Wet meadows, marshy grassland
Non-vascular plants	liverwort	*Adelanthus lindenbergianus*	Lindenberg's Featherwort	Wet meadows, marshy grassland
Reptiles & amphibians	amphibian	*Epidalea calamita*	Natterjack Toad	Wet meadows, marshy grassland
Terrestrial invertebrates	insect - butterfly	*Euphydryas aurinia form aurinia*	Marsh Fritillary	Wet meadows, marshy grassland
Terrestrial invertebrates	mollusc	*Omphiscola glabra*	Mud Pond Snail	Wet meadows, marshy grassland
Terrestrial invertebrates	mollusc	*Vertigo (Vertigo) modesta*	Cross Whorl Snail	Wet meadows, marshy grassland
Terrestrial invertebrates	mollusc	*Vertigo (Vertilla) angustior*	Narrow-mouthed Whorl Snail	Wet meadows, marshy grassland
Vascular plants	flowering plant	*Dactylorhiza purpurella subsp. cambrensis*	Welsh Marsh-orchid	Wet meadows, marshy grassland
Vascular plants	flowering plant	*Ranunculus reptans*	Creeping Spearwort	Wet meadows, marshy grassland
Vascular plants	flowering plant	*Stellaria neglecta*	Greater Chickweed	Wet meadows, marshy grassland

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6. Appendix VI: Climate Change Impacts

by Mike Rivington, Mohamed Jabloun, Zisis Gagkas and Robin Pakeman

0.1 Research questions

The key research questions that this section sought to answer were:

- *How will climate change impact Scotland's wetlands?*
- *How might these impacts affect wetland's ability to moderate extremes of drought and excess rainfall?*
- *Can we identify the more vulnerable wetland types and develop an approach to identify where they are?*

0.2 Objective

To inform stakeholders of the complexity of climate change impacts on wetlands' ability to moderate extremes of drought and excess rainfall events and identify the most vulnerable wetland types.

To produce projections of the key aspects of climate change that impact- on wetlands, particularly soil water balance and excess or low water quantities**.** This includes consideration of water quantities as inputs to and from wetlands, as well as the duration of extreme events (droughts) and frequencies of occurrence.

0.3 Approach

We reviewed the current understanding of climate projections and how extremes of dry and wet conditions will affect the ability of wetlands to act as buffers to moderate impacts.

We assessed the risks and opportunities posed by changes in water availability, particularly from droughts and floods due to climate change, to Scotland's wetlands and their buffering capacity. We use climate model data as input into a range of tools to spatially estimate the impacts of future daily weather conditions on soil water balance. To achieve this, we undertook climate impact assessments using spatial modelling, where climate projection, soil properties and wetland type (the HOST-DSM map of wetland coverage developed in Appendix VIII data were integrated to estimate daily soil water balance). Maps were produced indicating changes in climate conditions and how this results in changes in wetland water availability, providing information on the location of wetlands vulnerable to drying and flooding conditions.

1. Introduction

The climate in Scotland is likely to change over the next 3-4 decades in terms of inter- and intra-annual variability, extreme events and long-term averages. Such changes will alter the hydrological cycle and have impacts on soils, biological (vegetation, microbiome), chemical and physical processes and properties. How these impact on the structure, health and functional ability of wetlands is a complex mix of changes in precipitation, temperature and evapotranspiration and how soils, microbiome and vegetation respond to these, given that there are spatial and temporal distribution variations in these ecosystem components and the future climate projections.

Previous work within CREW has shown that there has been an observed change in the seasonal and spatial distribution of rainfall in Scotland (Rivington et al 2019). The west has become wetter whilst the east has become drier. This trend is likely to continue in the future, along with the occurrence of more extreme drought and high rainfall events.

1.1 Climate Projection Summary

This study uses the UKCP18 climate projections (see Methods) from which the following published key messages (UKMO, 2019) can be summarised as:

- Hot summers are expected to become more common. The summer of 2018 was the equal-warmest summer for the UK along with 2006, 2003 and 1976. Climate change has already increased the chance of seeing a summer as hot as 2018 to between 12-25%. With future warming, hot summers (like 2018) by mid-century could become even more common, near to 50%.
- The temperature of hot summer days, by the 2070s, show increases of 3.7 °C to 6.8 °C, under a high emissions scenario, along with an increase in the frequency of hot spells.
    - For the RCP8.5 emissions scenario (used in this study) the estimated probabilistic temperature increase for the UK by 2070 ranges between 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter.
- UKCP18 Global (60km), Regional (12km) and Local (2.2km) scale climate model simulations all project a decrease in soil moisture during summers in the future, consistent with the reduction in summer rainfall. Locally this could lead to an exacerbation of the severity of hot spells, although large-scale warming and circulation changes are expected to be the primary driver of increases in the occurrence of hot spells.
- The probabilistic projections (12-member ensemble) provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of seasonal average precipitation changes between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to -47% to +2% in summer, and -1% to +35% in winter (where a negative change indicates less precipitation and a positive change indicates more precipitation).
- Overall increased drying trends in the future, but increased intensity of heavy summer rainfall events, indicating greater variability and increased frequency of extreme events.
- Change in the seasonality of extremes with an extension of the convective season from summer into autumn, with significant increases in heavy hourly rainfall intensity in the autumn.
- By the end of the 21st century, lying snow decreases by almost 100% over much of the UK, although smaller decreases are seen over mountainous regions in the north and west.

These projected changes will impact wetlands by altering the amount, spatial distribution and timing of rainfall and increase surface water loss from evaporation.

2. Methods

Input data sets:

- Daily UKCP18 climate projections data (see below and Appendix C), downscaled and bias corrected to 1km resolution.
- UK Meteorological Office 1 km interpolated gridded observed precipitation and temperature, plus solar radiation derived from satellite data (SolarGIS).
- HOST-DSM wetland types (see Appendix VIII).

2.1 Climate Projections

This research uses the UK Climate Projections 2018 (UKCP18, 2018) daily weather data: precipitation (P, mm), maximum and minimum temperature (Tmax, Tmin, °C), and solar radiation (SR, MJ m^2 day^{-1}). As agreed with the Project Steering Group, a single greenhouse gas emissions scenario was used, referred to as the 8.5 Representative Concentration pathway (RCP8.5), which corresponds to the current high rate of emissions and continuing towards the end of the century. This pathway is likely to lead to a global average temperature increase above pre-industrial levels of 3-4°C. As such the RCP8.5 represents a plausible possibility, given that whilst GHG emissions from human activities may decrease, there is a risk that climate feedbacks result in emissions from natural sources (i.e., due to melting of Arctic permafrost and release of CO_2 and CH_4). It should also be noted that, regardless of changes to emissions in the next few decades, the global temperature increase is currently likely to be in the region of 2°C due to locked-in climate change.

The baseline and future periods considered in this study were 1994-2014 and 2030-2059, respectively. Previous research has assessed the utility of the data produced by the Regional Climate Model used to produce the UKCP data (Rivington et al 2008a) and found that it makes some systematic errors. To resolve this, a simple bias correction method was applied (a variation on Rivington et al 2008b, correcting for means and variance) to improve spatial resolution to 1 km and reduce biases but maintaining the climate signal within the data. This approach does not remove climate model representation uncertainty, but it does help with improving data utility when used to make estimates of soil water balance. It should be noted though that climate models in general are limited in their capability to estimate extreme events, particularly high rainfall, where amounts tend to be under-estimated. Hence occurrence of high rainfall events should be interpreted with caution, with a probability that the quantity may be larger than estimated.

Addressing uncertainty: The climate projections consist of an ensemble of 12 different model members run from the HadRM3 Regional Climate model. The 12 climate projections represent a range of possible futures, with substantial spatial and temporal differences between each ensemble member (see Appendix C: Probabilistic Climate Projections). The use of ensembles aims to capture some aspects of the uncertainty in estimating future climate conditions. In this respect it is important to note:

- Each ensemble member presents data that are projections, not predictions.
- Projections are based on a single emissions scenario (RCP.8.5), one parent Global Circulation Model (HadGEM3) and one Regional Climate Model (HadRM3), hence other projections exist, where precipitation and temperature changes may be more or less.
- Whilst spatially and temporally there may not be consistent agreement between ensemble members, each one is equally plausible, hence it is important to consider the range of projections as this will better capture the wider possible changes in variation and extremes.
- Agreement between members helps improve confidence in projected changes, but it is also necessary to recognise that the tails of the probability distribution (see Appendix C, Figure 116)

represent future possibilities that are equally plausible and may have more substantial impacts on wetlands, I.e. extremes.
- Areas of topographical diversity such as the Scottish Highlands are difficult areas for climate models to represent, which means there is likely to be less agreement between ensemble members.

Working with certainty: Whilst there is uncertainty about specific locations and impacts on particular wetlands, there are key issues where we can work with greater certainty:

- The UKCP18 climate projections key messages (above) are based on, and in agreement with, wider climate modelling community assessments (IPCC AR5, CMIP5).
- The restrictions on our ability to be more precise for specific wetlands should not mask key underlying principles. Whilst it may not be accurate to make specific projections of climate changes in space and time, it is possible to state generalisations:
  - Higher temperatures will increase evaporation and so alter soil moisture.
  - Warmer air can hold more moisture (7% for each 1 °C temperature rise), hence the higher probability of more intense rainfall.

Presenting the analysis: The number of possible analyses when using probabilistic projections poses challenges in how we present results, with potentially a very large number of map combinations (i.e., monthly data for 12 ensemble members = 144 maps). Here we present estimates of *where*, *when* and *how much* change may occur by first establishing the observed baseline against which future projections are compared. We then present maps detailing the level of agreement between ensemble members and hence where there is a higher probability of the estimated change occurring. Analysis is presented at the national scale, and in Appendix A for the Cairngorms National Park, Insh Marshes and three Alkaline Fens: Rassal (north-west), Mortlach Moss (east) and the Lendalfoot Hills Complex (south-west).

How to read the UKCP18 agreement (Certainty) maps: The maps presented are for areas classed as wetlands using the HOST-DSM (see Appendix VIII). Note: land areas shown as white are not classified as wetlands.

- Wetland areas indicated as uncertain (yellow) means there are differences between the 12 ensemble members, hence there is a variable probability of the change in sign when compared against the observed baseline (i.e. positive = earlier, or negative = later occurrence, or more or less precipitation or evapotranspiration).
- Positive change (blue) indicates there is an agreement between the ensemble members for the represented feature (to occur later in the year, or be more precipitation or evapotranspiration). Note: the postive change refers to the sign of the feature shown, not the impact on the wetlands.
- Negative changes (red) indicate there is agreement between the ensemble members for the represented feature (to occur- earlier in the year or to be more precipitation or evapotranspiration). Note: the negative change refers to the sign of the feature shown, not the impact on the wetlands.
- No change (green): estimated to be no change between the baseline period and the agreement between the 12 climate model ensemble members.

The purpose of presenting the information in this way is to communicate that there are differing levels of certainty and uncertainty in space and time when using the UKCP18 projections. For the levels of agreement maps (i.e. Figure 2), where there is either blue or red, then we can be more confident that the estimated change is likely to occur. Where there is green, then we can be confident that there is less likely to be much change. The yellow areas indicate a variable probability of change (could be either ealier / later, or more / less).

Note: To best interpret the results it is useful to consider both the agreement maps and those showing the individual ensemble member estimates, to gain a sense of the level of agreement and the range in variation. The maps provided on the agreement between climate projections use positive and negative changes in the sign of the feature shown. The use of positive and negative does not refer to the impact on the wetlands. We have presented the agreement map based on all 12 climate model ensemble members, yet is possible to have a situation where 11 are in agreement but 1 is not (for examples see Figures 88, 89, 90 and 91 in Appendix A). Our advice is to assess the number of ensemble members that are in agreement and guage how many indicate certainty.

2.2 Modelling Tools

Soil water balance

A simple tipping bucket model was used to estimate soil water balance. The daily soil water depletion of the root zone at the end of day i (Dr_i) was calculated as follows:

$$Dr_i = Dr_{i-1} - P_i + K_{s_i} ETo_i + DP_i$$

where Dr_{i-1} (mm) the root zone depletion at the end of the previous day i - 1, P_i (mm) the precipitation on day i, ETo_i (mm) the reference evapotranspiration on day i, Ks_i (-) the reduction factor under water limiting conditions, and DP_i (mm) is the water loss out of the root zone by deep percolation on day i. Deep percolation (or water surplus) was calculated as:

$$DP_i = P_i - ETo_i - Dr_{i-1}$$

For water limiting conditions, when soil water storage in the root zone has been depleted under a threshold value, the reduction factor is calculated as:

$$Ks_i = \frac{TAW - Dr_i}{TAW - RAW}$$

where Ks_i (-) is the reduction coefficient [0,1] on day i, TAW (-) the total available water (i.e. water stored in the root zone between field capacity and permanent wilting point; a root depth of 1m was assumed for all the wetland classes, Dr_i (mm) the rootzone depletion and RAW (mm) is the readily available water, a fraction of TAW beyond which crops start to suffer water stress. It was assumed that Ks=1 when 90% of TAW is depleted.

Drought is defined for conditions when precipitation cannot meet the evapotranspiration demand, i.e. when the climatic deficit (P-ETo) is negative for a specific period of time, in this report it is calculated on a monthly basis.

Climate Indicators

The climate indicators were calculated for the baseline and for each of the 12 members of the future climate ensemble, after which the projected change (defined as the difference between future and baseline period) amount and sign were calculated for each grid cell. The change maps from the 12 members were then combined and the different grids were classified into two main classes: class where all 12 ensemble menbers are in agreement for the change sign (with three subclasses: no change, positive and negative change), and a class where different change signs were obtained. The latter class represents where ensemble member change signal was uncertain. This made it easy to classify Scotland into different change agreement classes for the different climate indicators. See below for details on how to read the agreement maps.

Precipitation
The daily precipitation (P) was aggregated to monthly and the most frequent driest month (month with the minimum precipitation) was determined for the baseline period and each of the 12 climate model members. The change map was then calculated. The sign of the projected change would indicate whether the driest month will occur earlier, later during the year or would remain the same.

Dry spell
Dry spell was defined as the maximum consecutive count of days of P < 0.2 mm. It was calculated for each year, then the mean dry spell was calculated for the baseline and each of the 12 members. The change map was then calculated. To read the maps, the sign of the projected change indicates whether the dry spell would increase, decrease or remain at a constant level.

Reference evapotranspiration (ETo)
ETo was calculated using the Penman-Monteith equation (Montieth, 1965). The daily ETo was aggregated to monthly values and the most frequent month with the maximum ETo was determined for the baseline period and each of the 12 members. The change map was then calculated. To read the maps, the sign of the projected change indicates whether the hottest month will occur earlier, later during the year or would remain the same.

Climatic deficit
The climatic deficit (D) was calculated as the difference between input precipitation (P) and reference evapotranspiration (ETo) output which represent the climatic demand. A negative climatic deficit indicates drought conditions.

The climatic deficit was calculated on a daily timescale and aggregated to monthly for each grid cell. The inputs to estimate ETo are daily temperature and daily solar radiation.

The most frequent month with the maximum drought amount was determined for each year for the baseline and for each of the 12 menbers of the climate model ensemble. The change map was then calculated. The sign of the projected change would indicate whether the month with the maximum drought will occur earlier, later during the year or would remain the same.

The number of successive months with drought was also calculated. The sign of the projected change would indicate whether the drought frequency would increase, decrease or remain at the same level.

Water surplus
The water surplus (sum of runoff and deep percolation (Dpi)) was defined as the amount of water that exceeds the soil water holding capacity (SWHC). It was determined using a simple daily tipping bucket water balance. The SWHC was calculated using a maximum soil depth of 1m.

The calculated daily water surplus was aggregated to monthly values and the most frequent month with the maximum water surplus was determined for the baseline and each of the 12 members and the change was then calculated.

Agrometeorological Indicators
We have included outputs from other research projects (in Appendix B) on the spatial mapping of Agrometerological Indicators estimated using observed and UKCP18 climate projections for the whole of Scotland. The purpose is to provide an overview of changing climatic conditions to aid understanding of impacts on wetlands and vegetation. For example, Figure 114 shows projections of plant heat stress (the count of the number of days per year when maximum temperature is greater than 25°C), illustrating what the increase in temeprature represents in terms of impacts on plant stress.

3. Results and Key Messages

The results indicate that there are spatial and temporal variations in the climate projections and how they will impact wetlands. Based on the use of the probabilistic projections it is possible to summarise these changes as:

- **The timing of when dry conditions are likely to occur will change.**
- The month when the maximum drought amount will happen is likely to be later in the year, from currently May towards June in the east and central highlands, but either earlier in the north-west (from June and July towards May-June) or similar to the observed baseline (1994-2014).
- May has generally been the driest month, but this is estimated to shift to later (June) in the east (reasonable agreement between the climate projections). In the west the driest month is likely to be either similar to the present or later (varied agreement between climate projections).
- The number of months with successive droughts is likely to increase, mostly in the east (good agreement between the climate projections) but with some large variation seen between climate projections in the west.
    - This implies dry periods will last for longer.
- In the observed period, July was predominantly the month when the maximum amount of evapotranspiration occurred. There is general agreement between the climate projections that July will continue to be the month with the maximum evapotranspiration rate in the east and central Scotland, but later (August) in the west.
- The number of months with successive droughts is likely to increase in the south and east of Scotland, but with wider variation (greater uncertainty) in the west.
- There is a variable range of probability of change to the mean length of dry spells. In the central and eastern parts of Scotland it is estimated to increase, but in the west and north-west may decrease.
- The month when maximum evapotranspiration occurs was historically in July, and this is estimated to remain in the east, south and north-east of Scotland, but be later in the year in the west.

- **The balance between input precipitation and water returned to the atmosphere from evapotranspiration will change.**
- Precipitation intensity is likely to increase, but with longer dry spells.
- Total precipitation input is likely to be spatially and temporally variable.
    - May is estimated to have a variable spatial probability of a decrease in precipitation in the west but an increase in evapotranspiration.
    - There is good agreement between ensemble members that April is likely to be wetter in the west and south, July is likely to be wetter in the north-west, but the north of Scotland will see reduced precipitation in December, and the east will have a decrease in August, September and October.
- Between 1994-2014, July was the month with the highest amounts of evapotranspiration across most of Scotland. There is generally good agreement between the climate projections that this will remain the case in the eastern, south-eastern and north-eastern parts of Scotland. There is reasonable agreement between ensemble member that in the west and south-west the maximum evapotranspiration will occur earlier in the year.
- The net effect of changes in precipitation water input and evapotranspiration loss is likely to be less water available in eastern areas, but potentially more in the north-west.

- **The timing of when excess water occurs is likely to change.**
- There is good agreement between ensemble members in some western and southern parts of Scotland that the excess water will occur earlier in the year, i.e. shifting from December to November.

- **Other meteorological factors are likely to change.**
- Air temperatures will increase, impacting evapotranspiration rates and formation of surface dews.
- The length of the growing season will increase. Plants may be able to start growth earlier in the year and continue later into autumn or winter.
- The rate of thermal time accumulation (determining plant and insect phenology) will increase (growth stages will be reached earlier).
- There is likely to be a reduction in the number of frost days, with frosts starting later in autumn and ending earlier in spring.
- The number of days when plants may experience heat stress (i.e. above 25°C) is likely to increase.
- The number of dry days ($P < 0.2$mm) is likely to increase in the east, potentially to more than 200 days.
- Snow cover is likely to decrease after c. 2040-2050, changing the balance of water stored and released in upland areas.
- There is uncertainty about the impacts of climate change on wind speeds and direction, but there is a strong possibility that high wind speeds will increase.
- Storm intensity will likely increase.

The following Section presents mapped analysis at the national scale for a range of indicators aimed at showing how conditions will change in space, time and quantity. Please note that on the maps, white areas on land are not classified as wetlands.

4. Mapped Analysis at the National Scale for a Range of Indicators

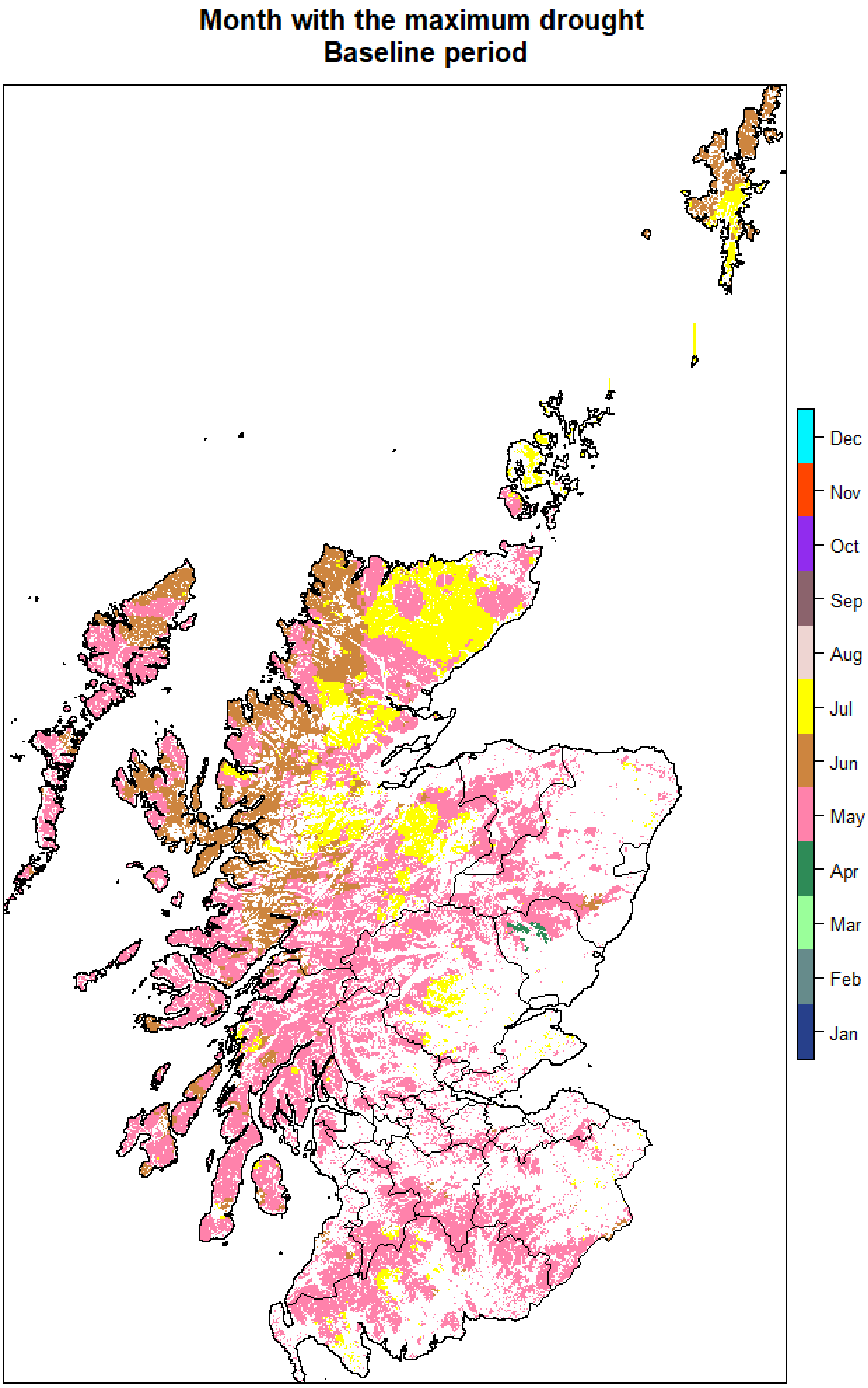

Figure 1. Spatial distribution of the month when the maximum drought occurs over the wetland areas for the baseline period (1994 –2014). Note: White areas not classified as wetlands.

The maximum drought during the baseline period occurred between April and August with May being the most frequent month in 67% of the total wetland area. Figure 1 serves as the reference condition to compare future projections with in Figure 2.

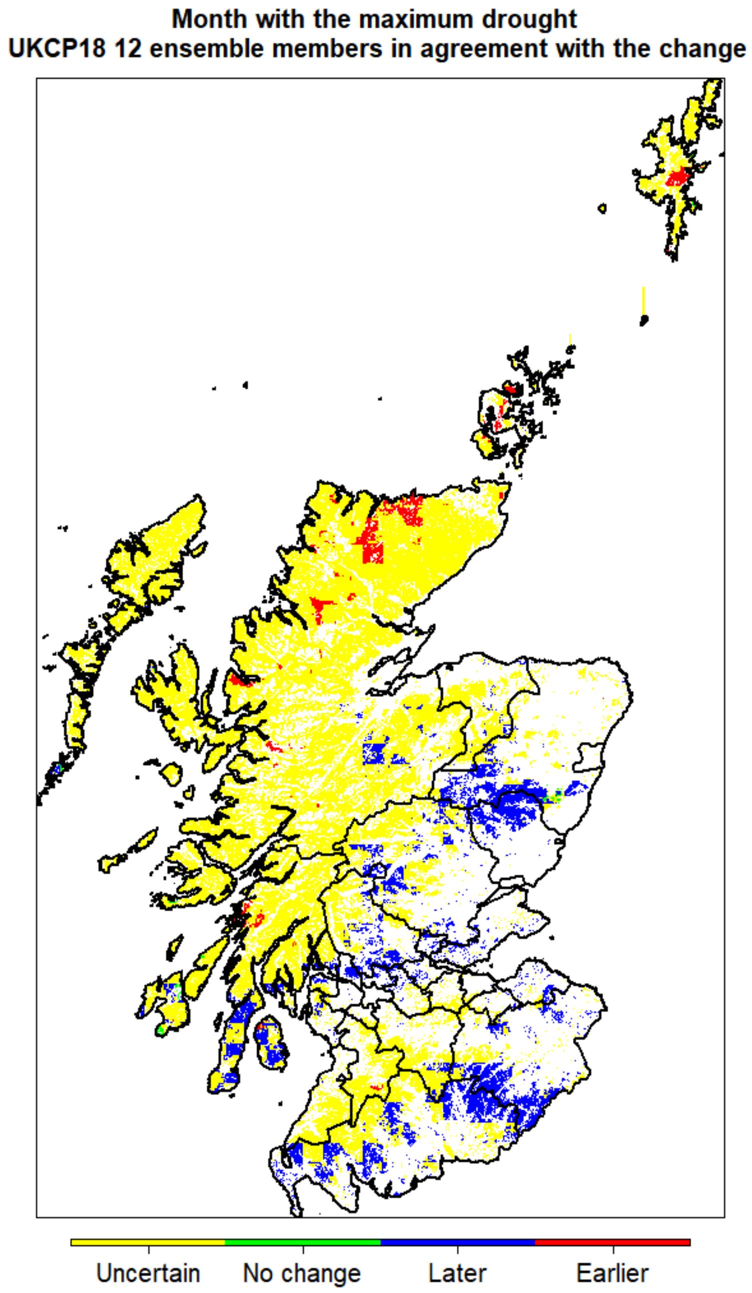

Figure 2. Spatial distribution of the level of agreement between climate projections in the month when the maximum drought occurs over the wetland areas over the period 2030-2059. Yellow = variable probability of change; Green = no change with baseline; Blue = month when the maximum drought occurs later (positive); Red = maximum drought month occurs earlier (negative); White = not wetlands. Note: positive and negative refer to the sign of change when the driest month occurs, not the impact on wetlands.

In Figure 2, areas shown as yellow indicate that there are differences between the ensemble member's estimation of when the maximum drought month will occur, hence there is a variable probability that it could be earlier or later than at present. There is an agreement between the 12 ensemble members projection change in 17% of the total wetland area with a later occurrence (blue, positive) change in 14% of the total wetland area. The implications are that the maximum drought will be more likely to occur in June, rather than May. Figure 3 indicates that there is likely to be a shift to the month with the maximum drought occurring later in most of Scotland, other than the north-west Highlands.

Impacts: These changes will have impacts on the biodiversity of wetlands. Appendix VII highlights wetland communities where there are species at risk of wetter or drier conditions. The predictions relating to the month of maximum drought indicate that species of drier microhabitats in wetlands in south and east Scotland (and in the areas with differences between ensemble members, Figure 3) might be impacted as conditions provide species of wetter parts of the habitat with a competitive advantage. The reverse is true for the small areas of the north and west where species of the drier microhabitats within habitats might be able to increase in abundance. It is not possible to predict how this would impact in terms of dominant species and overall community composition with current knowledge.

The changes in timing of maximum drought occurrence to earlier or later in the year may mean that water limitations occur differently from when plants are at key early growth stages. The consequences of this may vary depending on species phenological development and the warmer temperatures that may coincide with the drought period.

Knowledge Gap: To better understand the consequences of the change in when the maximum drought occurs, it is also necessary to estimate the precedent soil water state to understand if water availability will be limited. As well as potential impacts on overall water levels (period of drought or flood) there could also be more subtle changes in response to a changes in the relative proportions of groundwater and surface water supplying a given wetland and how water stress influences the plant annual cycle.

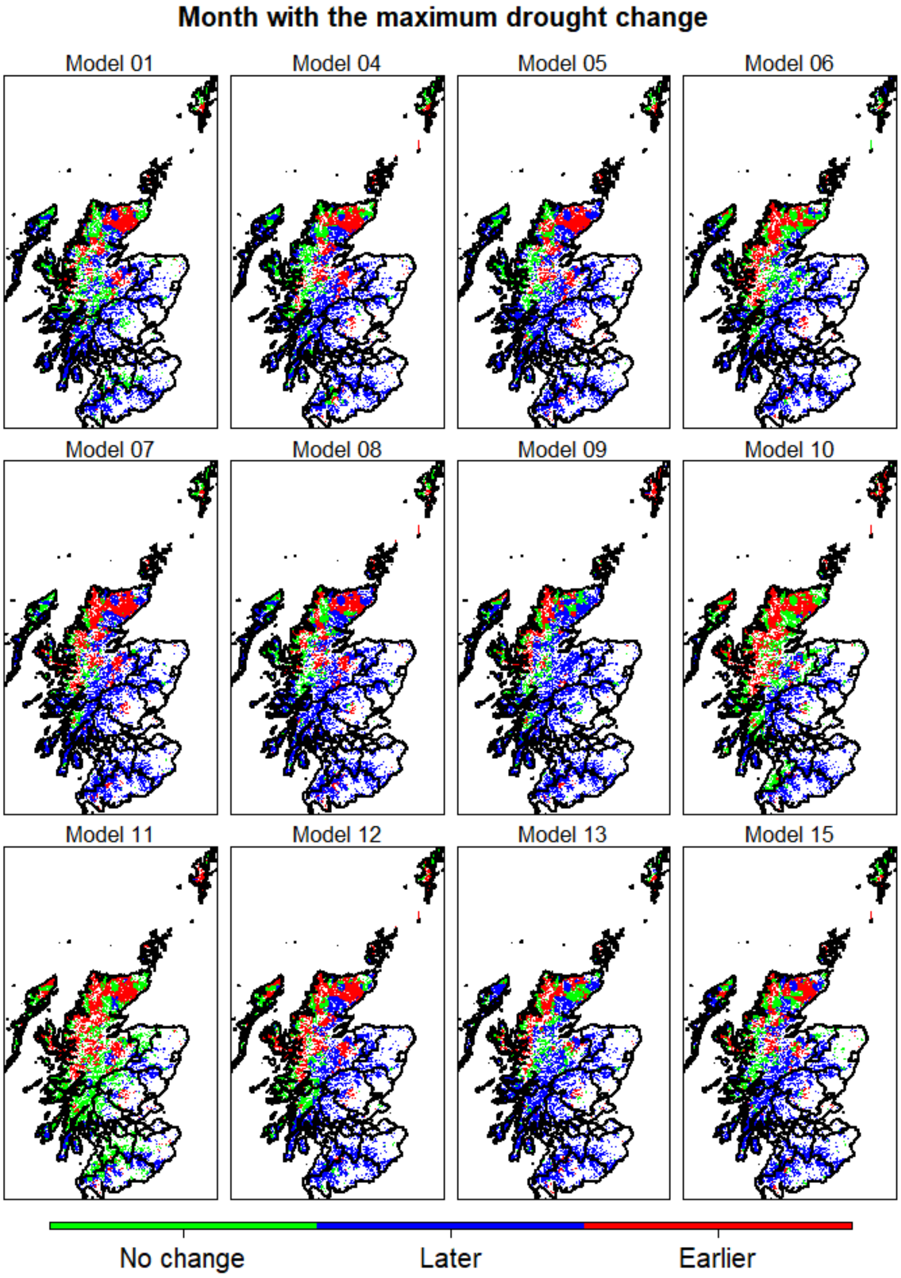

Figure 3. Variation between ensemble members in the month when the maximum drought occurs (green = no change from baseline, blue = later, red = earlier, white = not wetlands).

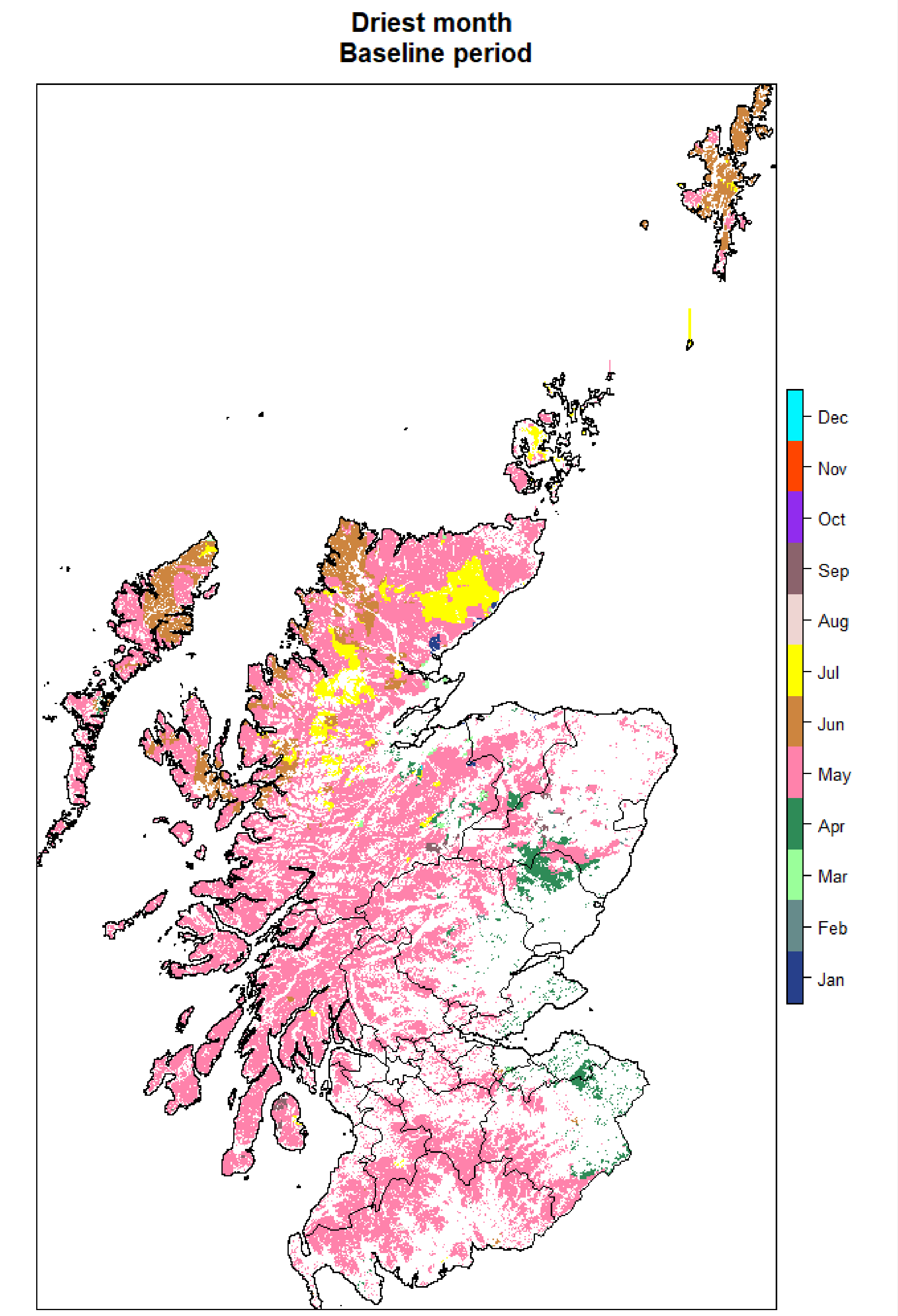

Figure 4. The time when the driest month occurs for the baseline period (1994-2014).

During the baseline period, May was the driest month in more than 81% of the total wetland area. April, July and August were the driest months in only 3, 9 and 5% respectively of the total wetland area (Figure 4).

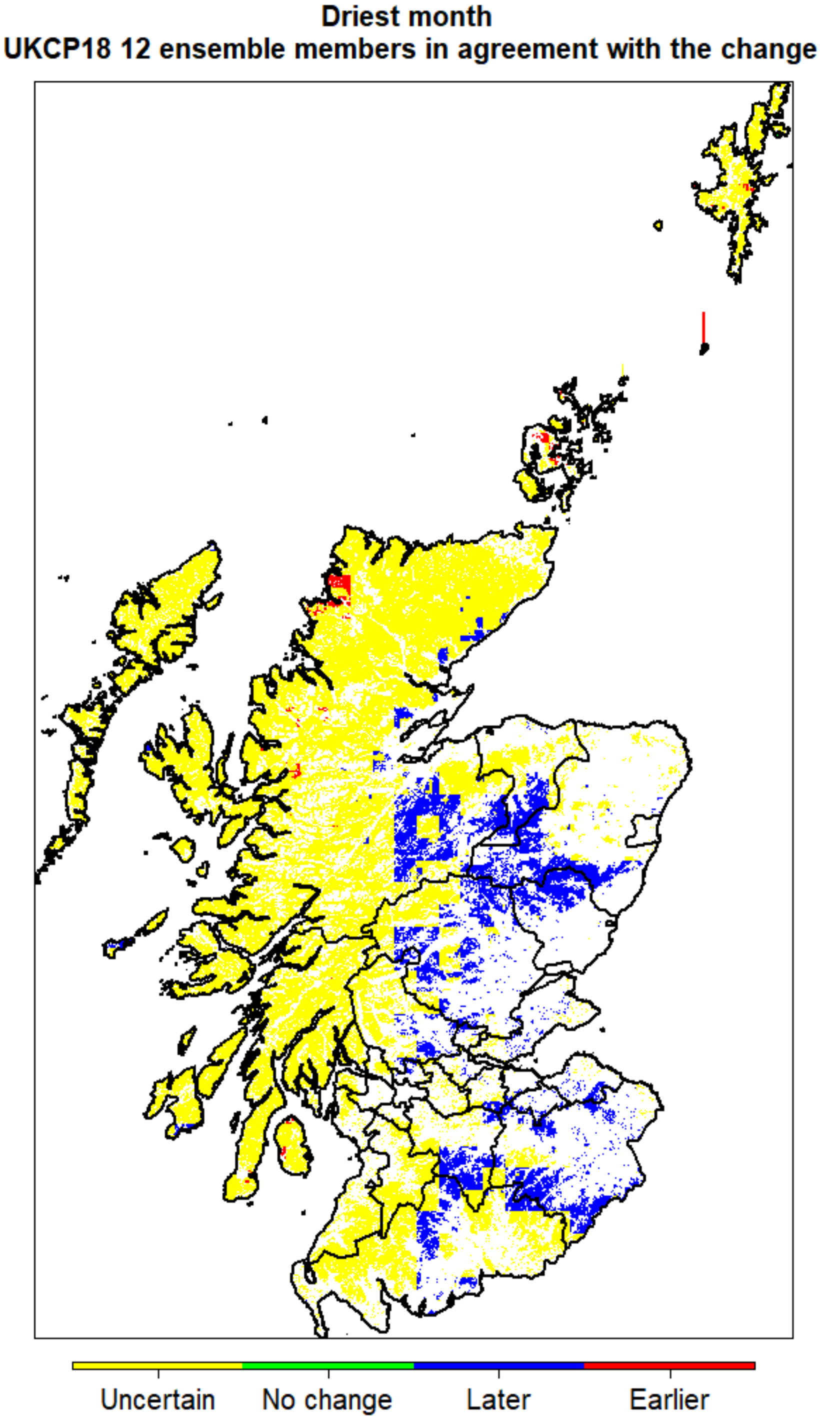

Figure 5. Spatial distribution of the level of agreement between ensemble members when the driest month occurs over the wetland areas over the period 2030-2059. Yellow = variable probability of change; Green = no change with baseline; Blue = month when the driest month occurs later; Red: driest month occurs earlier. Note: positive and negative refer to the sign of change in when the driest month occurs, not the impact on wetlands.

There is an agreement between the 12 ensemble members projection change in 18% of the total wetland area (Figure 5) with mainly a change to later in the year in 17.5% of the total wetland area. The driest month is likely to occur later in the eastern part of Scotland as compared to the baseline period. These estimates are similar to those seen for the month when the maximum drought occurs. The common feature is that in the east, there is projected to be a shift towards later in the year.

Considering each individual ensemble member (Figure 6), there may be a shift to the driest month occurring earlier in the year in the west or remaining similar to the current period. The east and central Scotland may see a shift to later occurrence.

Impacts: Similarly to the projections related to month with maximum drought, these estimates suggest that through eastern Scotland there will be a shift in competitive advantage towards species of the wetter microsites within wetland communities. It is not possible to predict how this would impact on dominant species and overall community composition. The SNIFFER (2014) ER37 Wetland Habitats Report indicates trajectories in shifts in wetland communities in relation to, amongst other pressures, higher or lower water levels. However, these trajectories will likely be subject to the site specificity of individual wetlands.

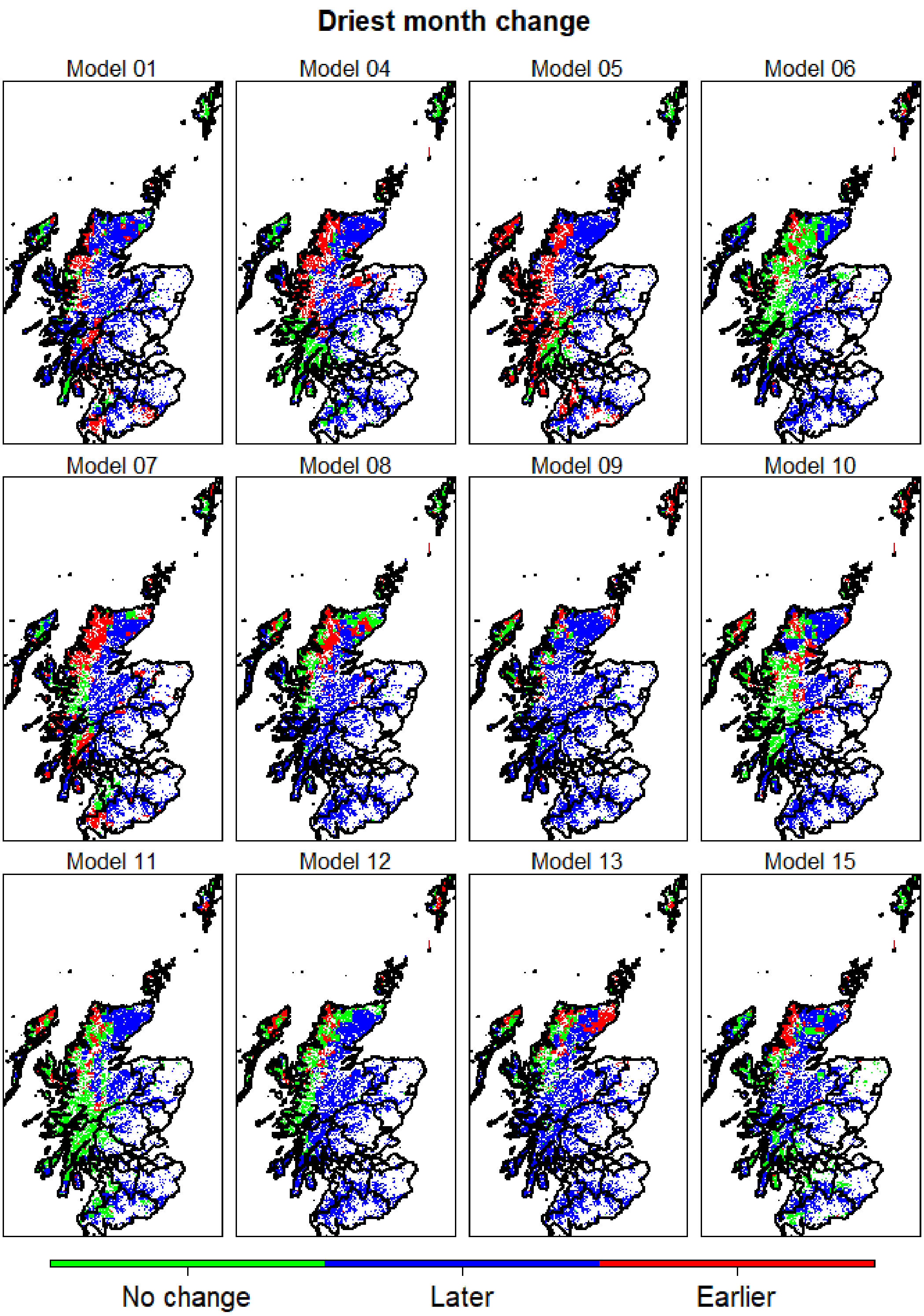

Figure 6. Variation between climate model ensemble members when the driest month occurs (green = no change from baseline, blue = later, red = earlier).

Number of successive drought months

Baseline period

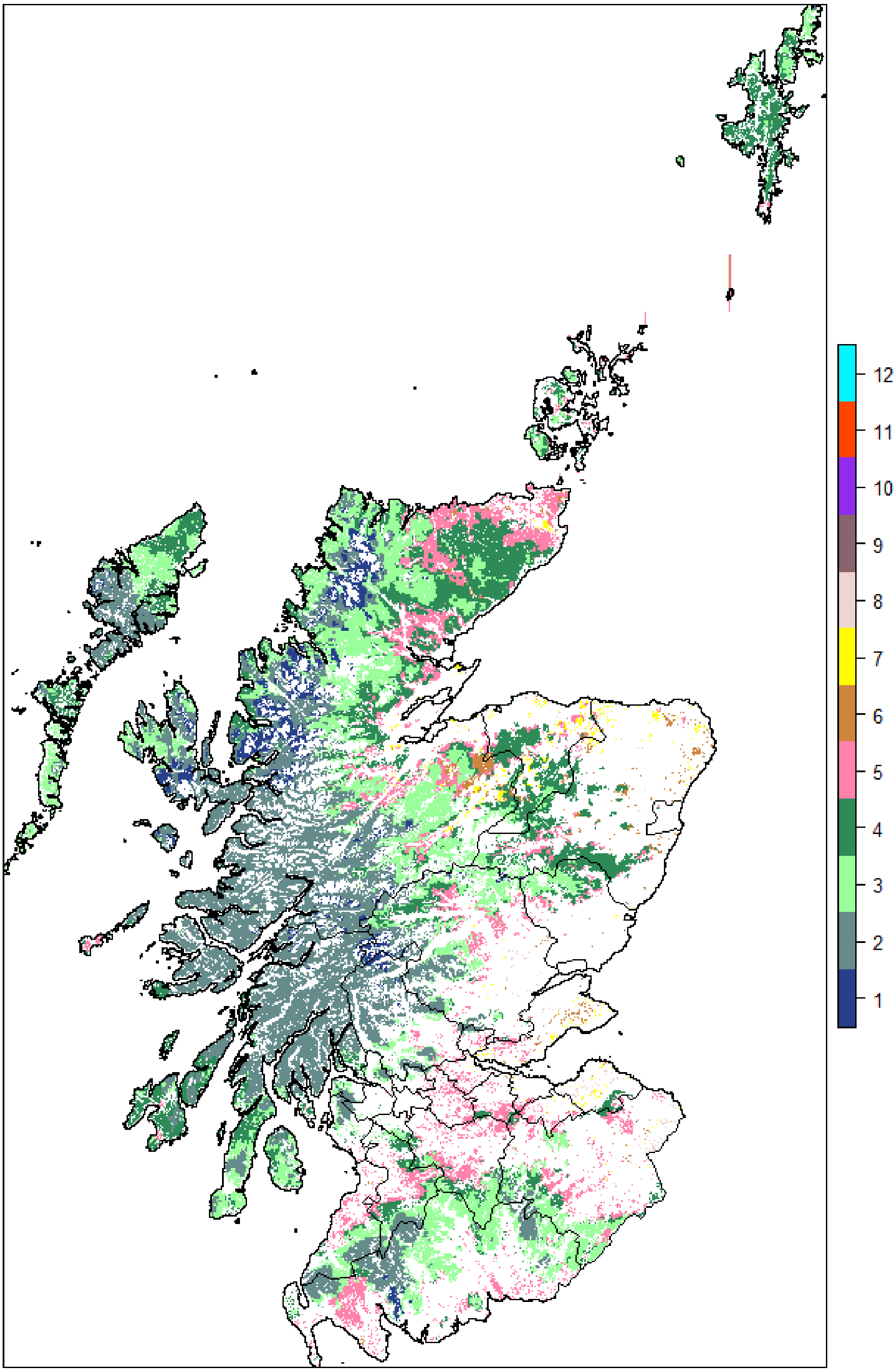

Figure 7. The number of successive months with drought during the baseline period (1994-2014).

The number of successive months with drought during the baseline period ranged mainly between 2 and 5 months with 2 months being the most frequent in 33% of the total wetland area (Figure 7). In very few wetland areas it can even reach 9 months. **Note** the definition of drought used here is when evapotranspiration exceeds precipitation.

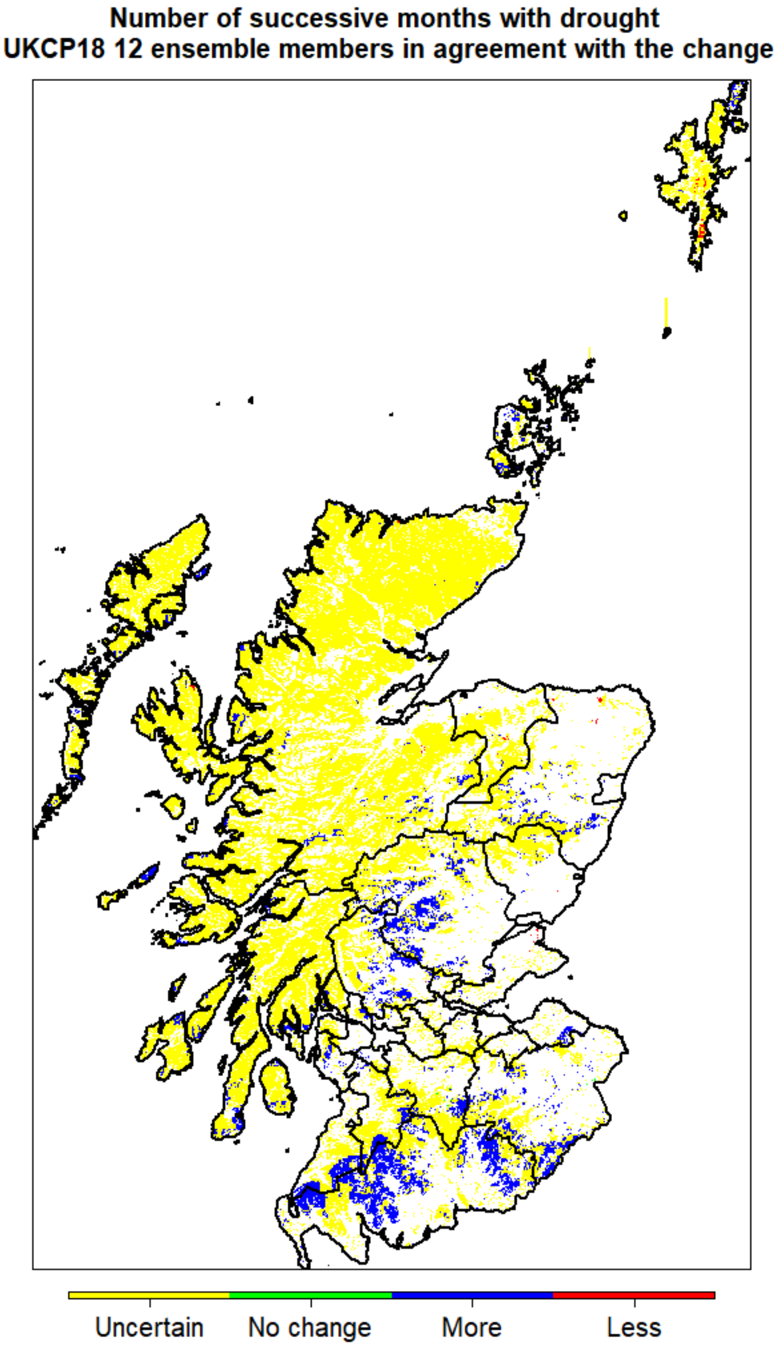

Figure 8. The level of agreement between ensemble members in estimates of the number of successive drought months. Yellow: variable probability of change; Green: no change with baseline; Blue: number of successive drought months increases; Red: number of successive drought months decreases. Note: positive and negative refer to the sign of change in number of successive drought months, not the impact on wetlands.

There is an agreement between the 12 ensemble members projection change in 11% of the total wetland area (Figure 8) with an increase in the number of successive drought months (positive change). This implies that in those 11% of the wetland area the average number of months with successive droughts would increase in the future for the 12 members. This increase is mainly observed in the southern part of Scotland. Most of the ensemble members indicate a general pattern of an increase in the number of months with successive drought in the south and east of Scotland (Figure 9) but gain with a more varied response in the west.

Impacts: In contrast to the previous two sets of predictions, month of maximum drought and driest month, this set of predictions suggest increased impacts on biodiversity in eastern and southern wetlands driving species community change towards those more typical of drier areas with the concomitant loss of species characteristic of wetter microsites in each habitat. This different conclusion highlights that we know little about how shifting hydrological conditions may affect biodiversity. Is it the intensity, length or timing of drought that results in the biggest impacts?

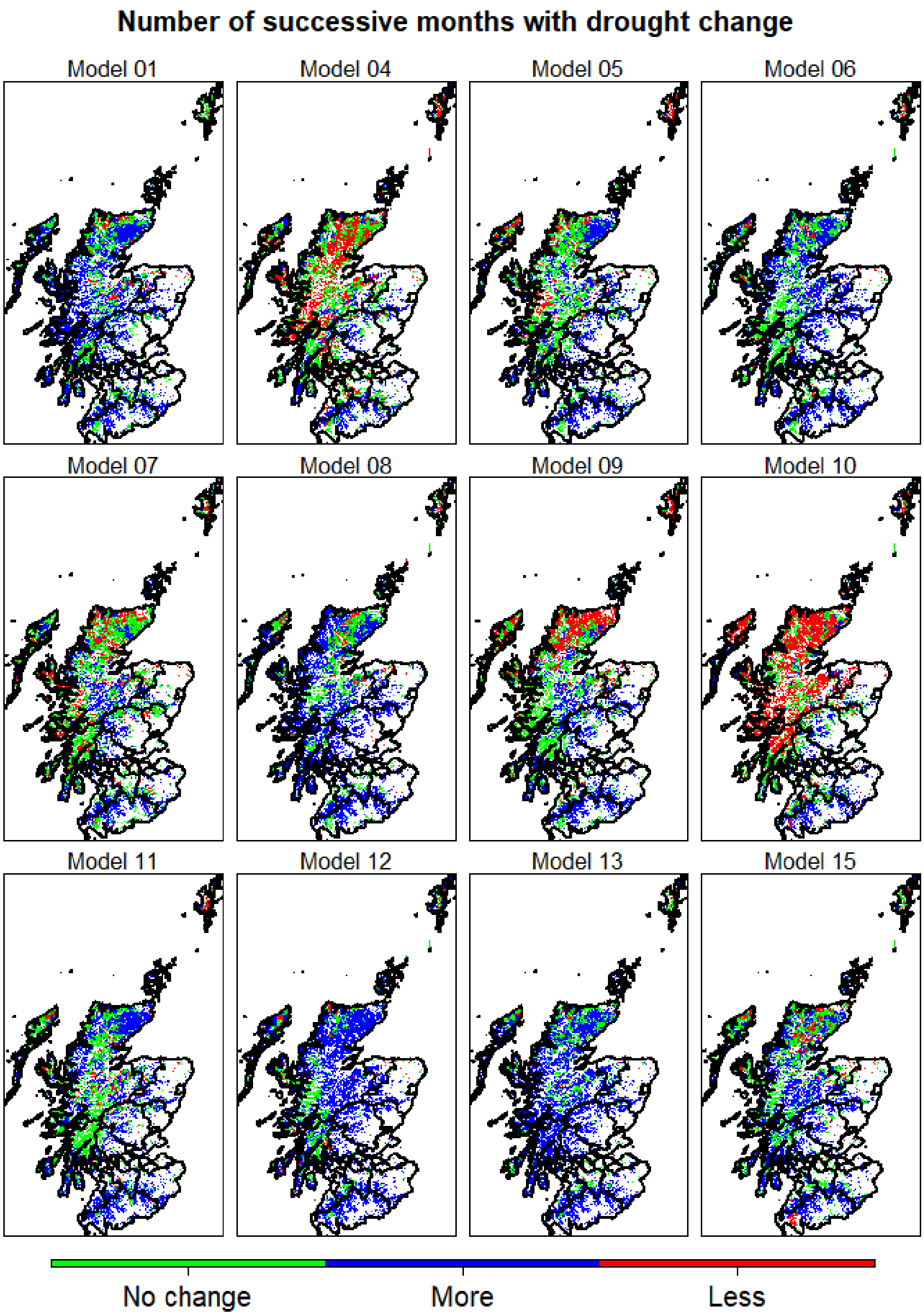

Figure 9. Variation between climate model ensemble members in the number of months with successive drought (green = no change from baseline, blue = increase, red = less). Note definition of drought used: when Evapotranspiration exceeds precipitation.

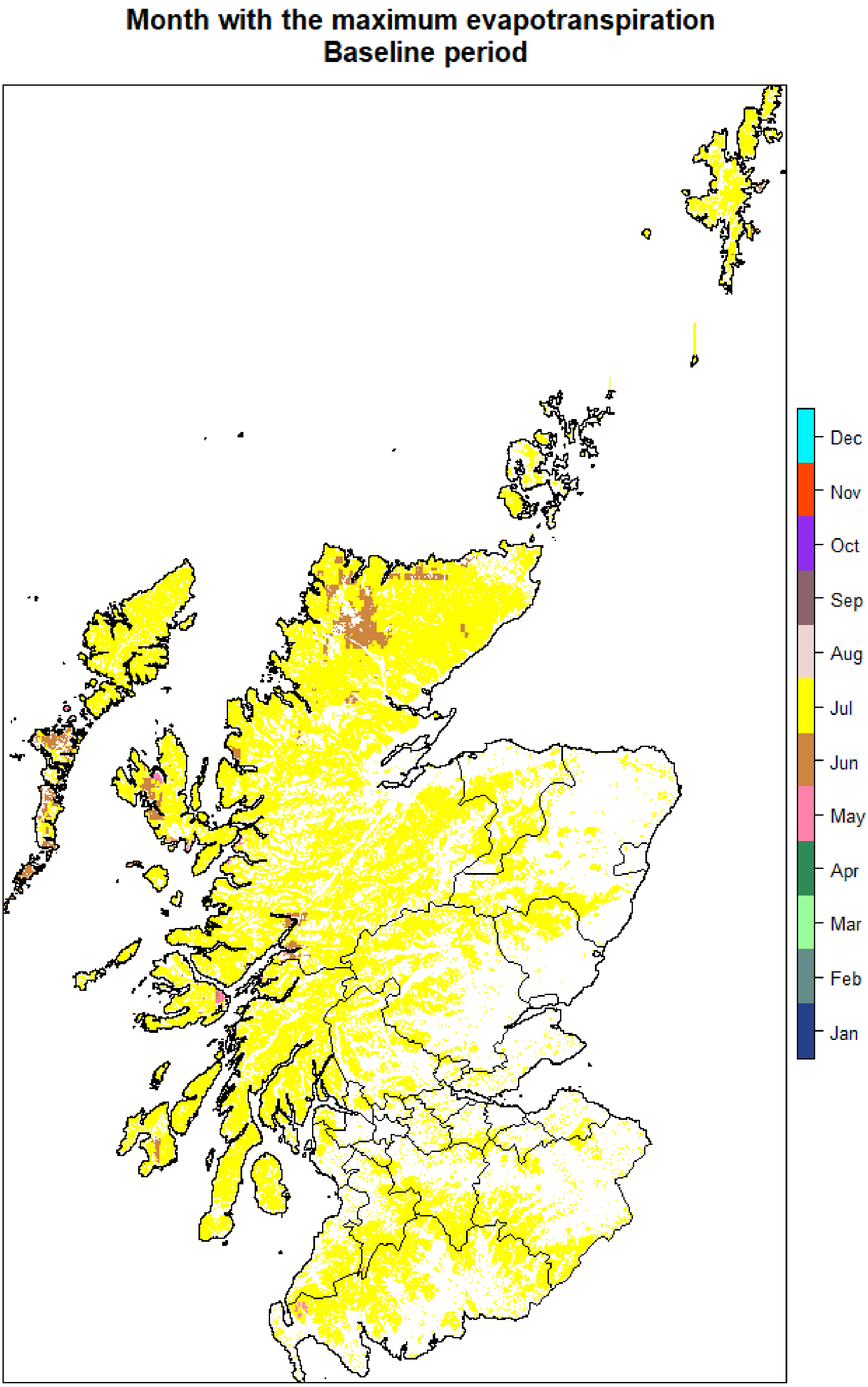

Figure 10. The month with the largest reference evapotranspiration (ETo) quantity in the observed period (1994-2014).

During the baseline period, July was the month with the highest reference evapotranspiration (ETo) in 96% of the total wetland area (Figure 10). In only 3% of the wetland area June was the month with the highest ETo.

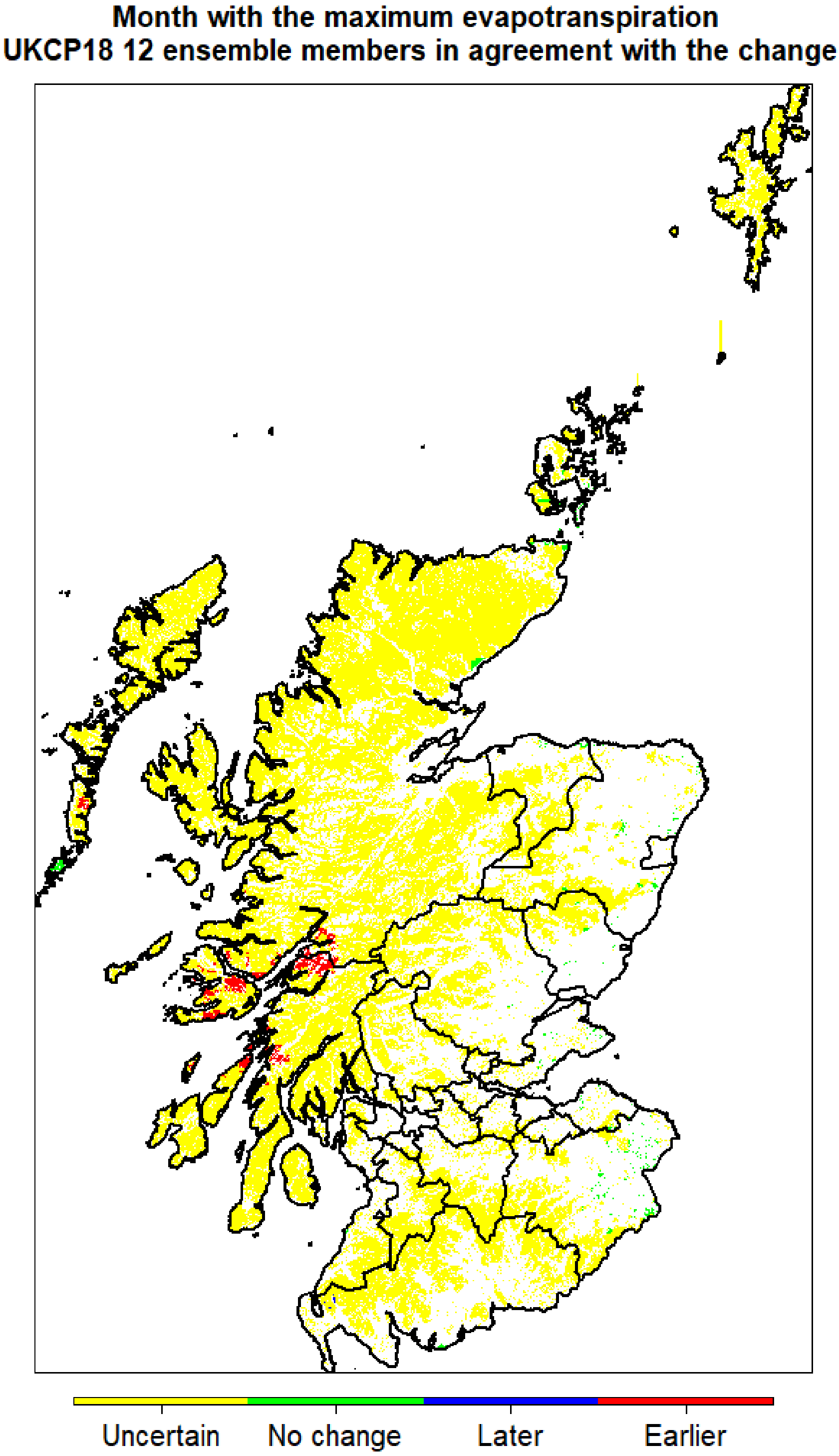

Figure 11. Level of agreement between climate projections for the month with the largest evapotranspiration amount. Yellow: Variable probability of change; Green: no change from baseline; Blue: month with maximum evapotranspiration is later (positive); Red: month with maximum evapotranspiration is earlier (negative). Note: positive and negative refer to the sign of change in the month with the largest evapotranspiration amount, not the impact on wetlands.

There is no absolute agreement between the 12 ensemble members on the projected change for the month with the maximum ETo except in only 1% of the total wetland area: it is projected to occur earlier during the year (Figure 11). However, when assessing the individual ensemble member's estimates (Figure 12), there is an indication that July will remain as the month with the largest evapotranspiration in the east, south and north-east of Scotland. The west is likely to see the month with the maximum evapotranspiration being earlier in the year.

Impacts: Given the level of uncertainty, it is not possible to suggest potential biodiversity impacts.

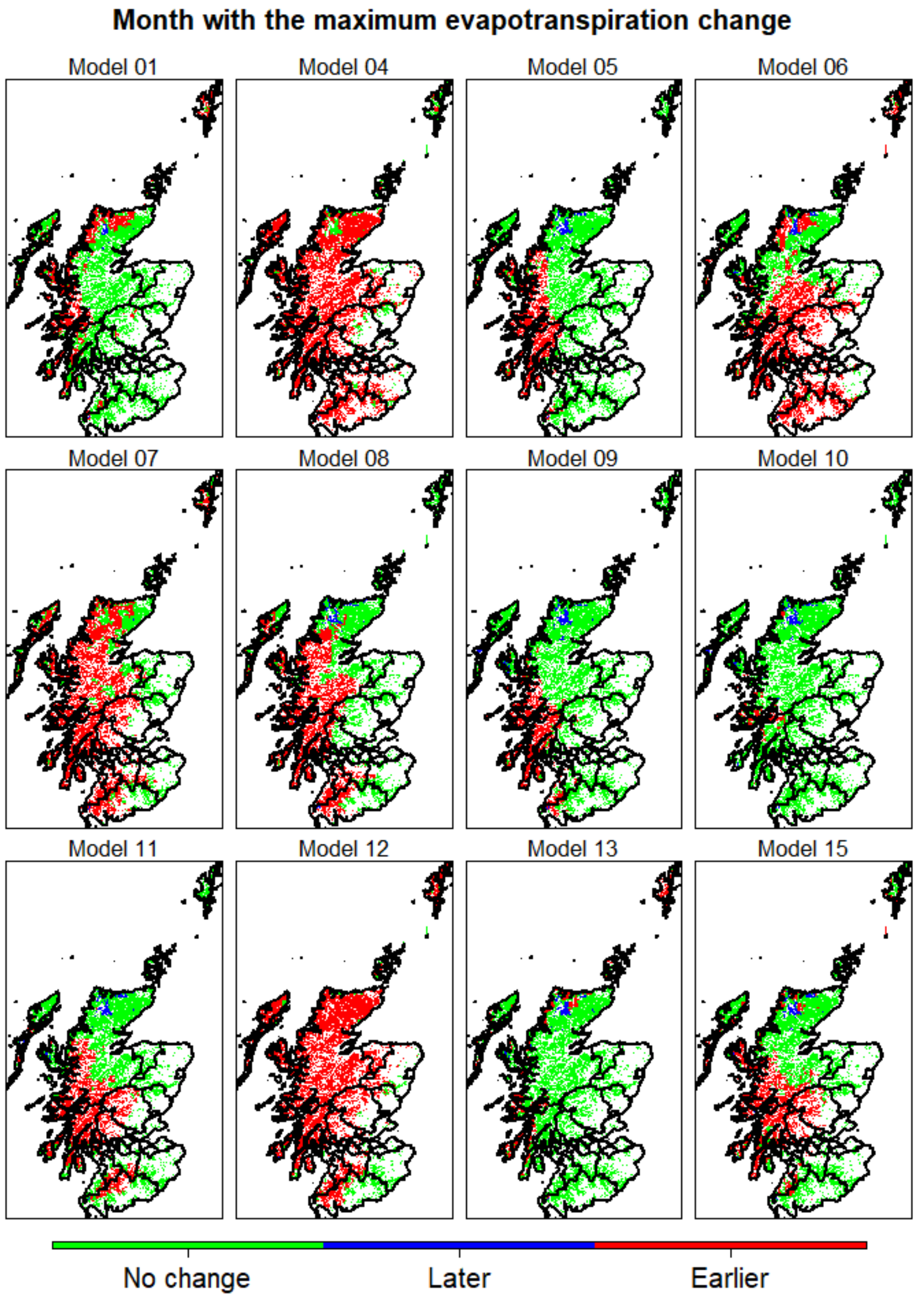

Figure 12. Variation between climate model ensemble members in the month when maximum evapotranspiration occurs (green = no change, blue = later, red = earlier).

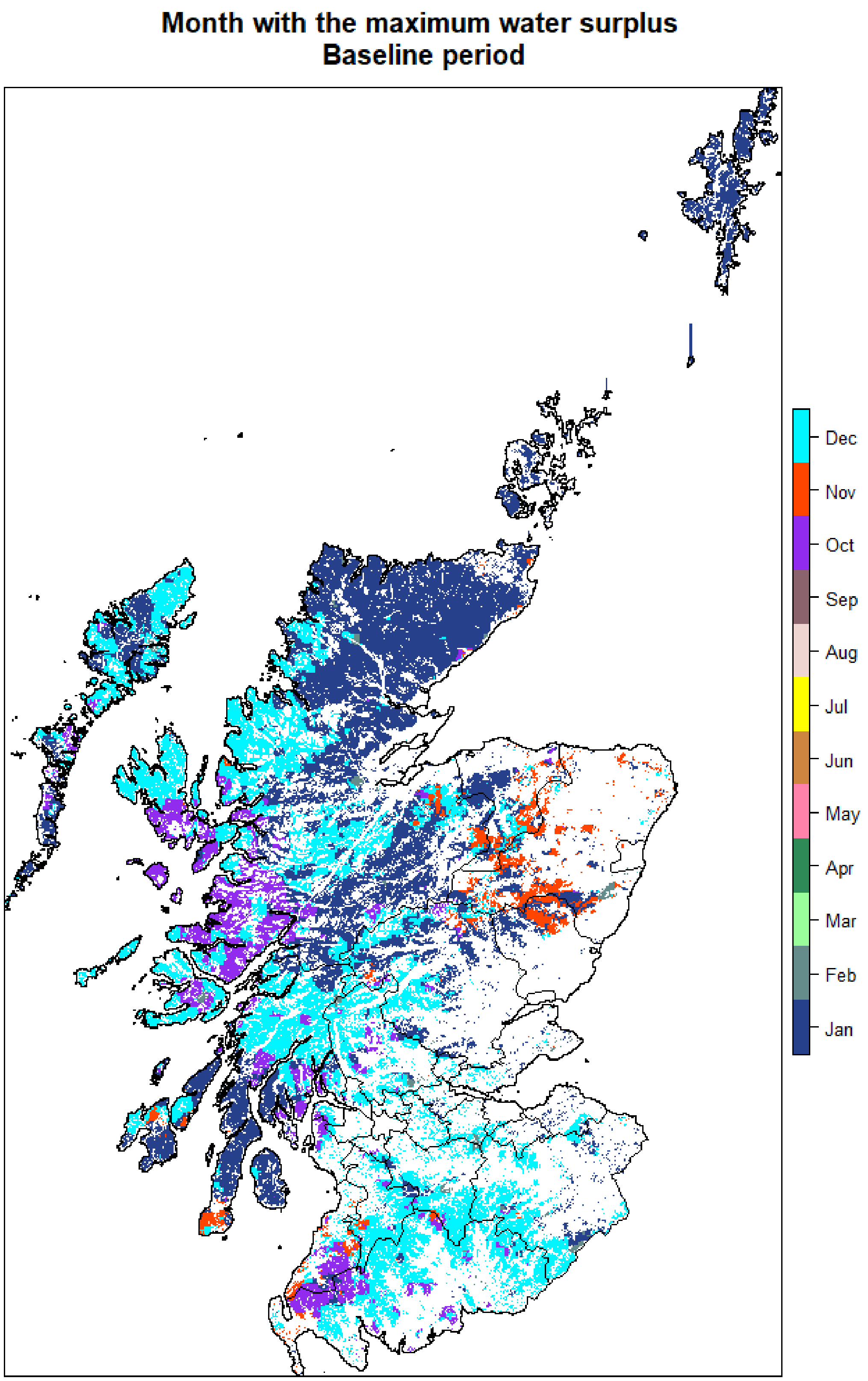

Figure 13. Month with the maximum surplus water for the observed period (1994-2014).

There is a wide spatial variation in when the maximum surplus water has occurred in the observed baseline period (Figure 13). December and January were the months with the highest water surplus in 38 and 46% of the total wetland area, respectively.

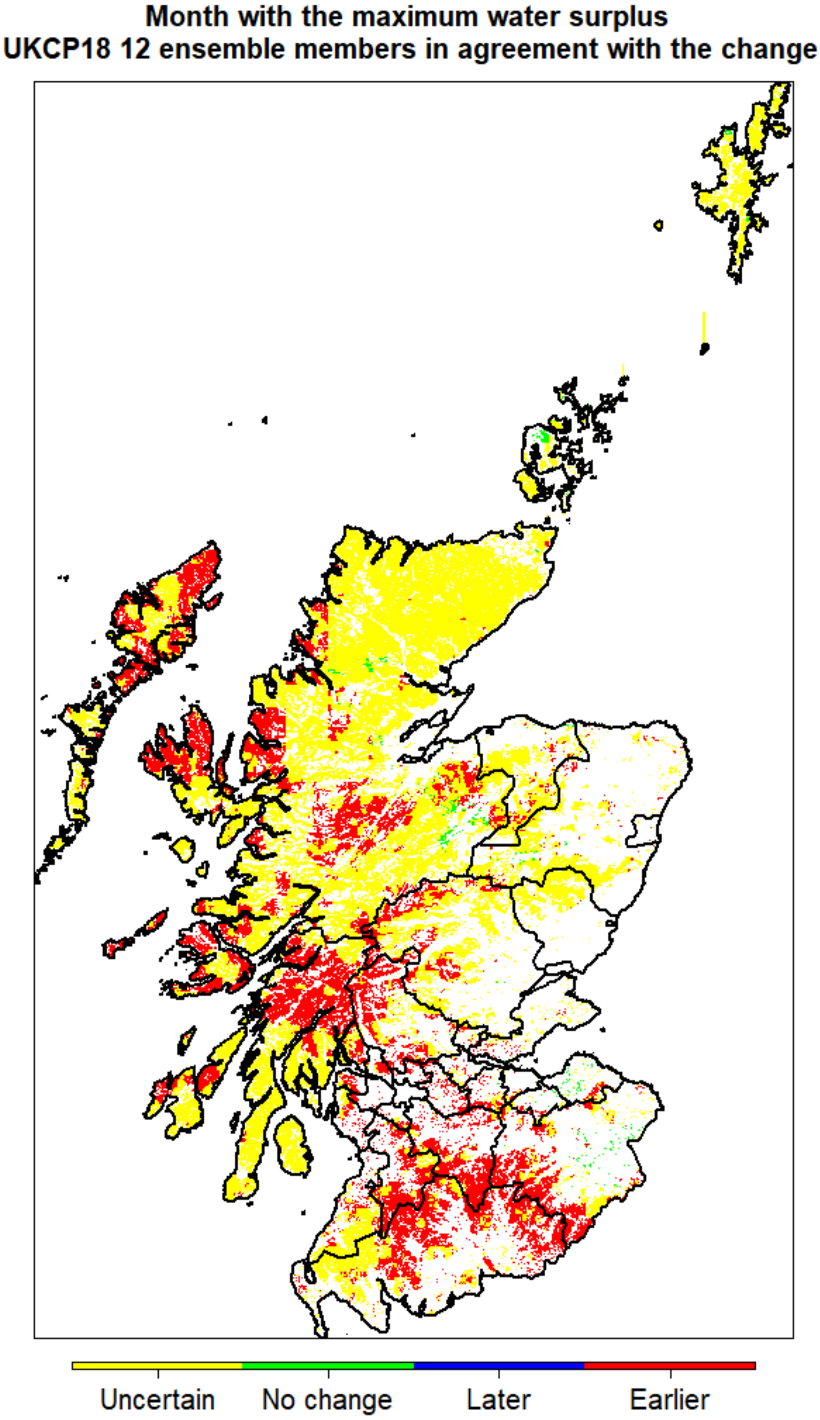

Figure 14. Levels of agreement between ensemble members in when the month of maximum surplus water occurs (green = no change from baseline, blue = later, red = earlier). Note: positive and negative refer to the sign of change in the month of maximum surplus water occurs, not the impact on wetlands.

There is an agreement between the 12 ensemble members projection of change in 33% of the total wetland area with mainly a change to earlier in the year (red, negative, Figure 14). This implies that in about 32% of the wetland area the water surplus would occur earlier during the year. This is mainly observed in the western and southern parts of Scotland.

Impacts: The role of winter water surpluses on biodiversity is not known. However, the limit of some species in wetlands is set by hypoxia, a lack of oxygen in the rooting zone, so a shift to earlier periods of maximum water surpluses may indicate improved conditions for species of drier microhabitats would occur earlier in the year. How important this would be for community dynamics is uncertain.

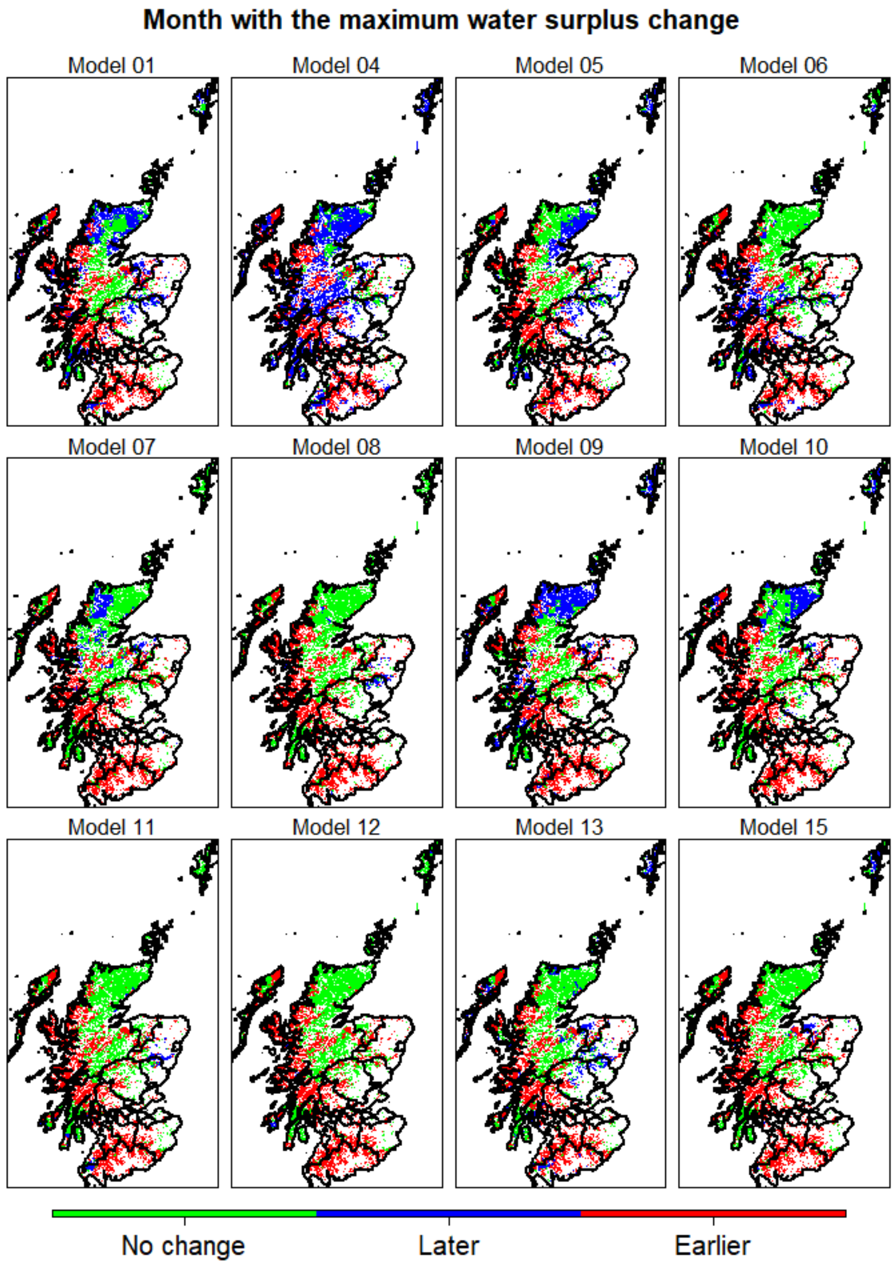

Figure 15. Variation between climate model ensemble members in the month when maximum water surplus occurs (green = no change, blue = later, red = earlier).

Average dry spell duration
Baseline period

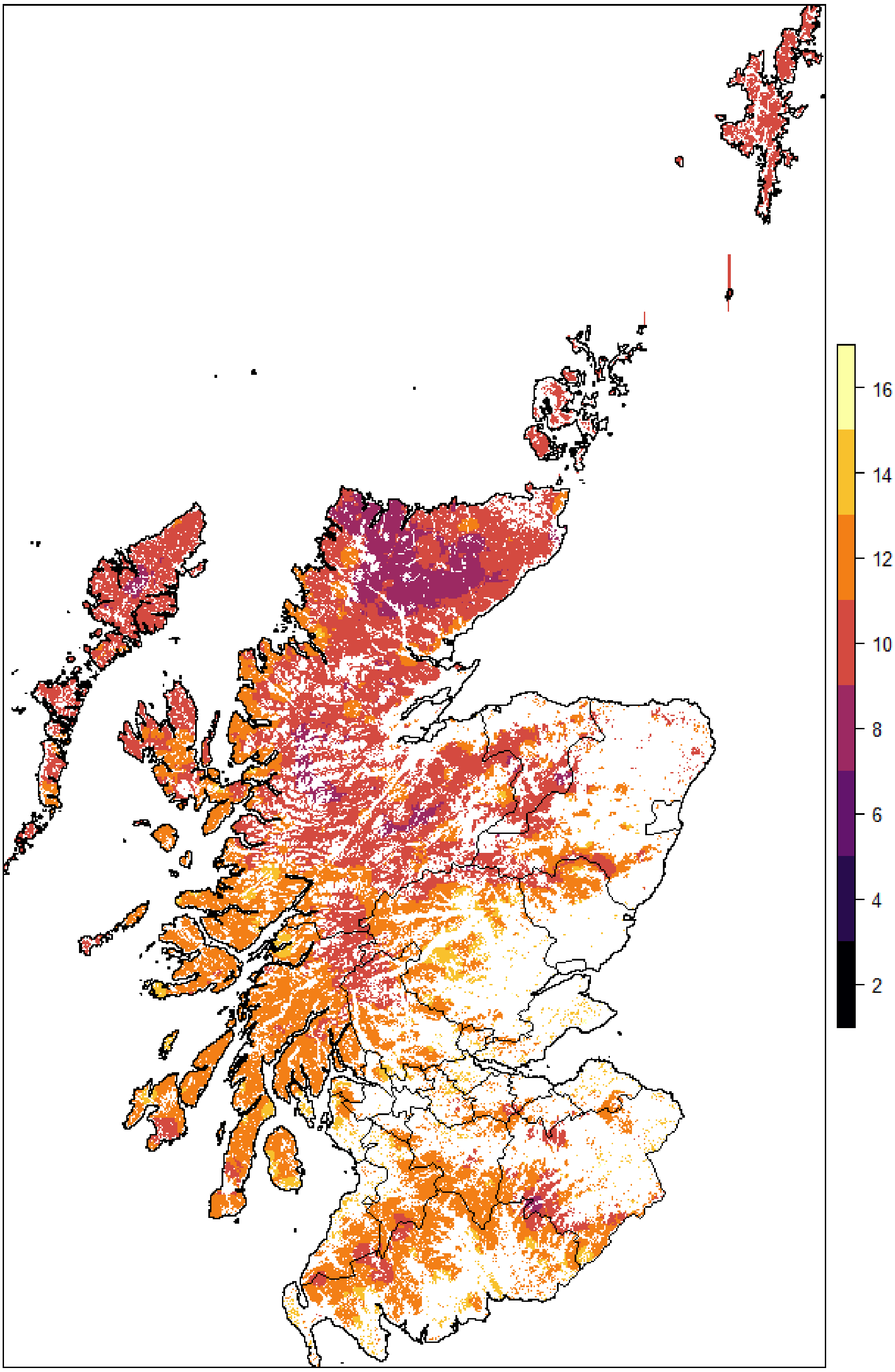

Figure 16. The number of days making up a dry spell for the observed baseline period (1994-2014).

The average dry spell during the baseline period varied between 7 and 17 days with more than 95% of the total wetland area having a dry spell of 9-13 days (Figure 16).

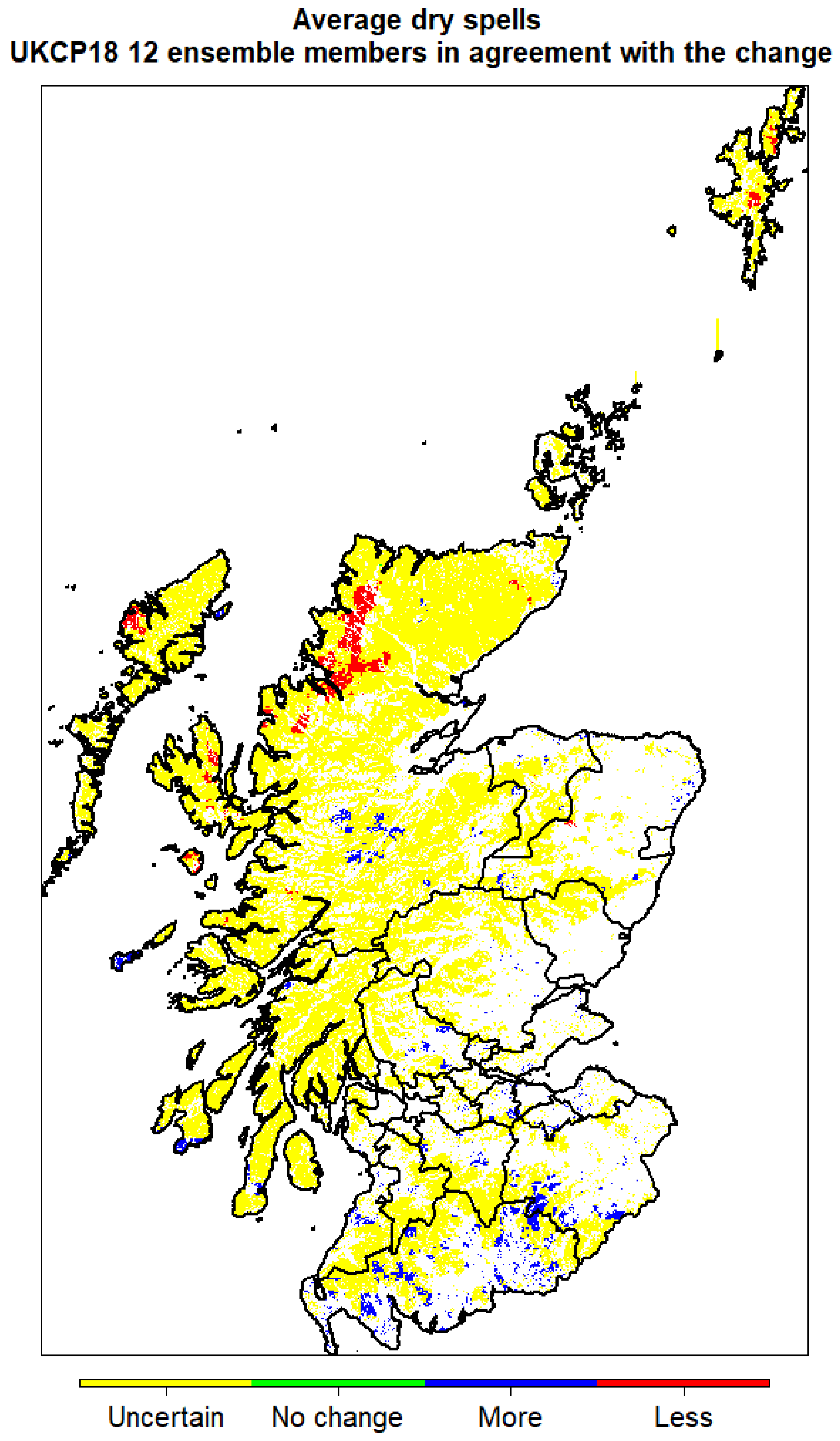

Figure 17. Levels of agreement between ensemble members on changes in average dry spell length. (yellow = variable probability of change, green = no change from baseline, blue = increase, red = decrease). Note: positive and negative refer to the sign of change in average dry spell length, not the impact on wetlands.

There is an agreement between the 12 ensemble members projection change in only 7% of the total wetland area with a positive and negative change in 4 and 3% of the total wetland area, respectively (Figure 17). Changes in the lengths of dry spells suggest improved conditions for species of wetter microhabitats in the north-west and for species of drier microhabitats in the south. The impact of this on overall community composition is difficult to predict.

5. Future Work: Risk and Opportunities Assessment Framework

Our proposed approach to further assess the vulnerability of Scotland's wetlands is to use a Risks and Opportunities Assessment Framework (ROAF) where **R**isk (and opportunities) to a wetland and impacts on its ability to provide ecosystem services is a function of its **V**ulnerability and how **E**xposed it is to a range of **T**hreats. This R=VET approach is widely used (IPCC, 2001) and enables a multi-facetted approach to CC impacts research. It is flexible enough to incorporate other types of threats beyond climate (e.g., disease). The ROAF consists of a range of modelling, analytical and data visualisation tools run using integrated spatial data and asset VET criteria. We suggest developing criteria for wetlands based on how the weather (immediate-term conditions) and climate (long-term trends) combine to affect them and their viability and functional ability. Using the high spatio-temporal resolution climate data available to the VET criteria to assess changes in risk level and what the impacts will be on wetlands will enable us to assess specific wetlands. Risk due to climate change is a complex mix of interacting factors at macro- and micro-scales, requiring a structure within which to organise concepts, data and analytical methods. The R=VET approach enables the key determinants of Risk (and opportunities) to be partitioned and assessed both independently and together to provide predictability details beyond just general indicators.

Vulnerability: is defined as "The degree to which a system [asset] is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation [Threat] to which a system is exposed, its sensitivity, and its adaptive capacity." (IPCC, 2001). Vulnerability is an indication of a wetland's resilience and includes its adaptive capacity (with or without human intervention), reflecting its ability to cope with or withstand different types of Threat (e.g., extreme events) or exceedance of variation (climate trends). Wetlands may have vulnerability tolerance thresholds (tipping points) beyond which it cannot or is unlikely to recover. Cascading vulnerability refers to the inter-connection with other land covers and uses, where wetland may have low direct vulnerability to climate change but is influenced by other land covers and uses that have high vulnerability.

Exposure: "The nature and degree to which a system is exposed to significant climatic variations" (IPCC, 2001). Exposure is concerned with the spatial extent and quantity of an asset (abundant versus rare) and sensitivity to different threats and their probabilities (frequency and spatial distribution of droughts).

Threat: encompasses different types of threat (climate, social, biological) an asset is exposed to and whether it is direct (climate extreme event, flood, drought, storm) or indirect (fire susceptibility due to drought, altered energy and nutrient transformation in food webs). This includes the nature and severity of the climate threat, its spatial extent, frequency and intensity and or duration.

Risk assessments of wetlands need to incorporate variation both in natural processes and data used to represent them and how they might respond to climate change. One suggested solution is to use probabilistic approaches to capture the range of uncertainty in estimating future risks.

6. Knowledge Gaps

- Our ability to estimate soil water balance (Appendix I) and evapotranspiration for different vegetation and wetland water surfaces is currently limited and there is a substantial gap in spatial and temporal data appropriate for model calibration and validation.
- The evapotranspiration method used here employs parameters for a reference grass crop, yet this is only partially representative of the diversity of wetland vegetation communities.
- We do not fully understand the consequences of back-to-back successive extreme dry years on – either for wetlands or other ecosystem types. Whilst wetland ecosystems may be able to recover over time from an extremely dry springs and or summers, it is not known what the tolerance will be to successive annual dry periods. Future projections indicate an increased probability of more frequent dry summers.
- Groundwater hydrology and variations in water table level: there is need to better integrate surface level (top 1 m) soil water balance modelling with groundwater modelling.
- The recharge rates of groundwater under future climate conditions remains uncertain.
- The role of occult precipitation in providing surface level water to enable key species such as *Sphagnum* to survive dry periods needs further research.
- Biodiversity. The ability to model future climate highlights the difficulty of predicting impacts on biodiversity. Even for the group for which we have the best data, plants, we know very little about what facets of hydrology control the distribution of species and communities within wetlands. For instance, are species' niches controlled by the intensity, length or timing of droughts, or by periods of flooding (causing hypoxia in the root zone). Even then we don't know how this would translate into community change as competitive interactions under changed hydrological conditions have been little studied. Finally, how these changes at the plant community level then cascade into driving change in other species is also unknown.

7. Recommendations

To improve our understanding of how climate change will impact wetland health and functional ability, there is need to:

- Improve soil water modelling through incorporation of groundwater hydrology and how this affects water table levels and recharge rates after dry periods.
- Use location specific surface characteristics (vegetation type) to better estimate evapotranspiration.
- Develop a network of monitoring sites to improve capabilities to measure and monitor wetland water states (Appendix IV), this will also assist model validation and refinement hence improving future projection estimates.
- A restriction on the ability to calibrate and test models is due to a lack of location specific observed data. There is good scope for developing a shared database using observed historical experiment and monitoring data.
- Increase the use of remote sensed data to measure and monitor wetland sites' water state.
- Link this to the monitoring network to ground-truth remote sensed data.
- Improve vegetation monitoring to assess responses to new ranges of meteorological variation: identify species tolerance ranges; understand community competition responses.
- Improve our understanding of vegetation responses to climate extremes, particularly prolonged dry periods, to assess their resilience.
- Particular attention should be paid to key species such as *Sphagnum*.
- Where comparable, assessments of wetland and vegetation responses to observed extremes, i.e. the summers of 2003 and 2018 in upland England may provide useful indications of how future extreme events may impact Scottish sites.
- Better understand the probabilities of successive drought months and years and assess wetland species' resilience to more frequent and severe droughts.
- Improve our understanding of the role of occult precipitation (mist, dew) to provide water to surface vegetation, and if this is a critical water input to enable plant survival, how will future climate conditions affect occult precipitation formation?

Climate projections: This assessment of climate change impacts on wetlands has used a single emissions scenario (RCP8.5), which arguably represents a plausible high-end emission and impacts condition. For the purposes of this study this is an acceptable approach. We have also used a single climate model (HadRM3-PPE), but to better assess the range of uncertainties in wetland responses, it would be preferable to use multiple climate models and emissions scenarios. However, it should be noted that the projected impacts out to around 2040-2050 do not differ greatly between emissions scenarios. Climate models are generally not good at representing extreme high rainfall events. To resolve this, we suggest the additional use of the UKCP18 2.2km resolution Convection Permitting Model data to assess local risks and opportunities.

8. References

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Appendix A: Wetland Vulnerability Maps

This section presents maps of the same analysis presented at the national scale but focussing in on different areas. This includes the Cairngorms National Park, the Insh Marshes and three Alkaline Fens: Rassal (north-west), Mortlach Moss (east) and the Lendafoot Hills Complex (south-west).

The purpose of these examples is to illustrate that the analysis can be focussed onto specific wetlands. Whilst not presented here, it is also possible to analyse and present daily time series data for each grid cell (1 km resolution) to assess observed and projected changes. This may be particularly useful in assessing conditions beyond normal variation including extremes, and changes in their frequency.

Cairngorms National Park

The Cairngorms is the largest National Park in the UK and one of two National Parks in Scotland. At its core is the largest area of high mountain plateau in the UK. Around this are extensive areas of hill ground dominated by blanket bog. There are also extensive tracts of woodland, including relatively extensive areas of semi-natural pine forest. There is limited farmland, most of it associated with the major river valleys of the Dee, Don and Spey. These valleys also have some significant wetland areas associated with them.

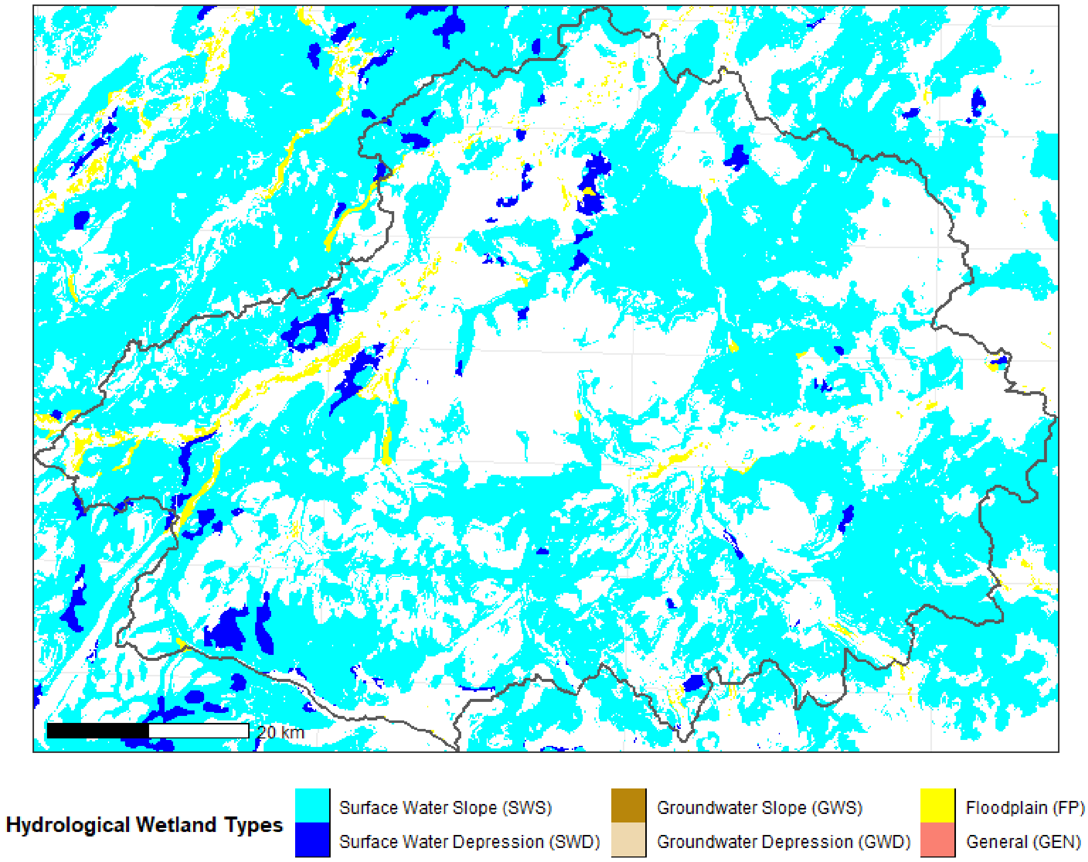


Figure 18. Wetland classes map for the Cairngorms National Park.

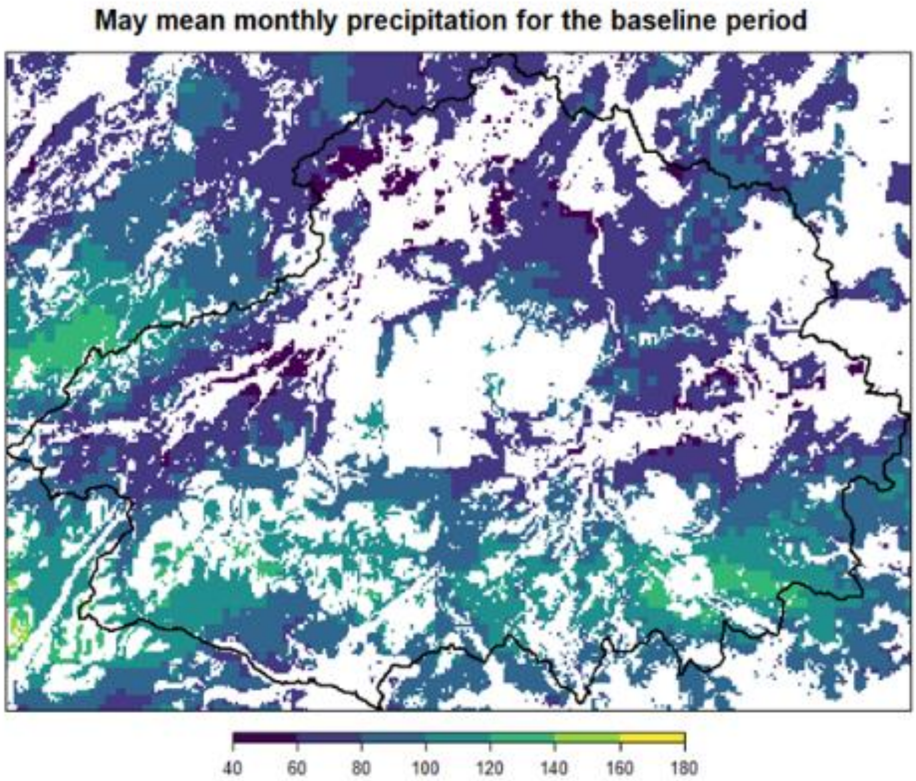


Figure 19. Observed May mean monthly precipitation (mm) at Cairngorms National Park.

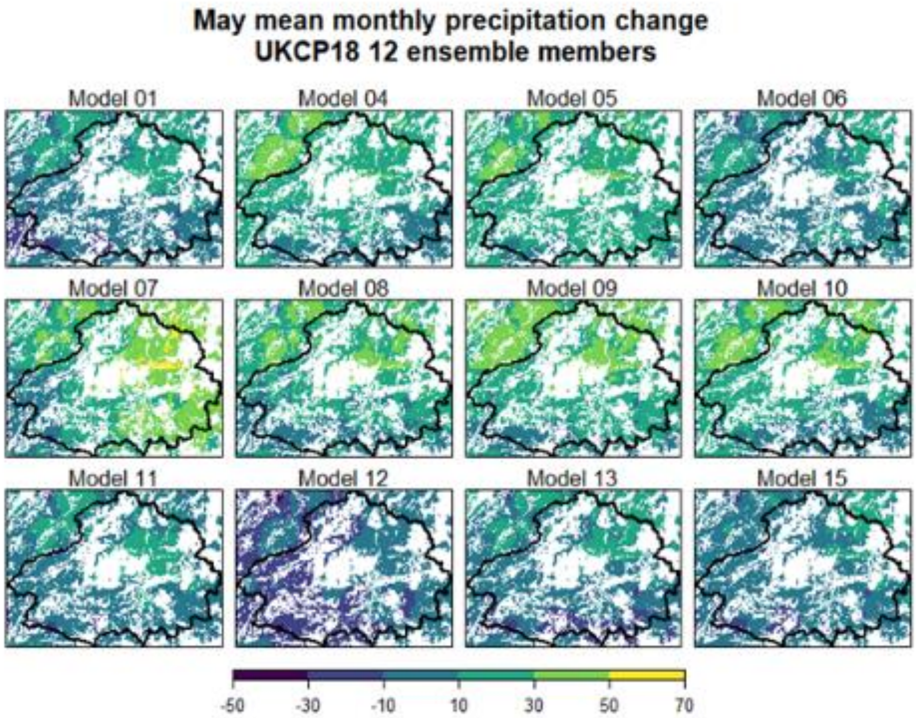


Figure 20. Projected change in May mean monthly precipitation (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Cairngorms National Park.

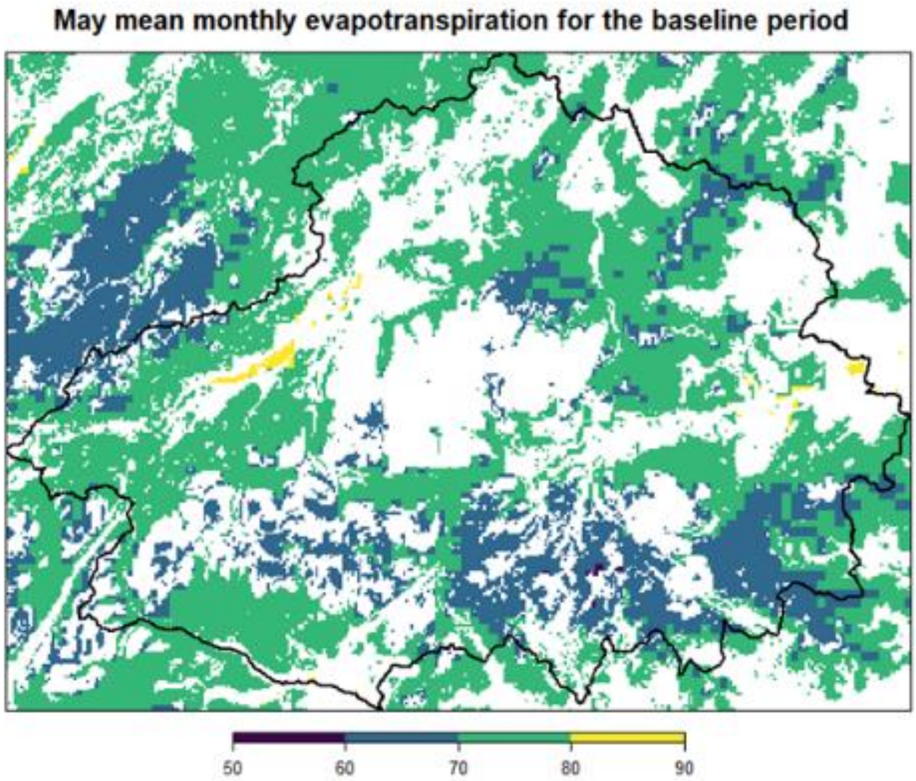


Figure 21. Observed May mean monthly evapotranspiration (mm) at Cairngorms National Park.

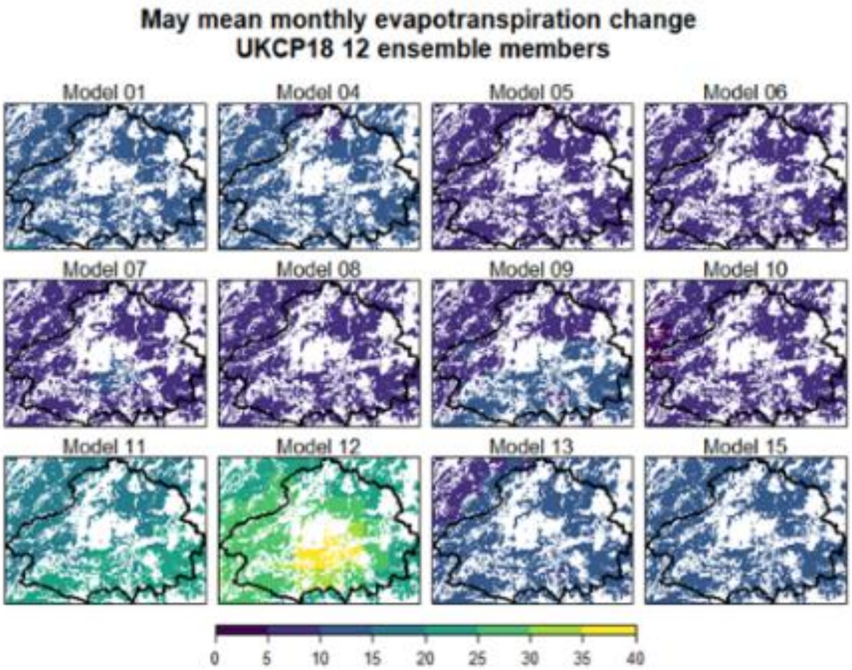


Figure 22. Projected change in May mean monthly evapotranspiration (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Cairngorms National Park.

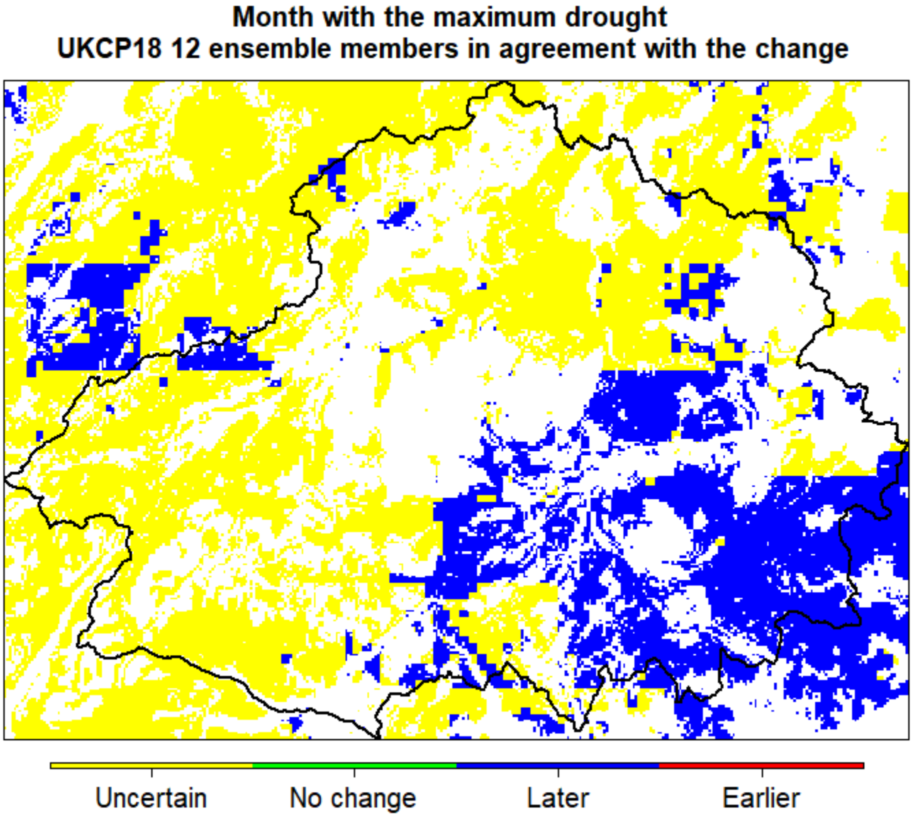


Figure 23. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum drought occurs at Cairngorms National Park (blue = later, yellow = no agreement). Note: positive and negative refer to the sign of change in the month when the maximum drought occurs, not the impact on wetlands.

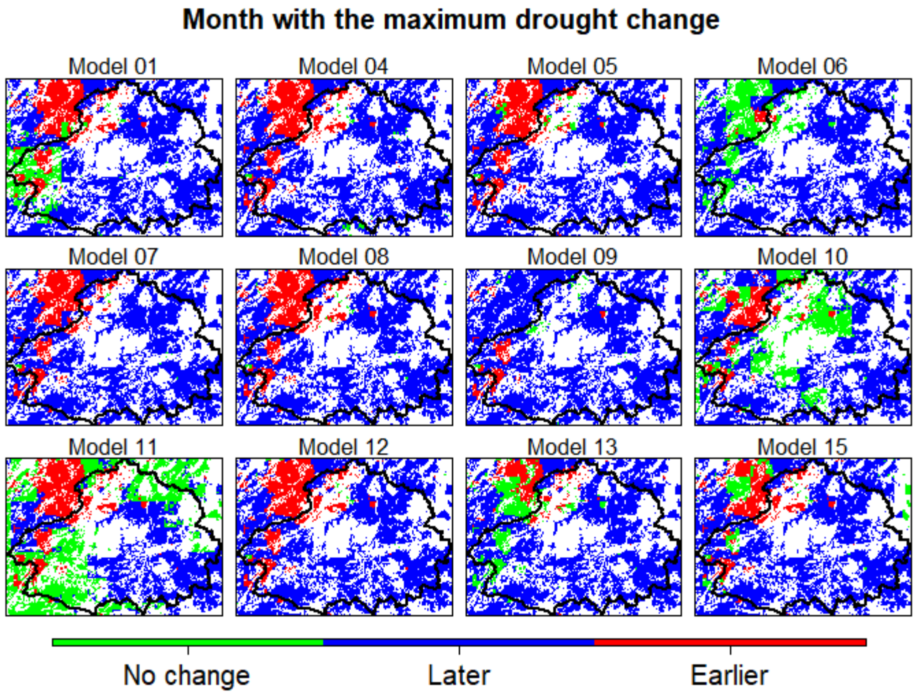


Figure 24. Variation between ensemble members in the month when the maximum drought occurs at Cairngorms National Park (blue = later, red = earlier).

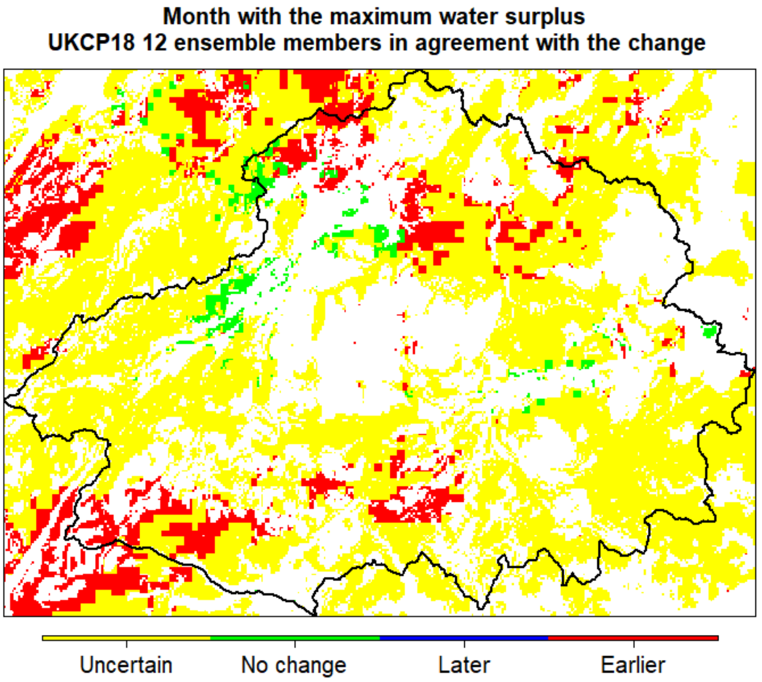


Figure 25. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum water surplus occurs at Cairngorms National Park (red=earlier, green = no change, yellow = no agreement). Note: positive and negative refer to the sign of change in the month when the maximum water surplus, not the impact on wetlands.

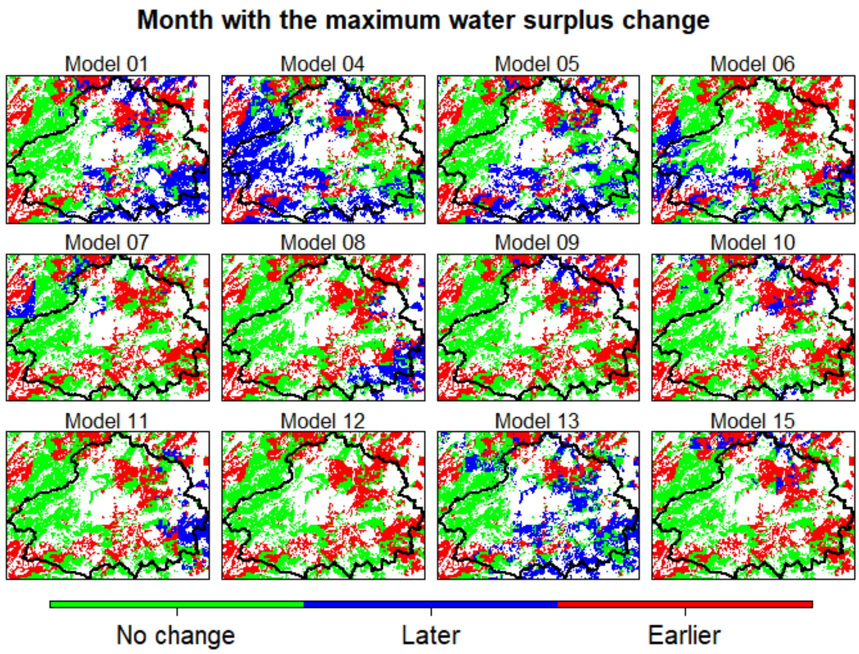


Figure 26. Variation between ensemble members in the month when the maximum water surplus occurs at Cairngorms National Park (blue = later, red = earlier, green = no change).

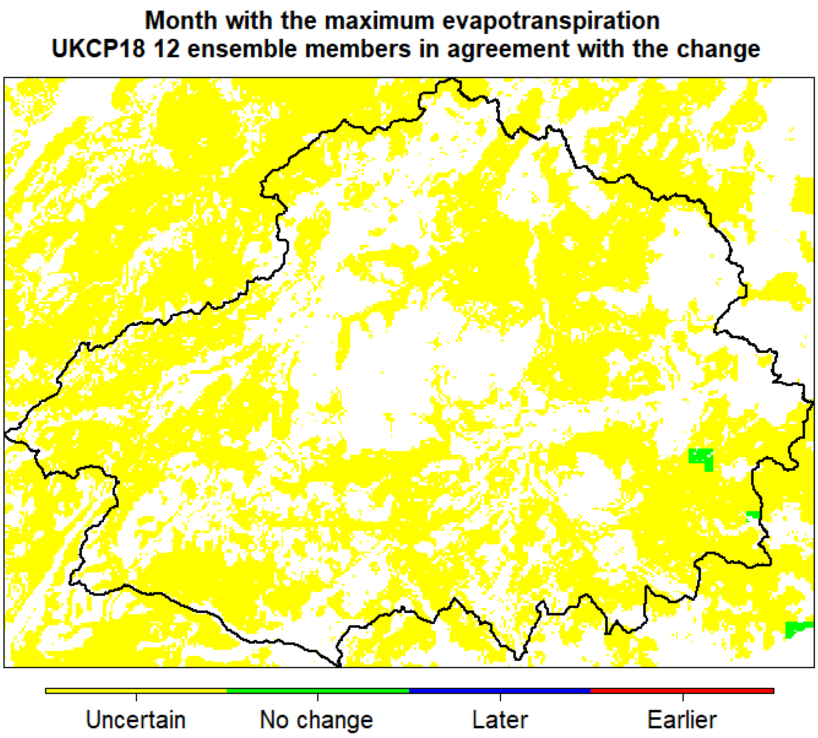


Figure 27. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum evapotranspiration occurs at Cairngorms National Park (yellow = no agreement, green = no change). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

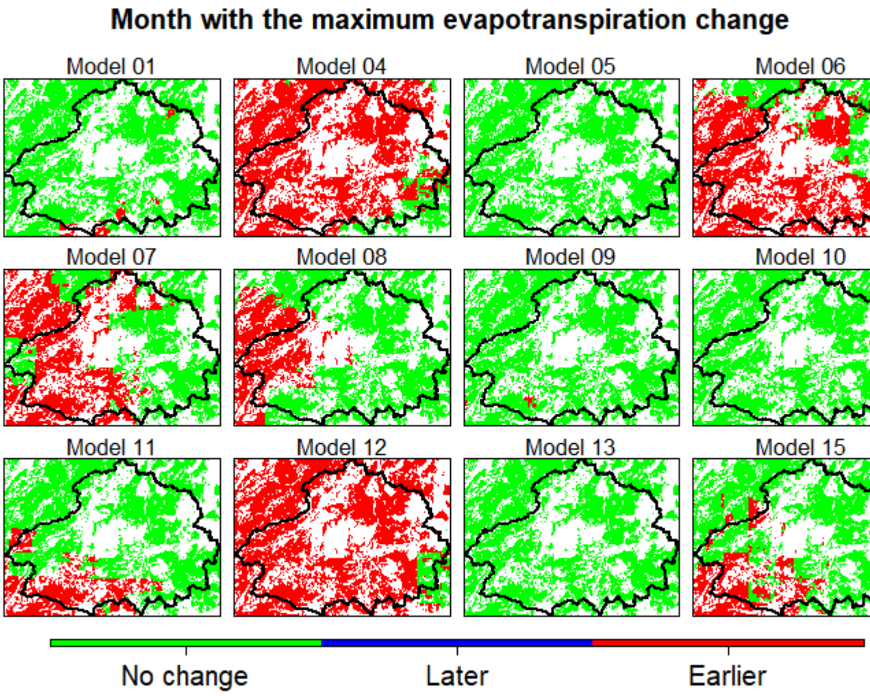


Figure 28. Variation between ensemble members in the month when the maximum evapotranspiration occurs at Cairngorms National Park (red = earlier, green = no change).

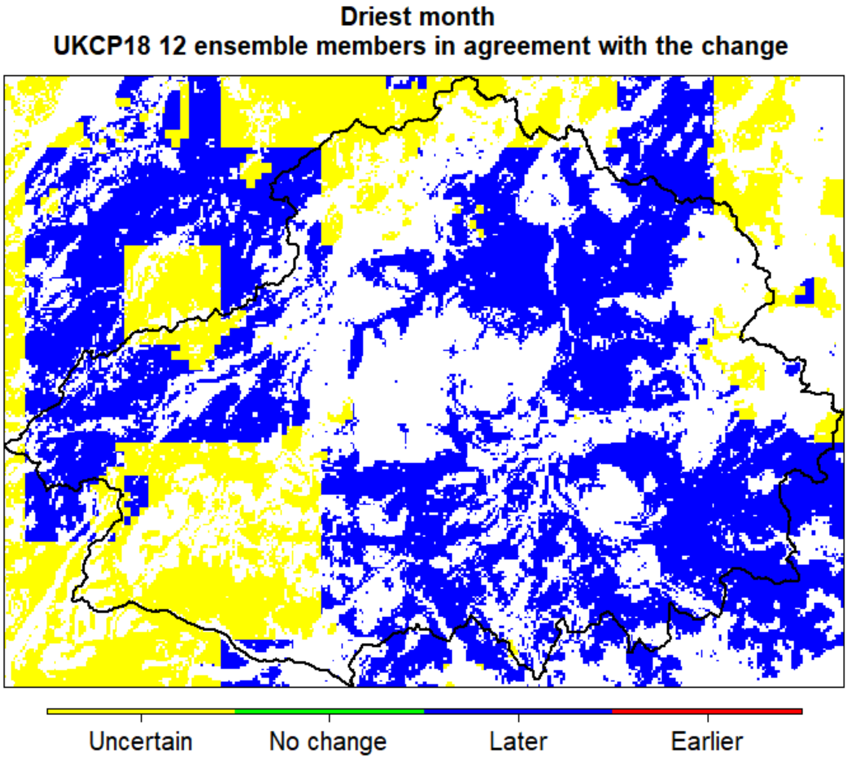


Figure 29. UKCP18 ensemble members in agreement with the sign of their change in the driest month at Cairngorms National Park (blue = later). Note: positive and negative refer to the sign of change in the driest month, not the impact on wetlands.

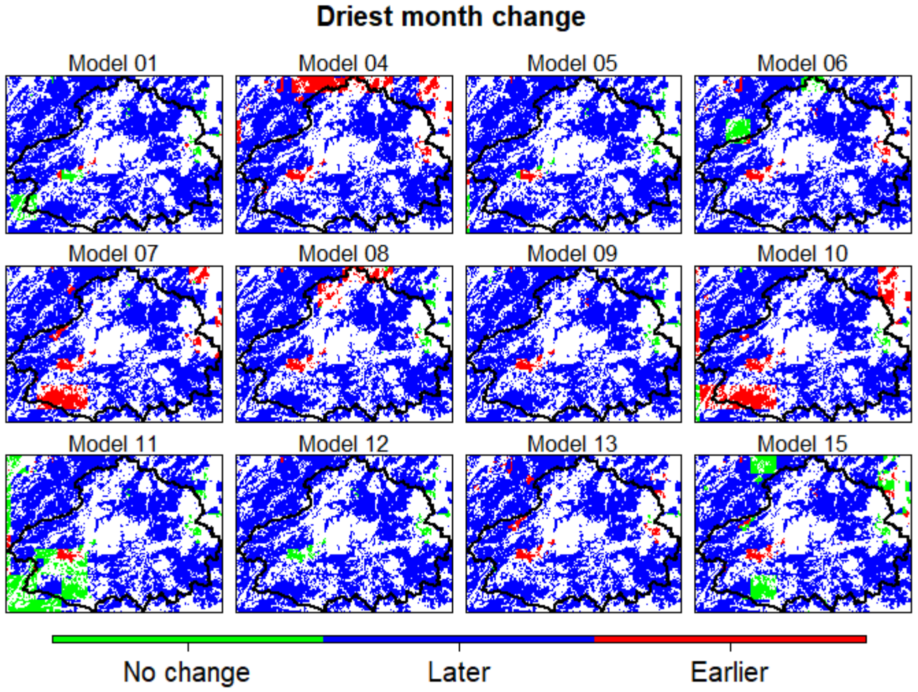


Figure 30. Variation between ensemble members in the driest month at Cairngorms National Park (red = earlier, blue = later).

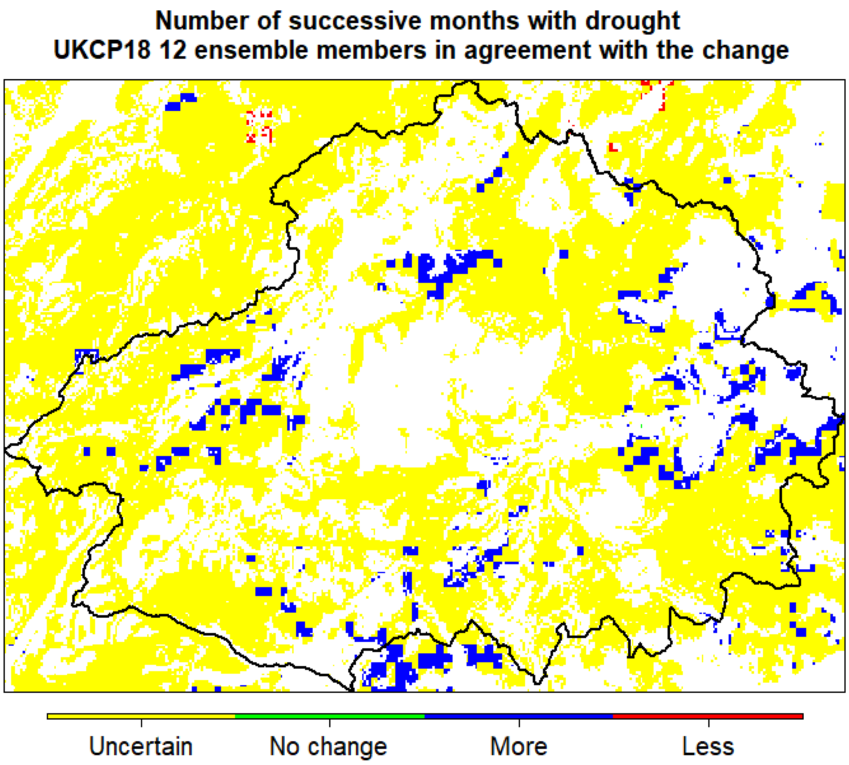


Figure 31. UKCP18 ensemble members in agreement with the sign of their change in the number of successive dry months at Cairngorms National Park (blue = more). Note: positive and negative refer to the sign of change in the number of successive dry months, not the impact on wetlands.

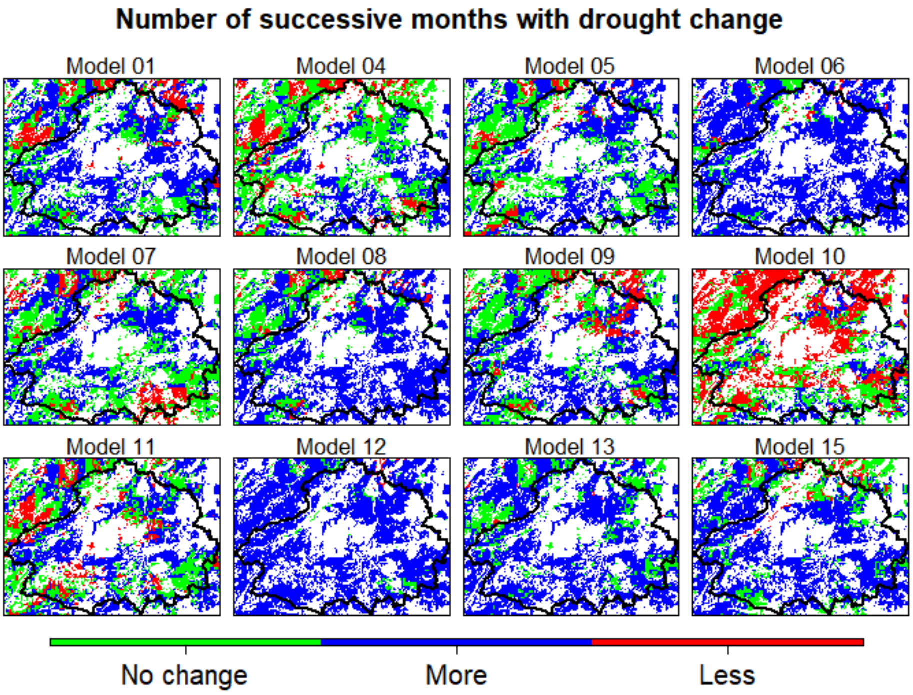


Figure 32. Variation between ensemble members in the number of successive dry months at Cairngorms National Park (red = less, blue = more).

Insh Marshes

Insh Marshes is Britain's largest naturally functioning floodplain over 5 miles (8km) long and nearly 2 miles (3km) wide in places. It is a National Nature Reserve (NNR), a Site of Special Scientific Interest (SSSI), a Special Area of Conservation (SAC), a special Protection Area (SPA) and a RAMSAR site. The vegetation consists mainly of sedge dominated 'poor' fen communities but reed bed, herb-rich swamp and willow carr wetland habitats are well represented. It is the main UK stronghold for string sedge *Carex chordorrhiza* and holds other rare plants including least water-lily *Nuphar pumila*, awlwort *Subularia aquatica*, cowbane *Cicuta virosa* and shady horsetail *Equisetum pratense*. It also has a rich assemblage of breeding birds, including osprey *Pandion haliaetus*, wigeon *Anas penelope,* shoveler *Anas clypeata* and goldeneye *Bucephala clangula,* and a major concentration of breeding waders such as redshank *Tringa totanus*, common snipe *Gallinago gallinago* and curlew *Numenius arquata*. Insh marshes is also the best site in Scotland for rare wetland invertebrates including the wetland spider *Wabasso replicatusis* known only from this site in the UK and the aspen hoverfly *Hammerschmidtia ferruginea*.

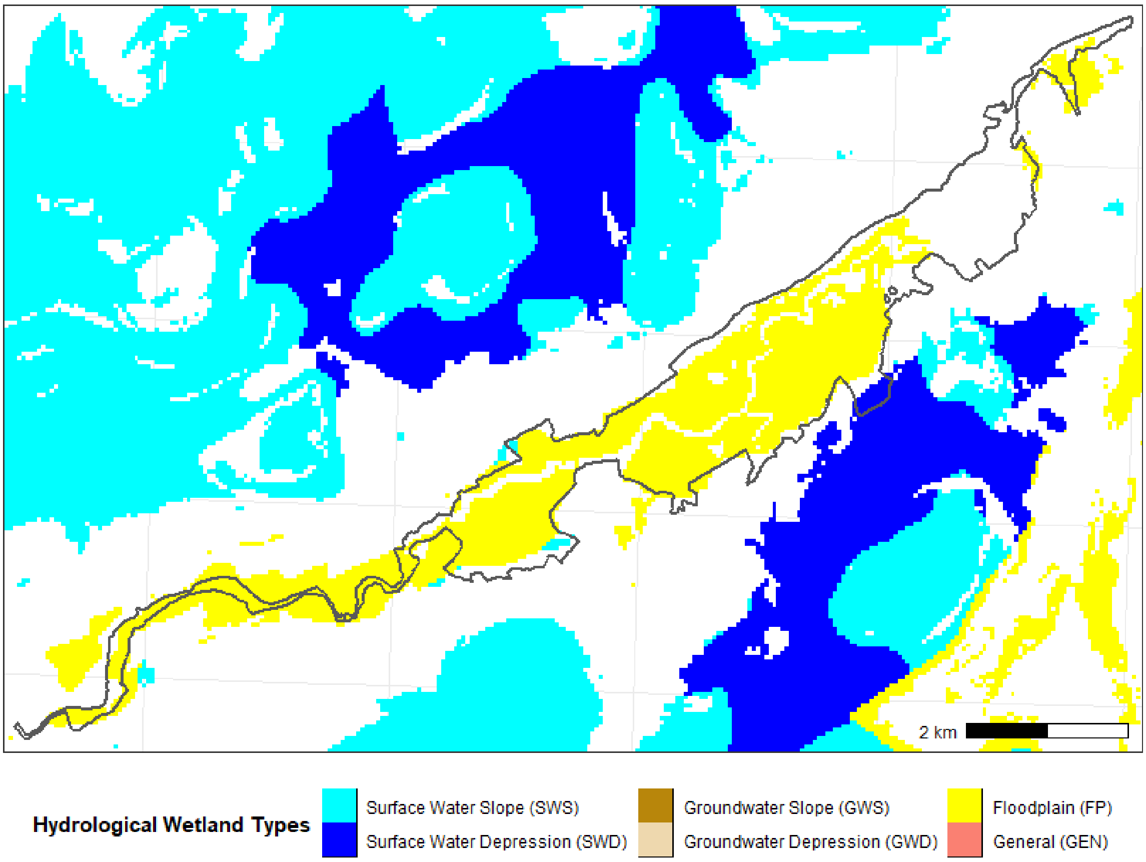


Figure 33. Wetland classes map at Insh Marshes.

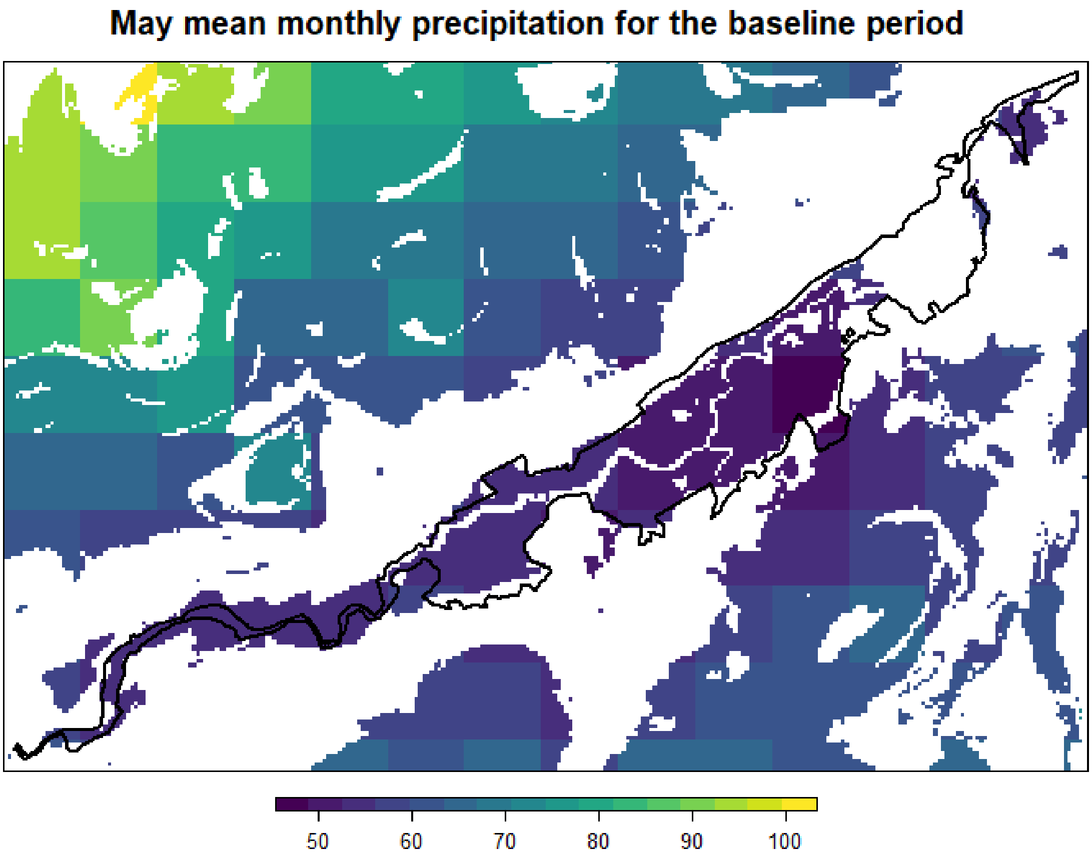


Figure 34. Observed May mean monthly precipitation (mm) at Insh Marshes (Baseline period 1994-2014).

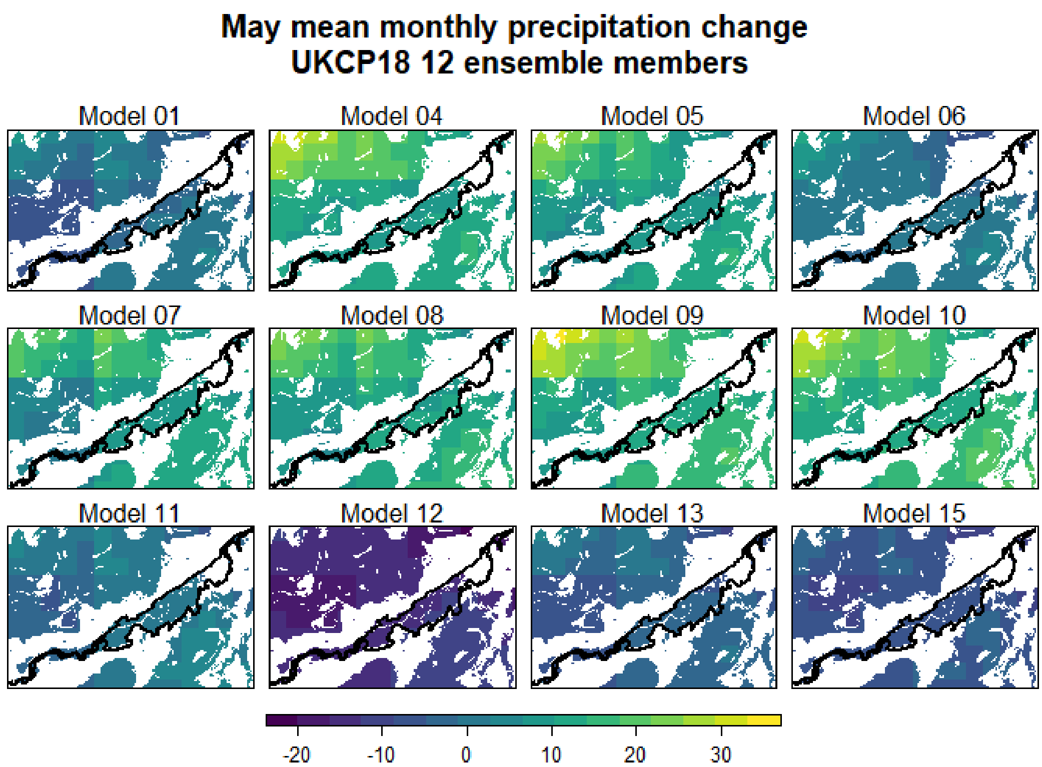


Figure 35. Projected change in May mean monthly precipitation (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Insh Marshes.

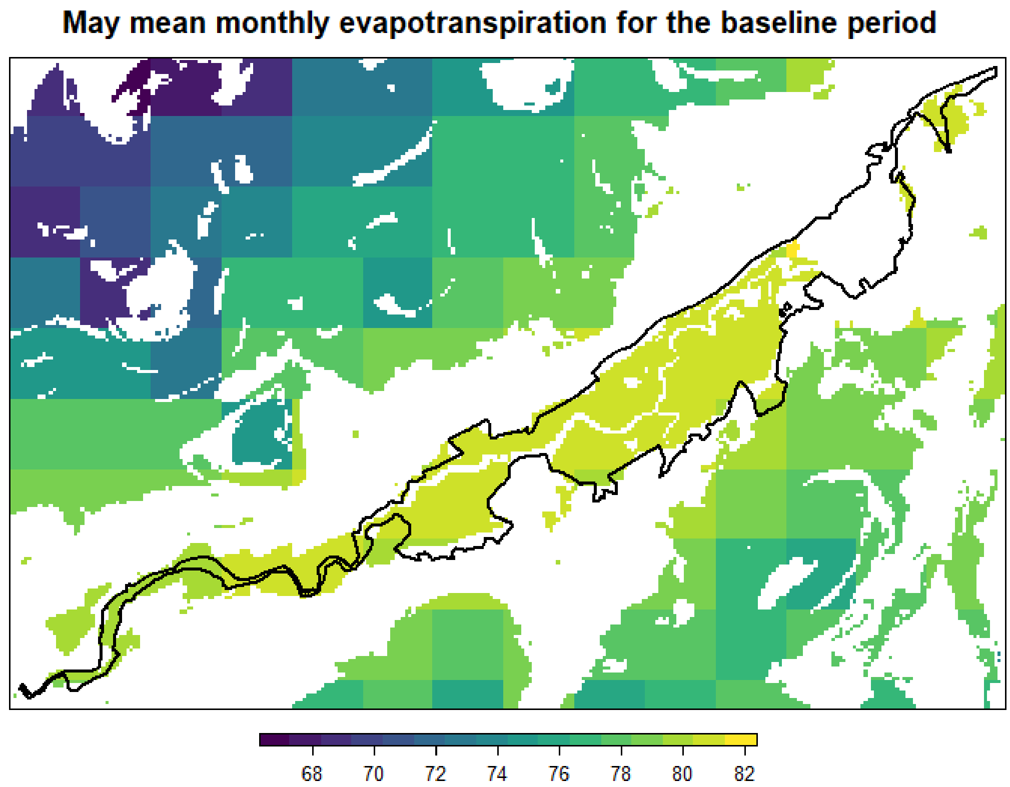


Figure 36. Observed May mean monthly evapotranspiration (mm) at Insh Marshes.

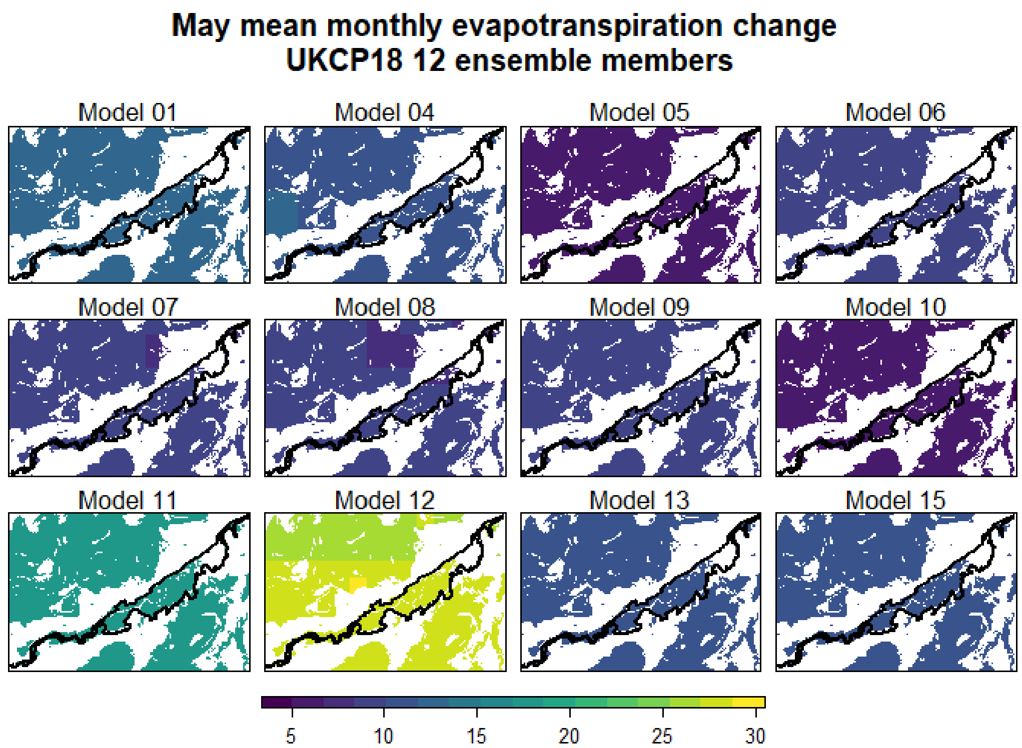


Figure 37. Projected change in May mean monthly evapotranspiration (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Insh Marshes.

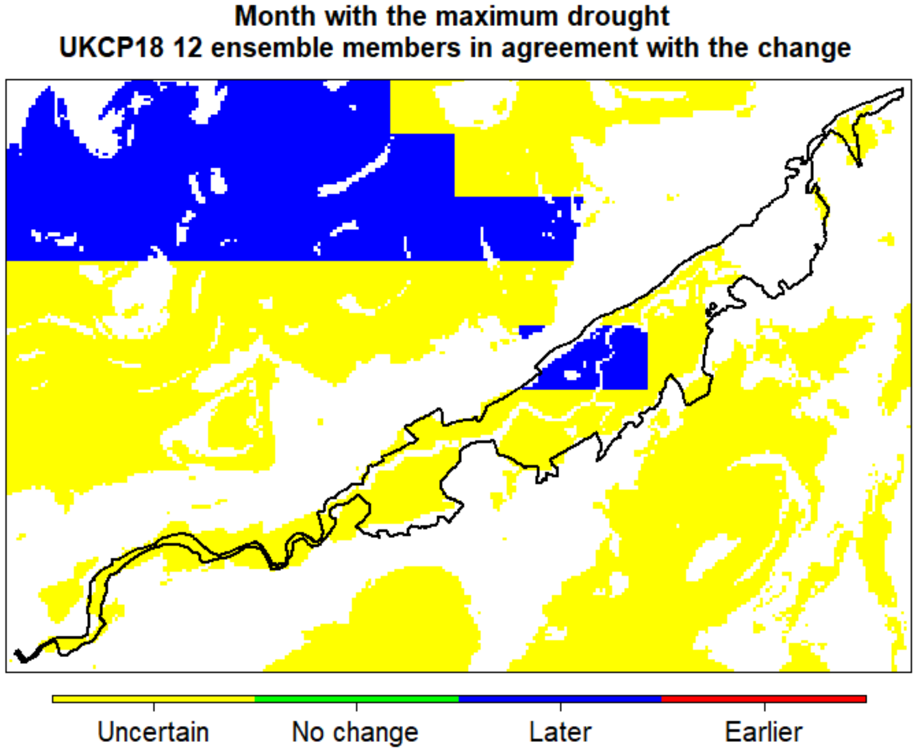


Figure 38. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum drought occurs at Insh Marshes (blue = later, yellow = no agreement). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

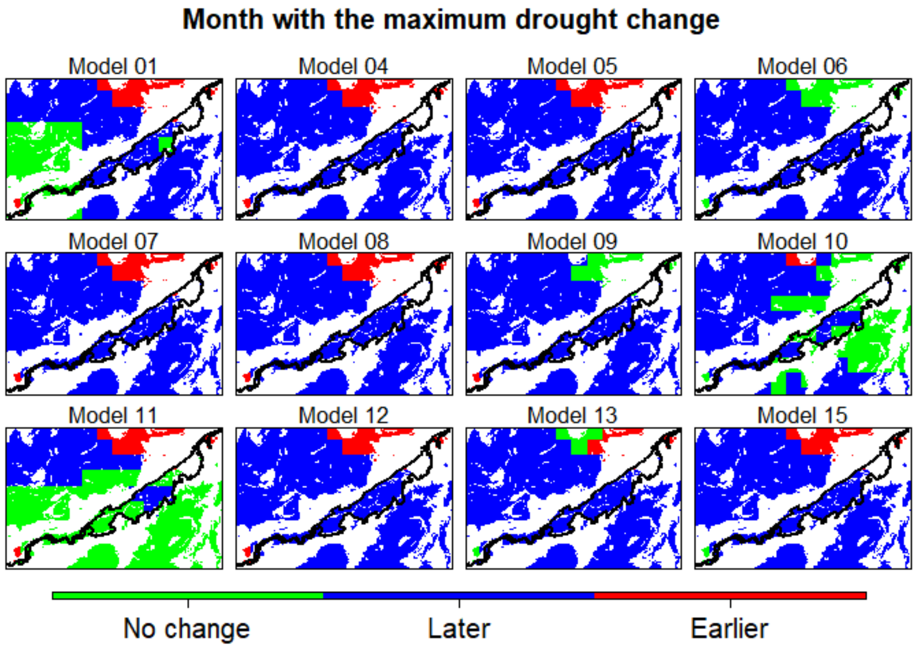


Figure 39. Variation between ensemble members in the month when the maximum drought occurs at Insh Marshes (blue = later, red = earlier, green).

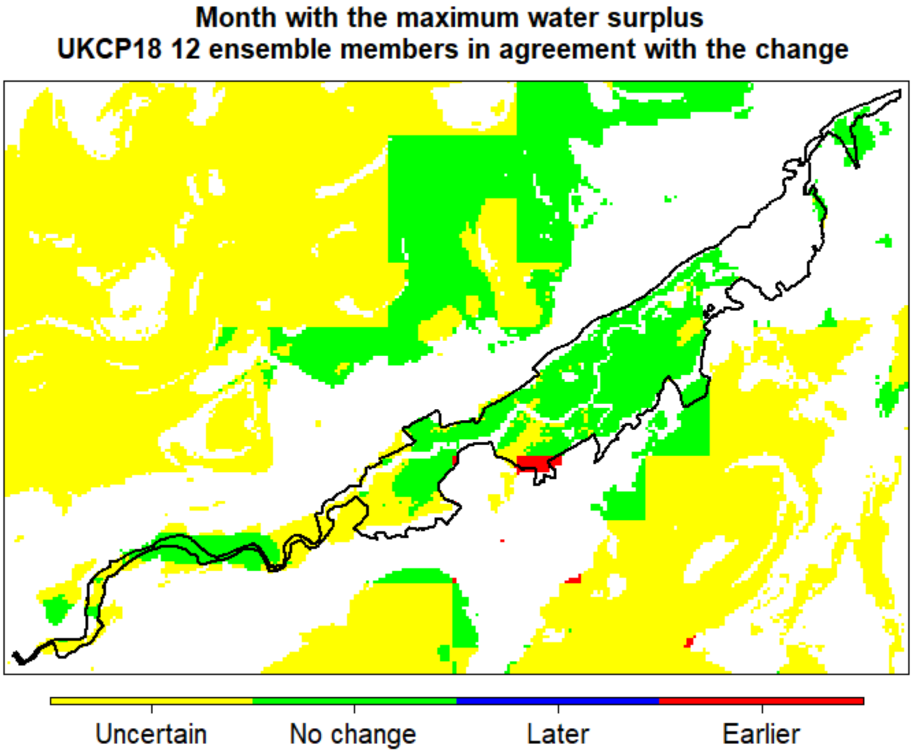


Figure 40. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum water surplus occurs at Insh Marshes (green: no change, yellow: no agreement). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

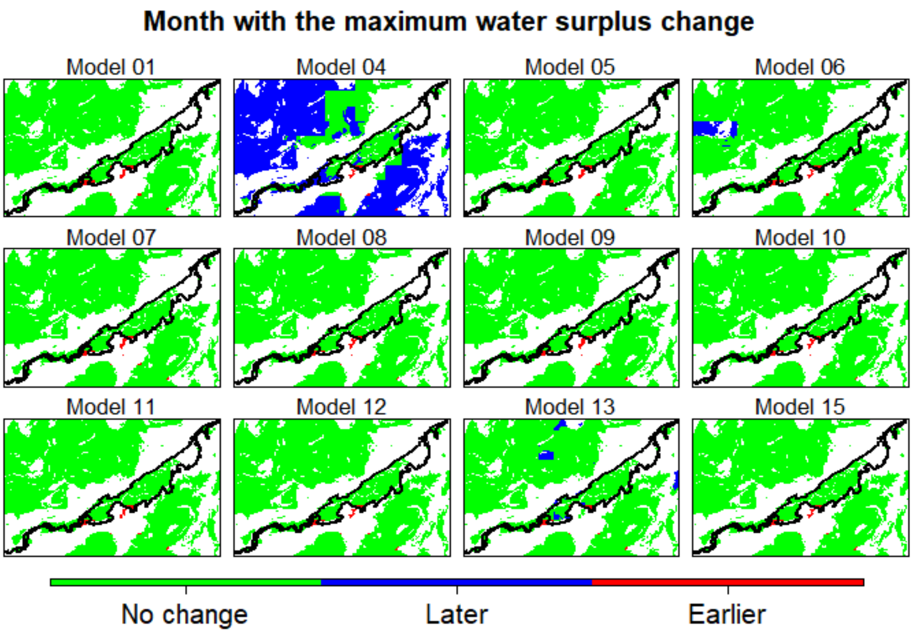


Figure 41. Variation between ensemble members in the month when the maximum water surplus occurs at Insh Marshes (blue = later, green = no change).

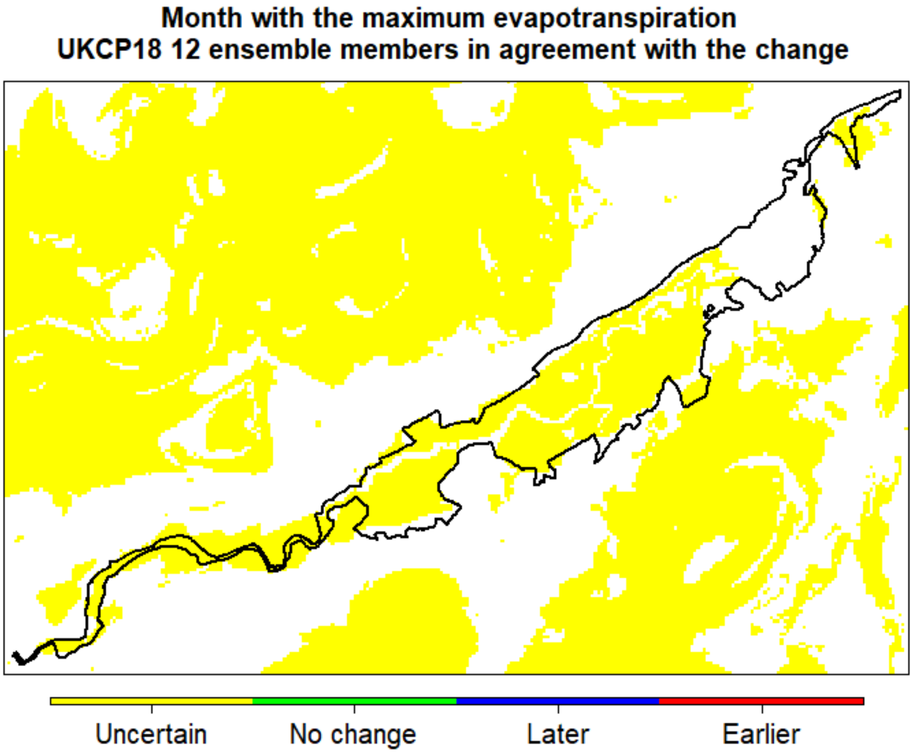


Figure 42. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum evapotranspiration occurs at Insh Marshes (yellow = no agreement).

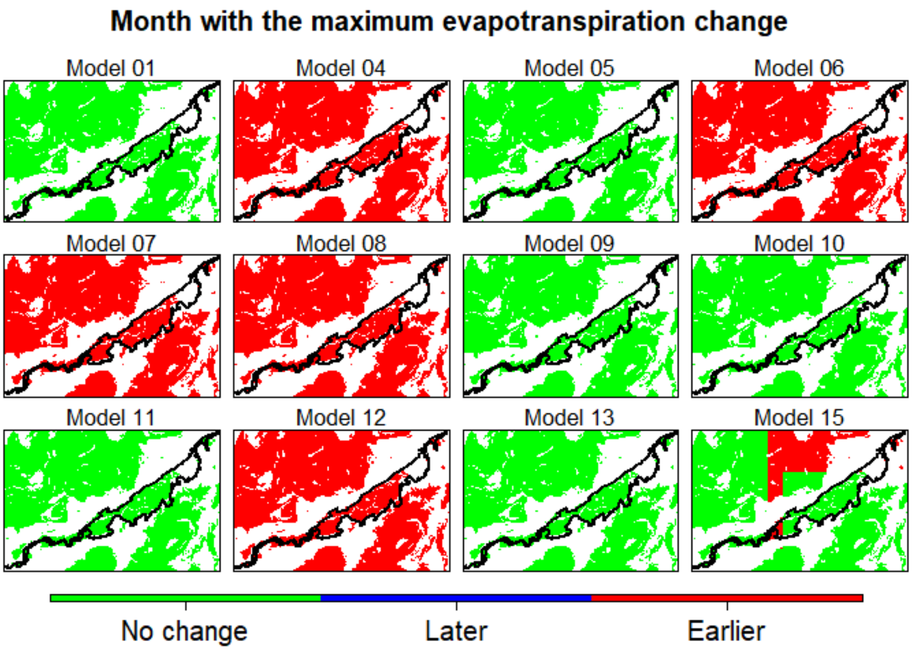


Figure 43. Variation between ensemble members in the month when the maximum evapotranspiration occurs at Insh Marshes (red = earlier, green = no change).

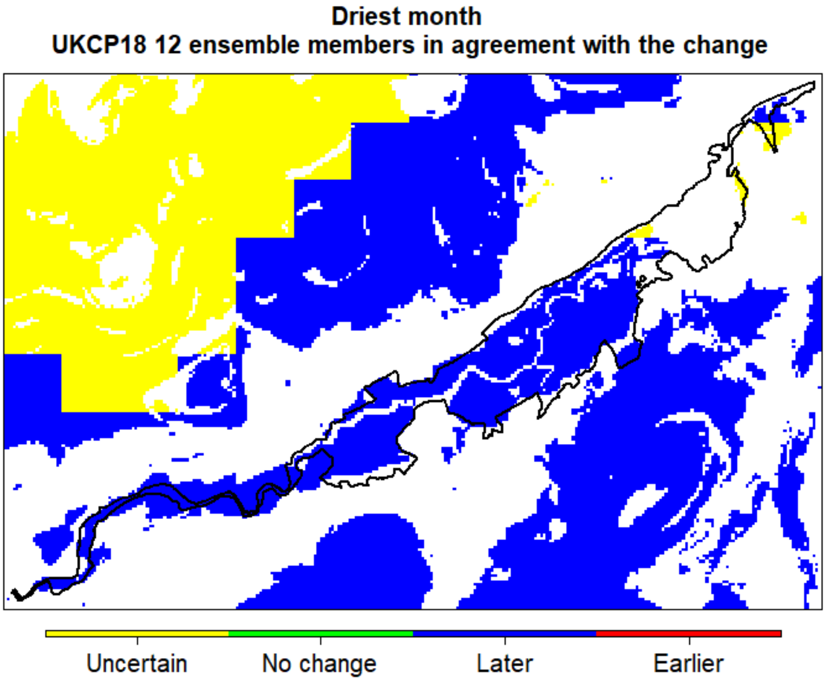


Figure 44. UKCP18 ensemble members in agreement with the sign of their change in the driest month at Insh Marshes (blue = later). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

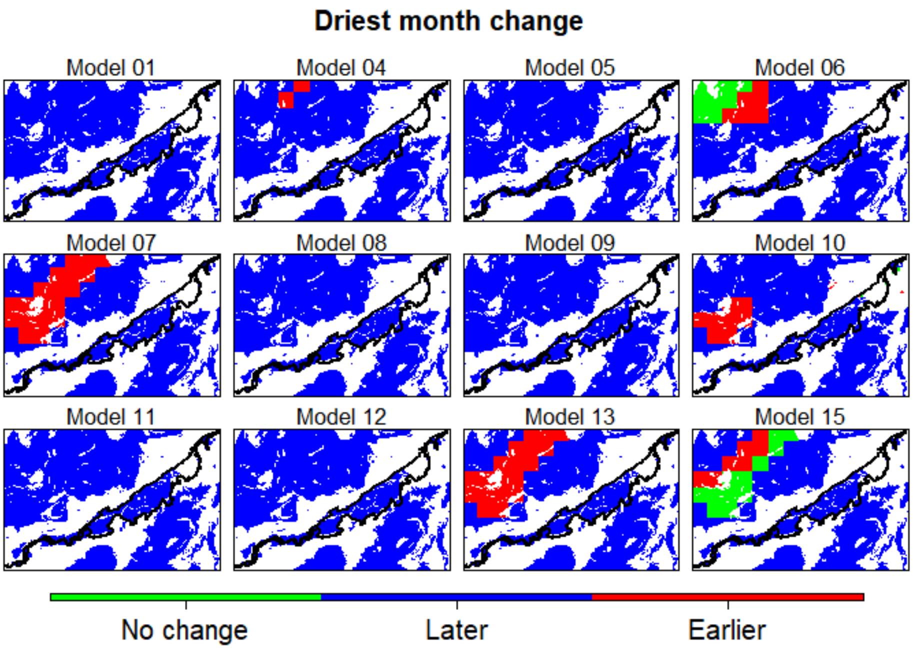


Figure 45. Variation between ensemble members in the driest month at Insh Marshes (red = earlier, blue = later).

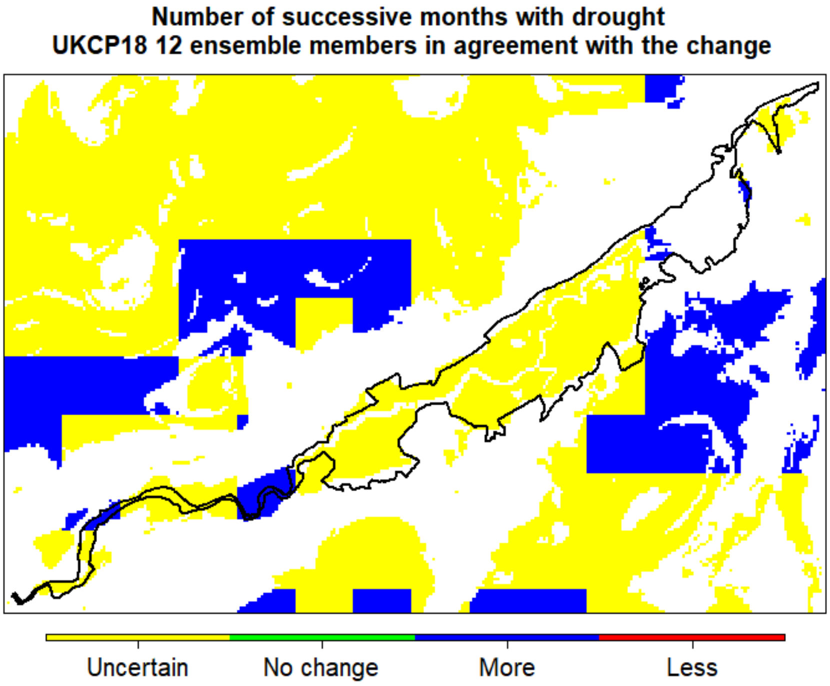


Figure 46. UKCP18 ensemble members in agreement with the sign of their change in the number of successive dry months at Insh Marshes (yellow = no agreement blue = more). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

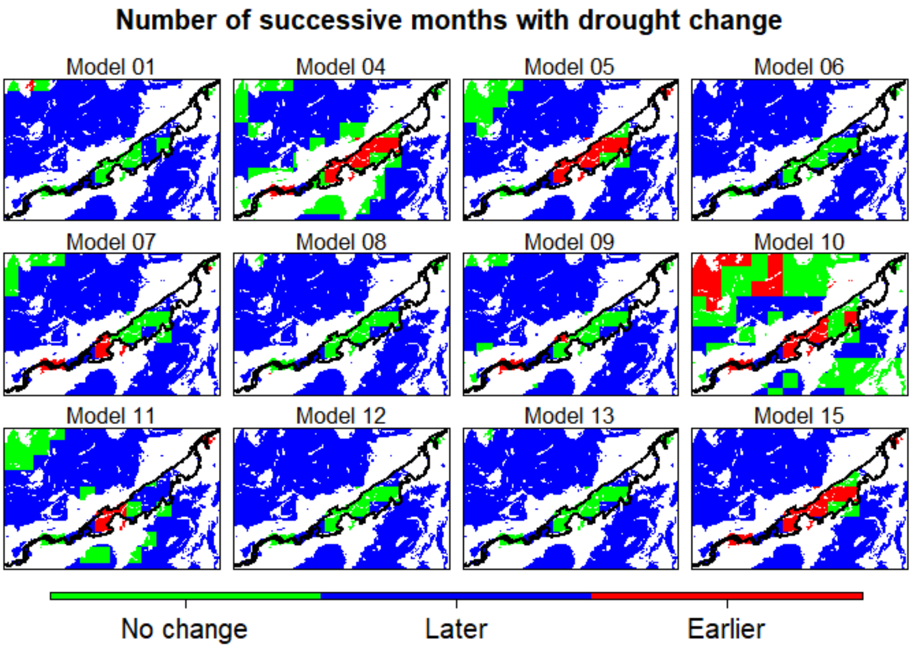


Figure 47. Variation between ensemble members in the number of successive dry months at Insh Marshes (red = less, blue = more).

Rassal

Rassal (https://sac.jncc.gov.uk/site/UK0030243) is both a SSSI and a SAC. It is located between Shieldaig and Lochcarron. The site contains a large exposure of limestone, limestone pavement, the largest ashwood on limestone in the Highlands and the best example of rich western valley woodland on calcareous soils. Numerous springs, flushes and base-rich fen areas occur, including tufa forming springs dominated by the moss *Cratoneuron* and areas dominated by sedges, black bog-rush *Schoenus nigricans* and broadleaved cotton grass *Eriophorum latifolium*. The calcareous seepages also support the rare cranefly *Orimarga virgo* and the nationally scarce cranefly *Gonomyia conoviensis*.

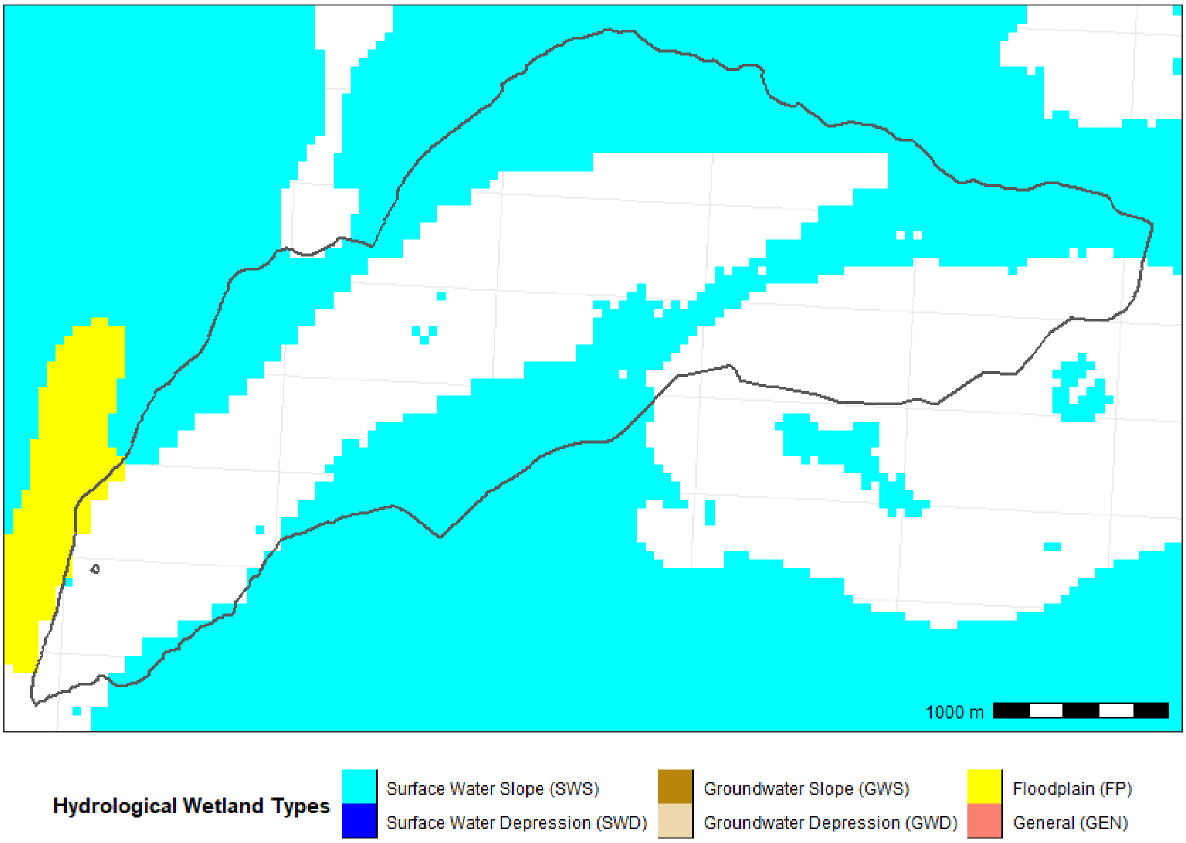


Figure 48. Wetland classes map at Rassal.

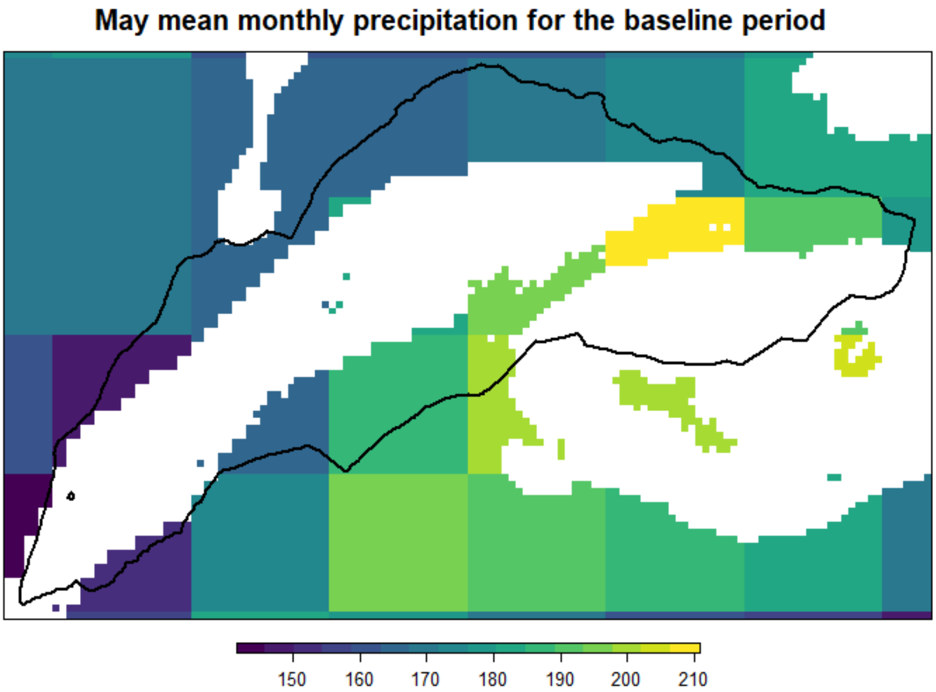


Figure 49. Observed May mean monthly precipitation (mm) at Rassal.

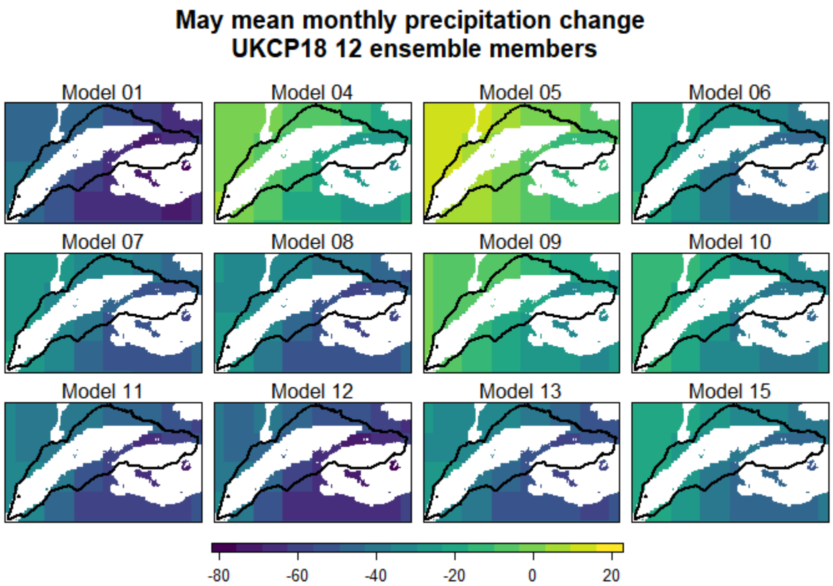


Figure 50. Projected change in May mean monthly precipitation (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Rassal.

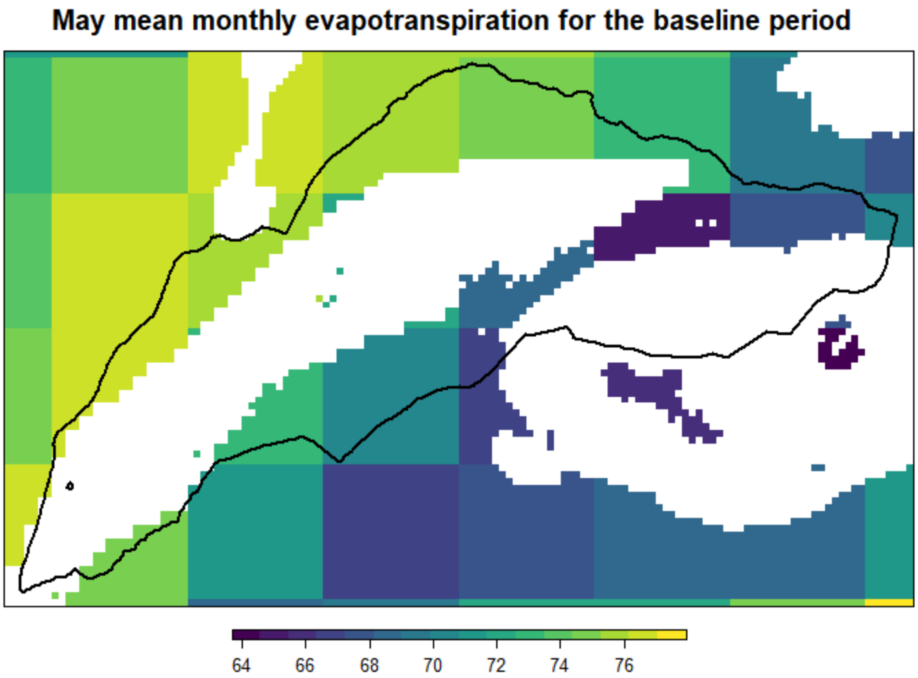


Figure 51. Observed May mean monthly evapotranspiration at Rassal.

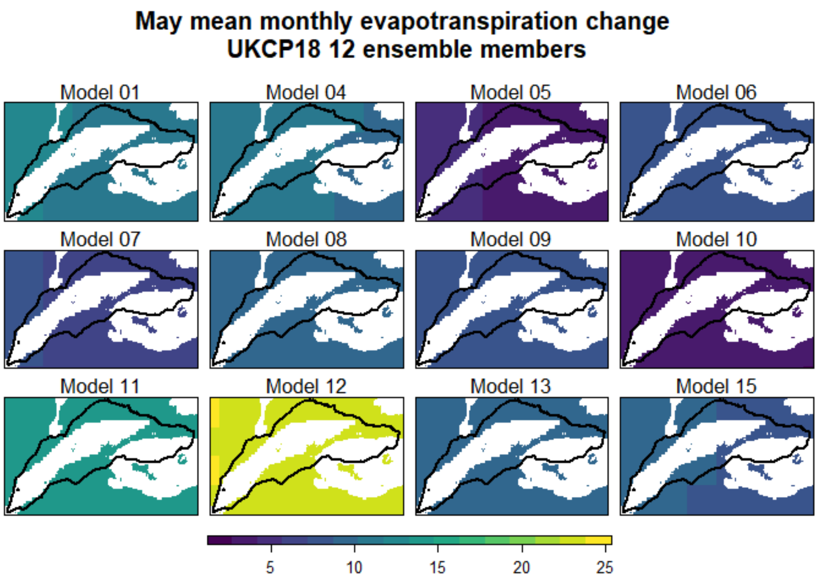


Figure 52. Projected change in May mean monthly evapotranspiration by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Rassal.

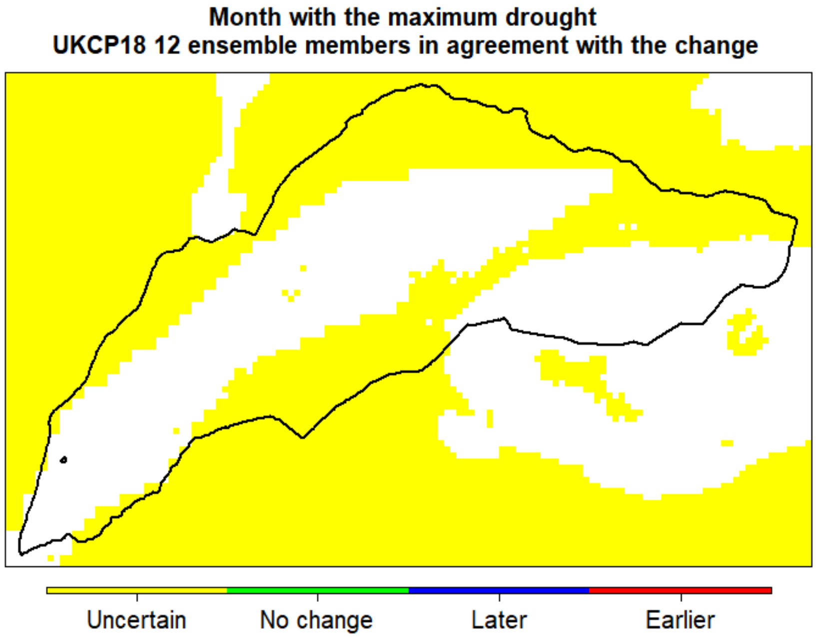


Figure 53. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum drought occurs at Rassal (yellow = no agreement).

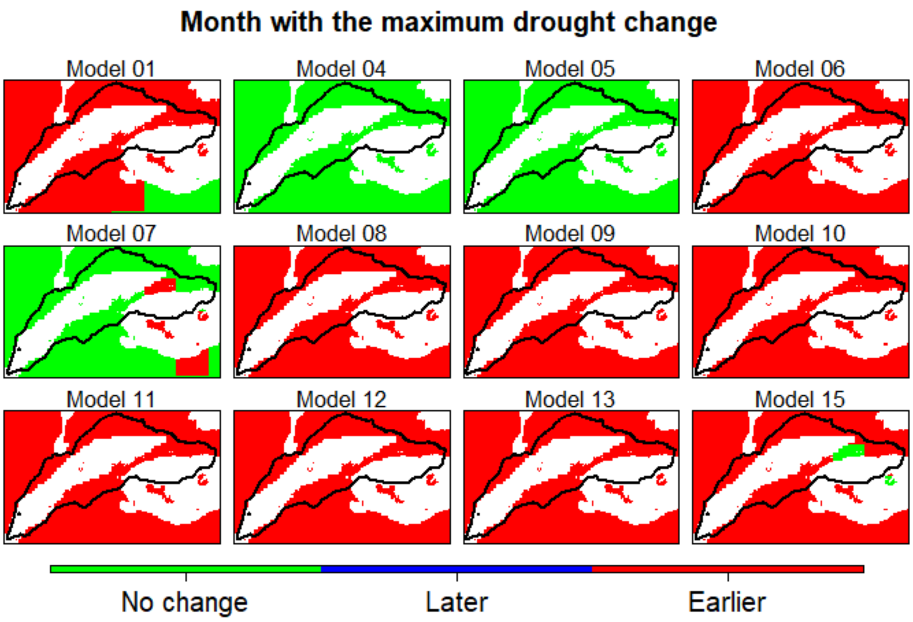


Figure 54. Variation between ensemble members in the month when the maximum drought occurs at Rassal (red = earlier, green = no change).

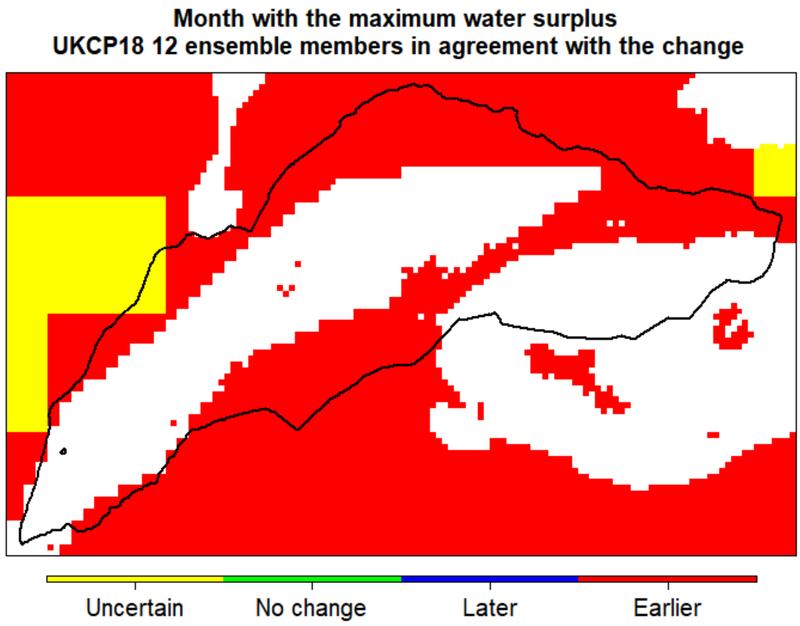


Figure 55. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum water surplus occurs at Rassal (yellow = no agreement, red = earlier). Note: positive and negative refer to the sign of the feature shown, not the impact on wetlands.

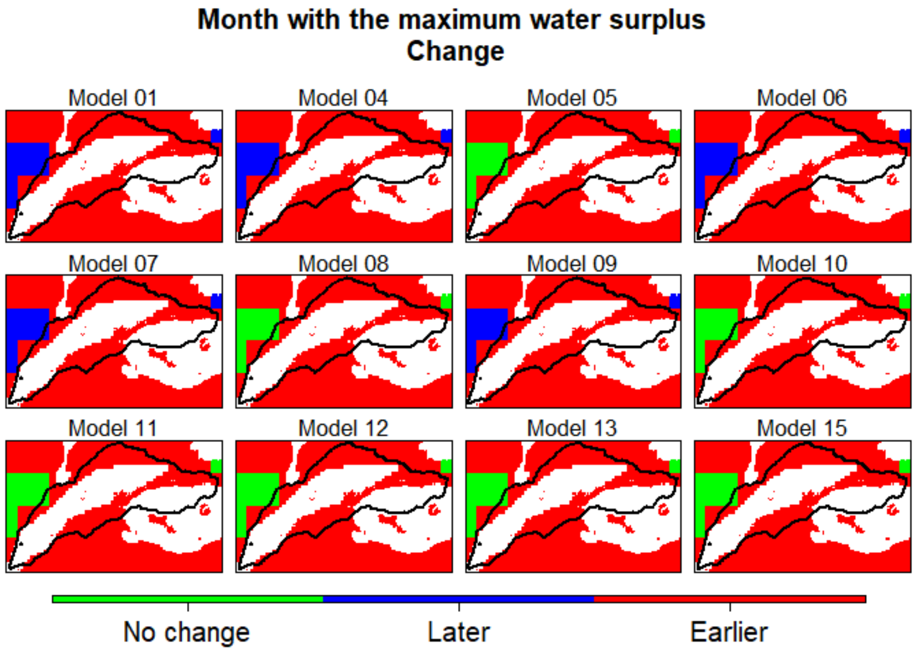


Figure 56. Variation between ensemble members in the month when the maximum water surplus occurs at Rassal (blue = later, red = earlier, green = no change).

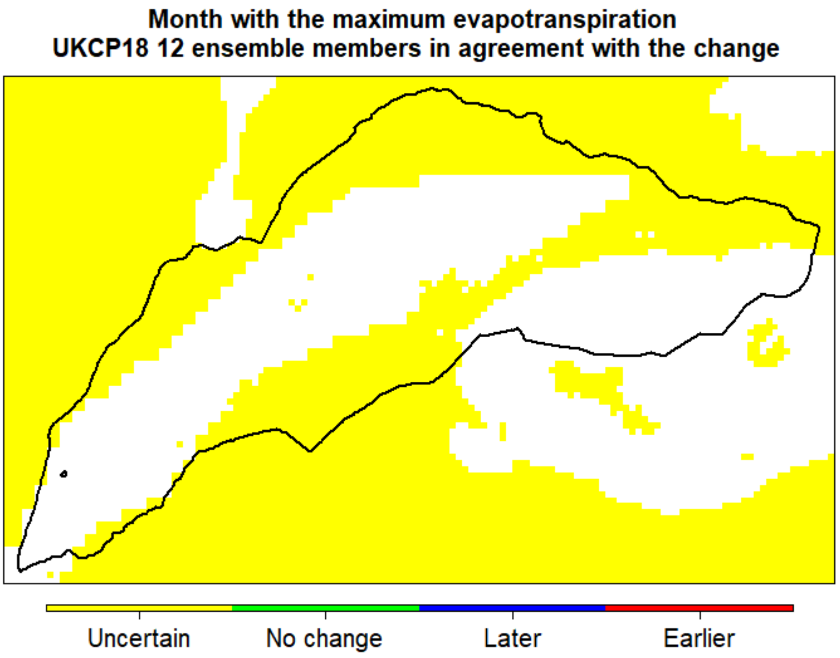


Figure 57. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum evapotranspiration occurs at Rassal (yellow = no agreement).

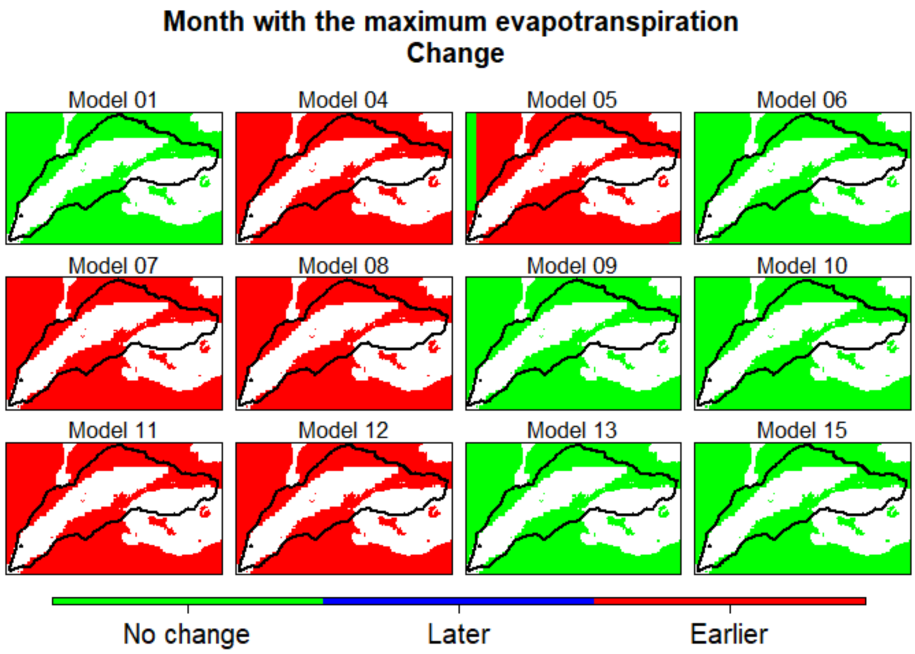


Figure 58. Variation between ensemble members in the month when the maximum evapotranspiration occurs at Rassal (red = earlier, green = no change).

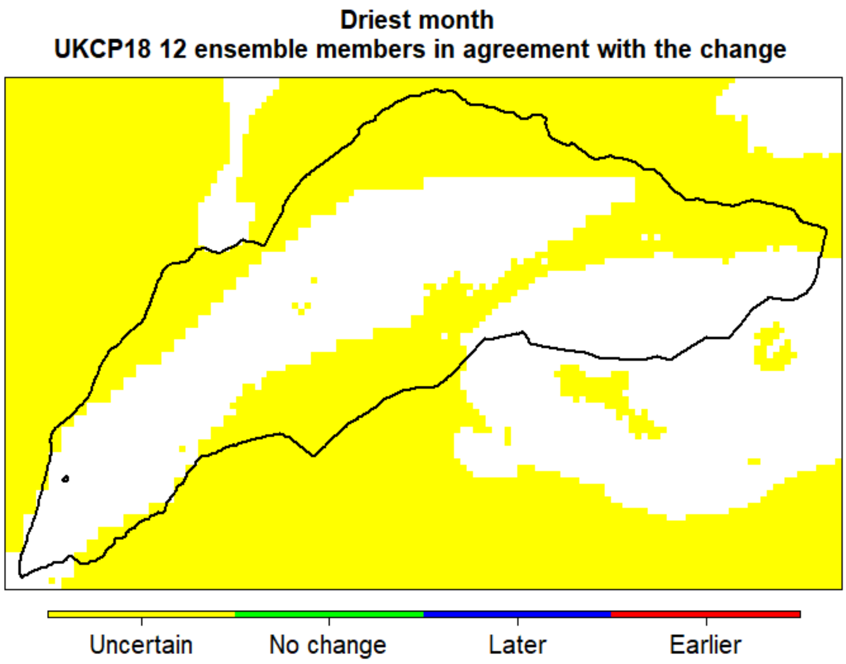


Figure 59. UKCP18 ensemble members in agreement with the sign of their change in the driest month at Rassal (yellow = no agreement).

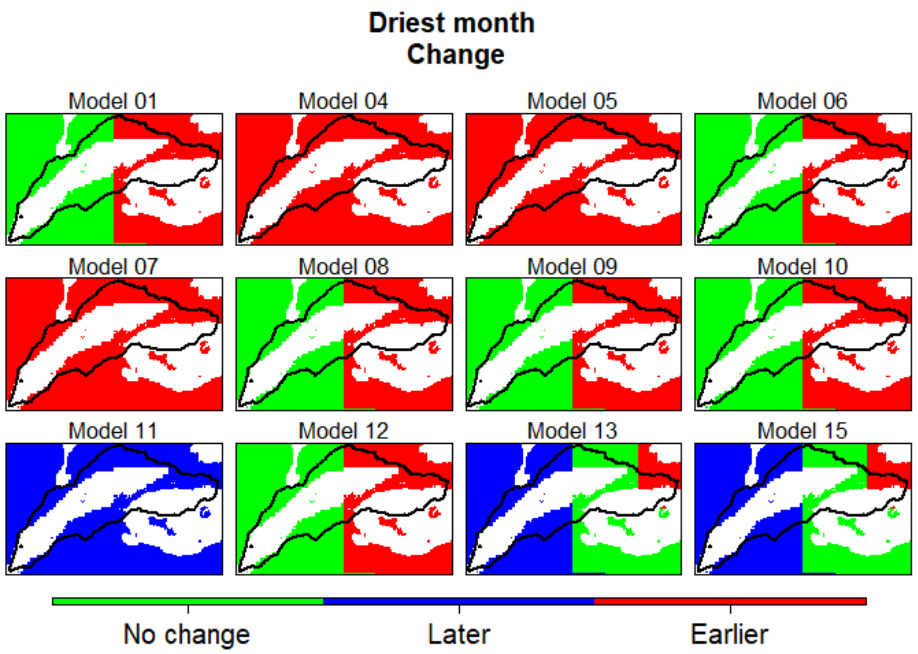


Figure 60. Variation between ensemble members in the driest month at Rassal (red = earlier, blue = later).

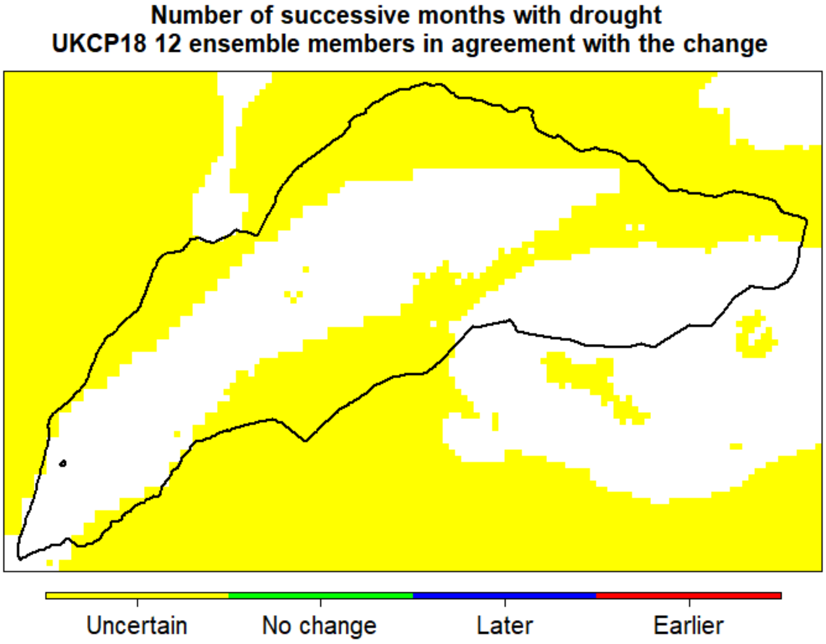


Figure 61. UKCP18 ensemble members in agreement with the sign of their change in the number of successive dry months at Rassal (yellow = no agreement).

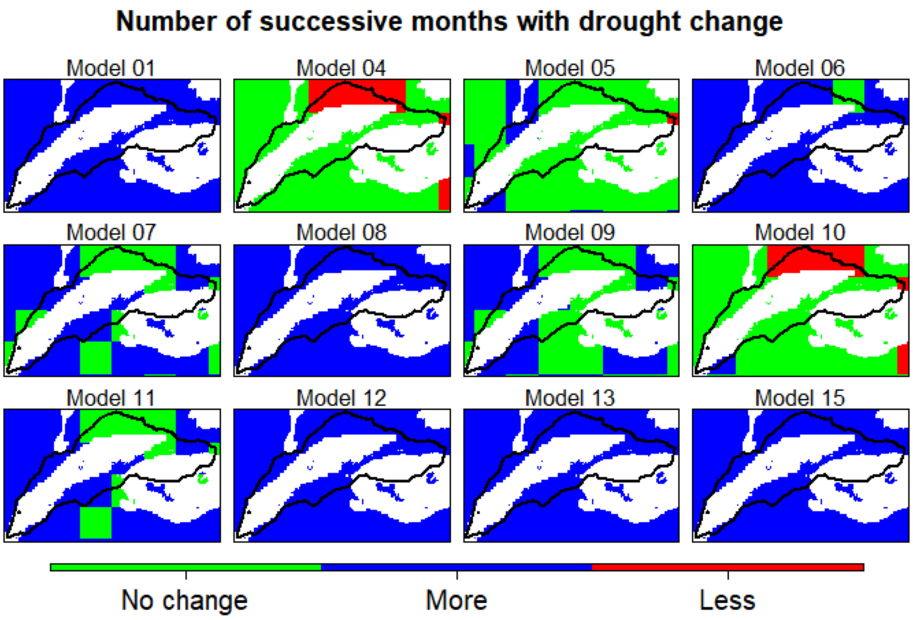


Figure 62. Variation between ensemble members in the number of successive dry months at Rassal (red = less, blue = more).

Mortlach Moss

Mortlach Moss (https://sac.jncc.gov.uk/site/UK0030216) is an alkaline basin-fen located 5 km north of Huntly and is designated as an SSSI and SAC. The basin-fen community, with abundant bottle sedge Carex rostrata and lesser tussock sedge Carex diandra, is nationally rare and the best example of its type in north-east Scotland. The locally-rare black bog-rush *Schoenus nigricans* dominates the adjacent flushes. Notable species include grass of Parnassus *Parnassia palustris* and lesser butterfly orchid *Platanthera bifolia*.

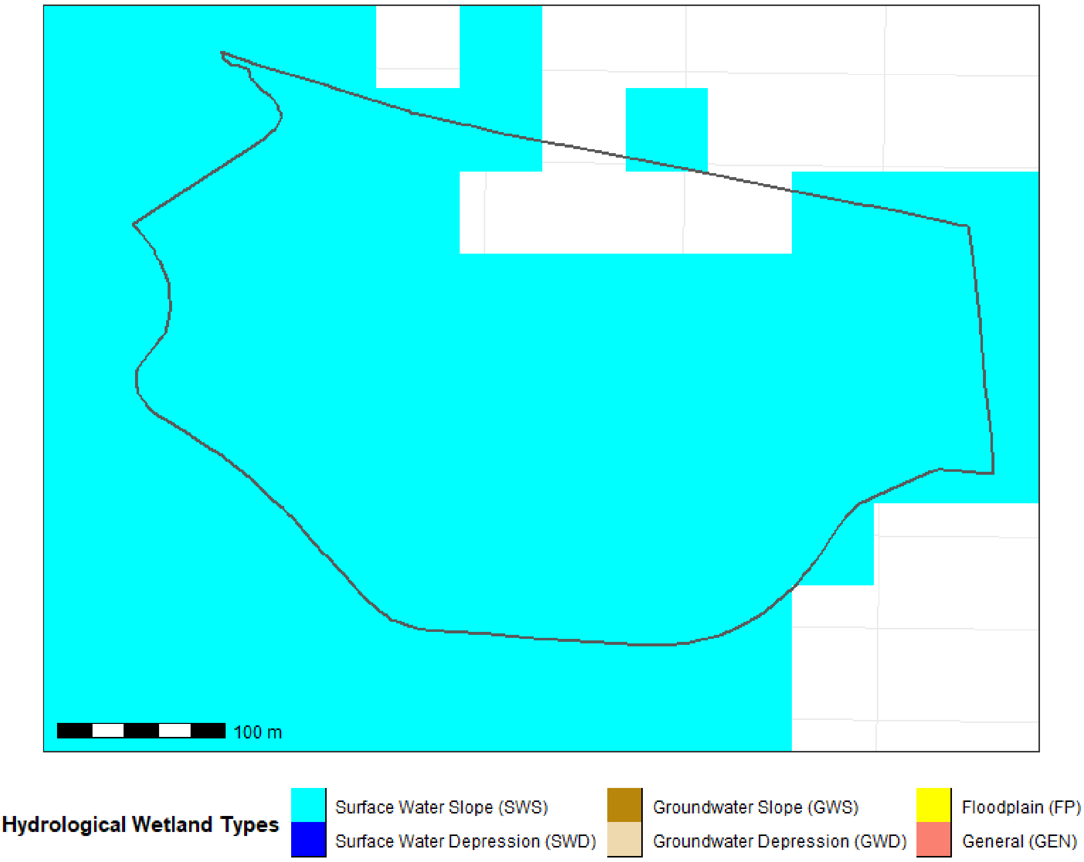


Figure 63. Wetland classes map at Mortlach Moss.

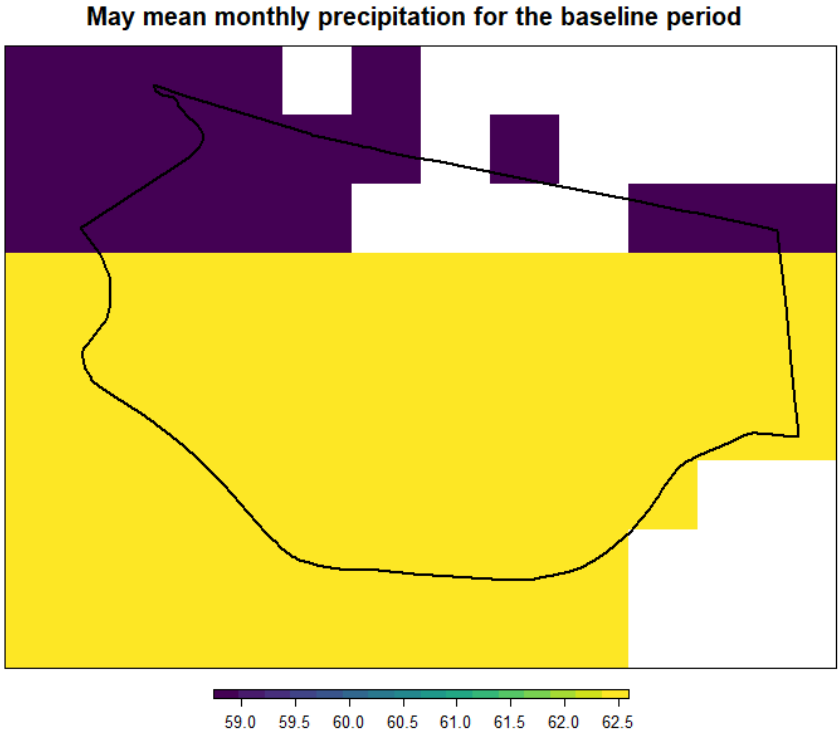


Figure 64. Observed May mean monthly precipitation (mm) at Mortlach Moss.

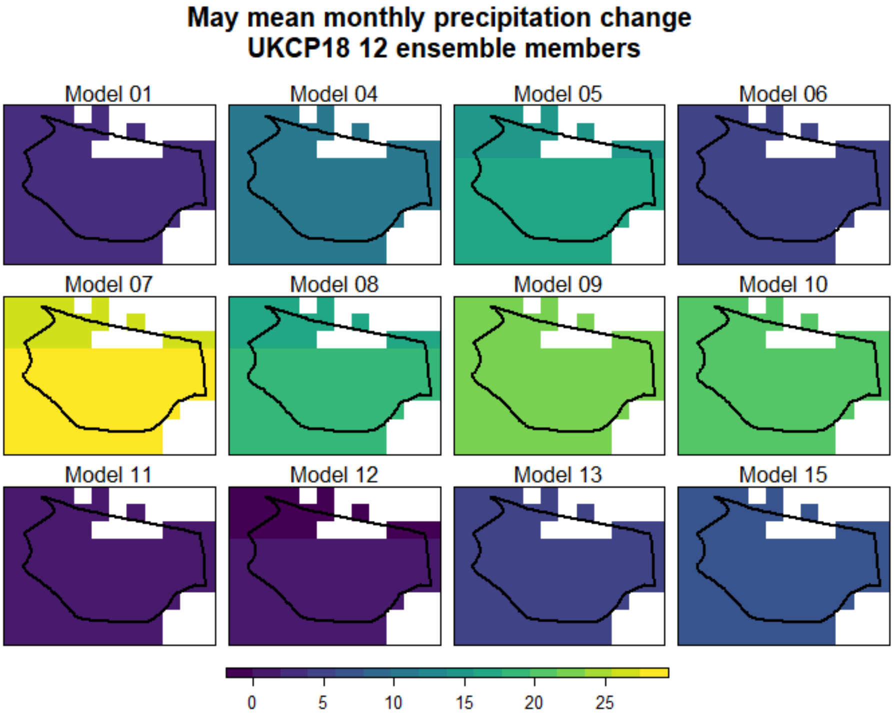


Figure 65. Projected change in May mean monthly precipitation (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Mortlach Moss.

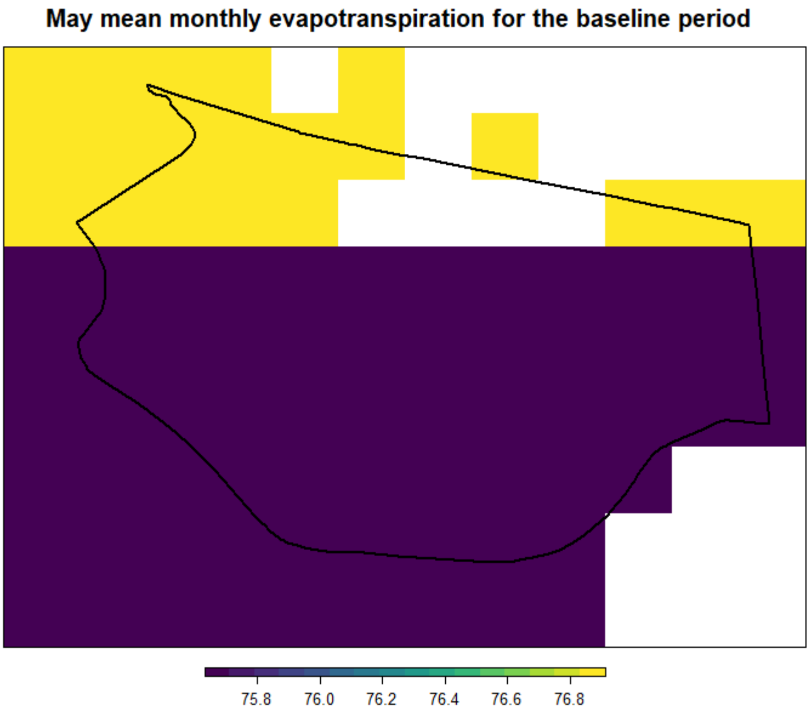


Figure 66. Observed May mean monthly evapotranspiration (mm) at Mortlach Moss.

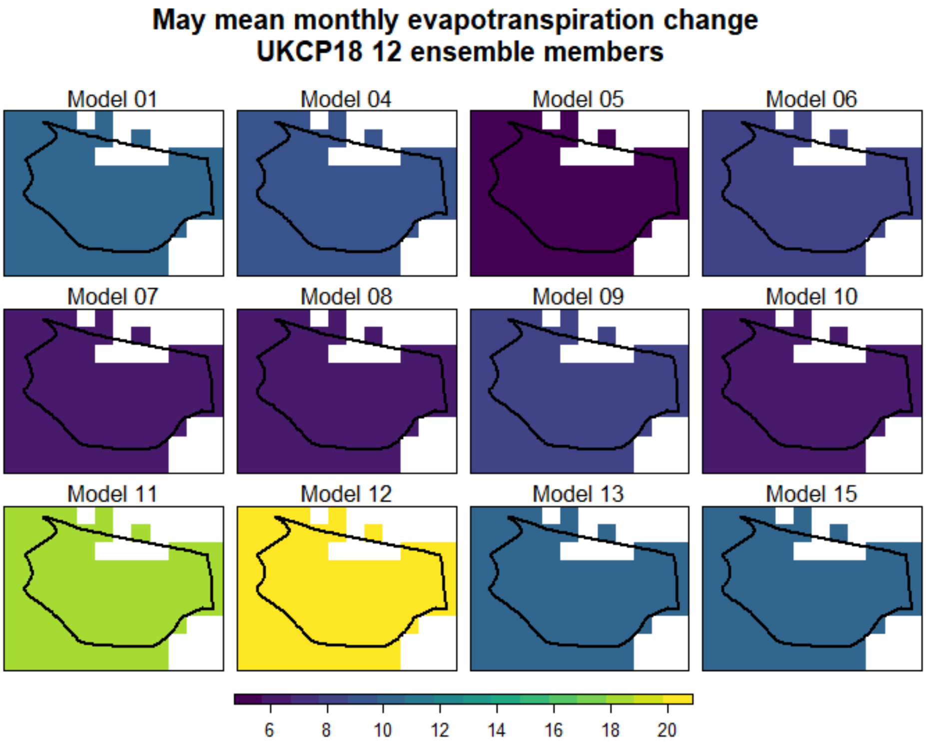


Figure 67. Projected change in May mean monthly evapotranspiration (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Mortlach Moss.

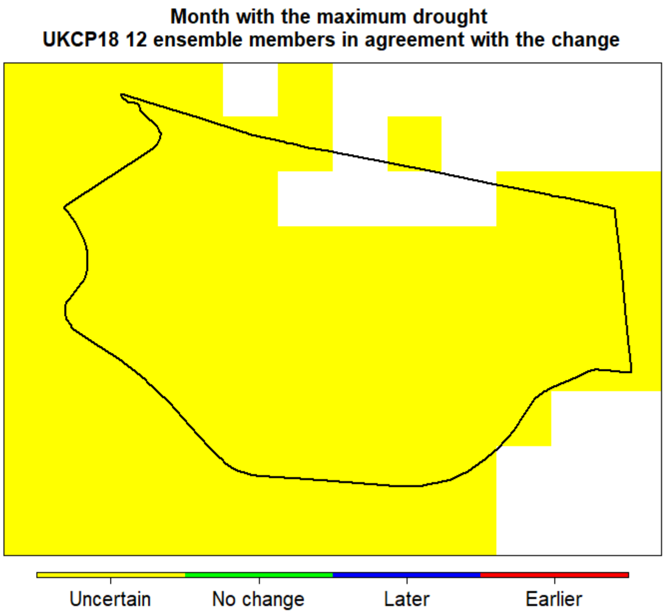


Figure 68. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum drought occurs at Mortlach Moss (yellow = no agreement).

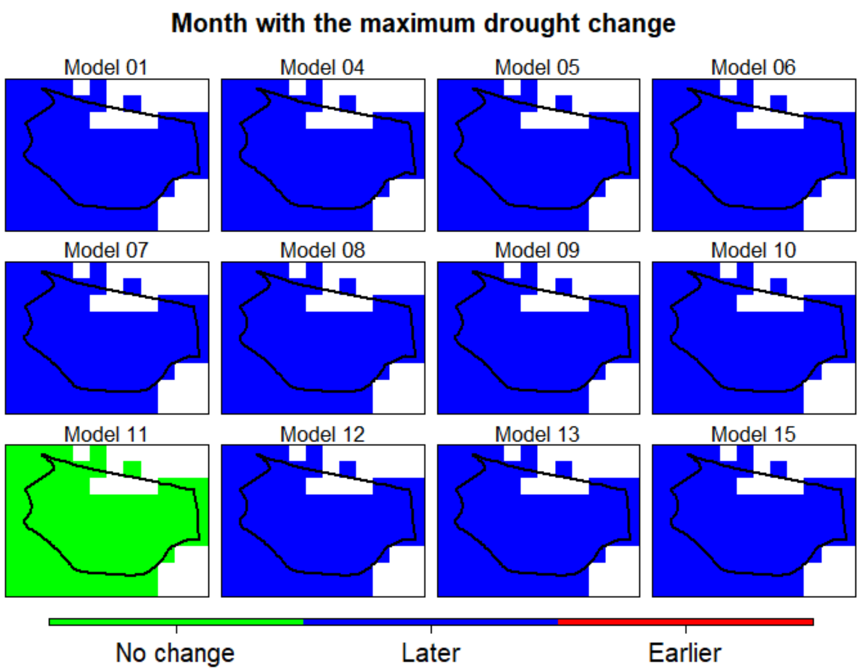


Figure 69. Variation between ensemble members in the month when the maximum drought occurs at Mortlach Moss (blue = later).

Figure 85 highlights the issue of how to evaluate the uncertainty when not all 12 climate model ensemble members being in agreement, yet 11 are. These emphasise the need to use multiple visualisations.

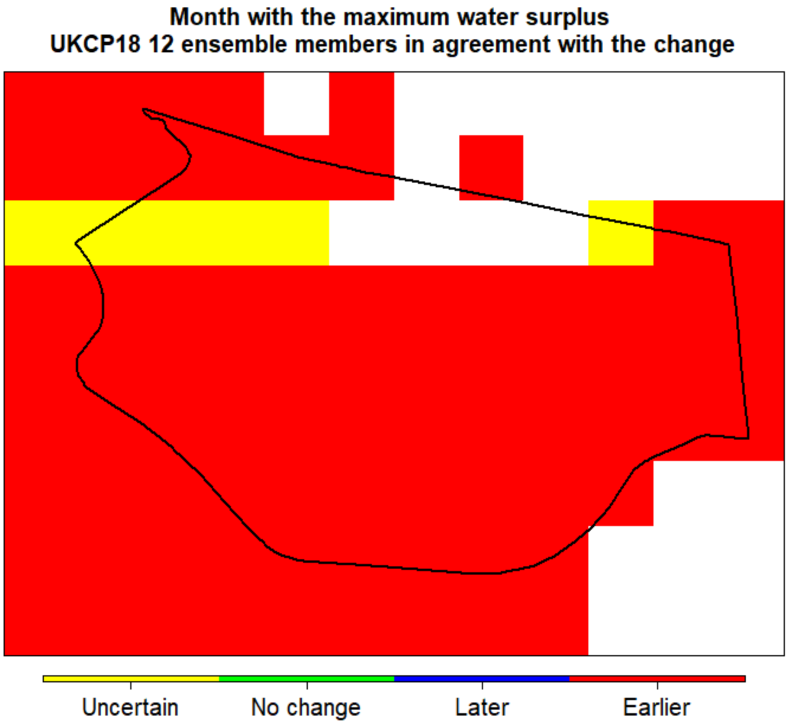


Figure 70. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum water surplus occurs at Mortlach Moss (red = earlier).

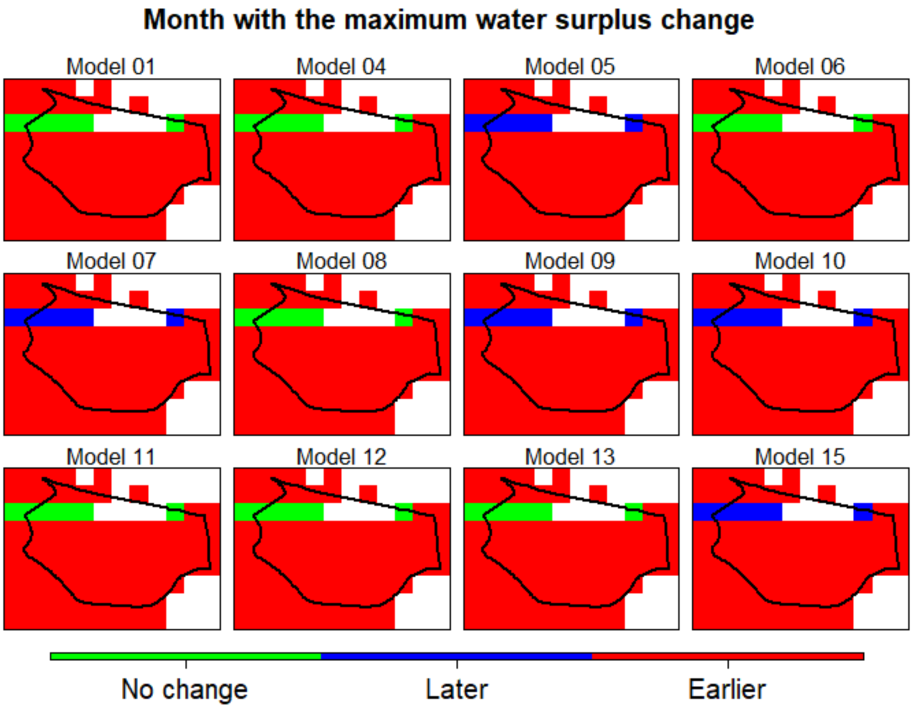


Figure 71. Variation between ensemble members in the month when the maximum water surplus occurs at Mortlach Moss (red = earlier, blue = later).

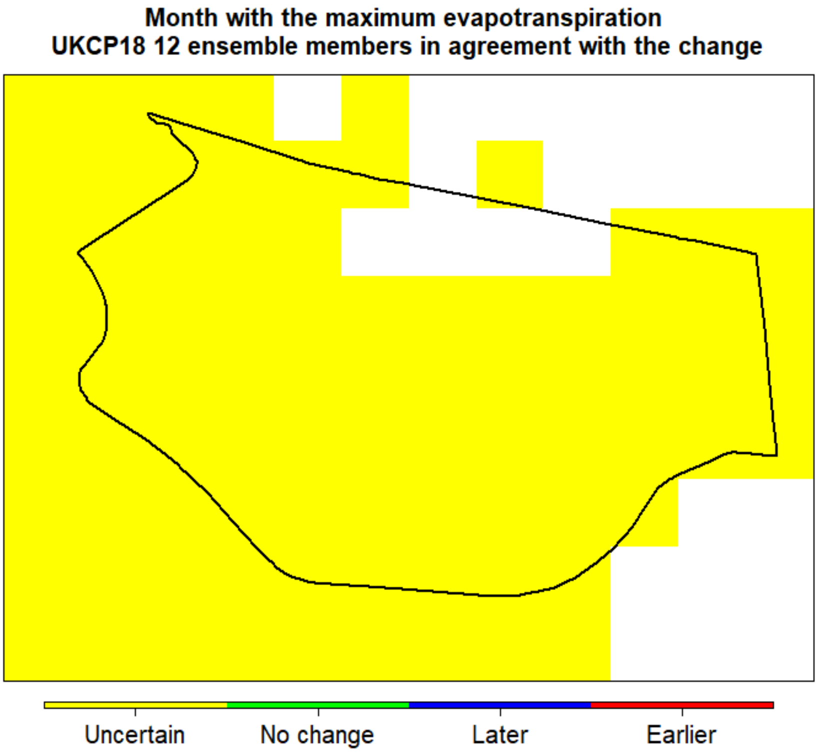


Figure 72. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum evapotranspiration occurs at Mortlach Moss (yellow = no agreement).

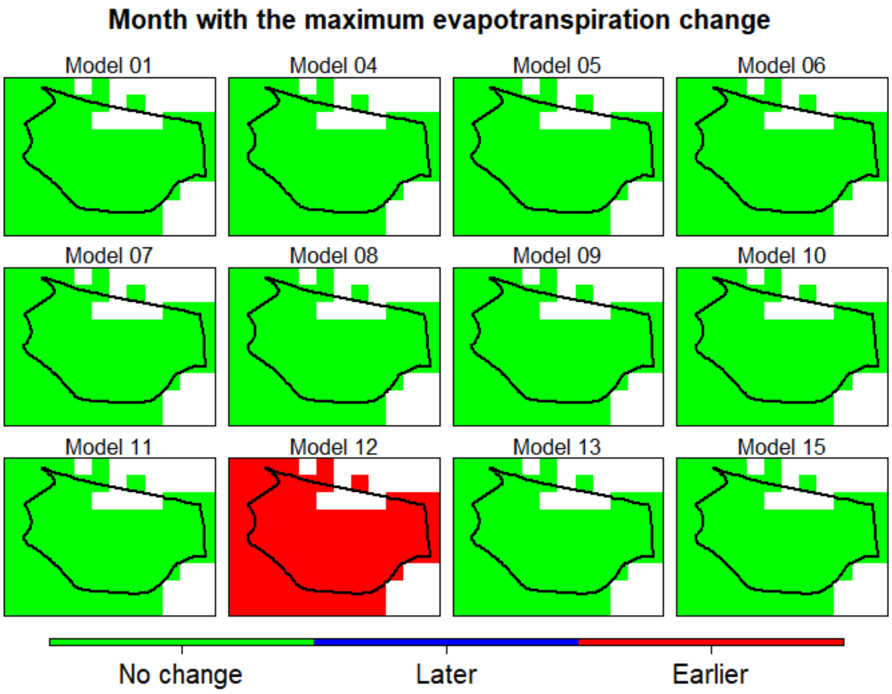


Figure 73. Variation between ensemble members in the month when the maximum evapotranspiration occurs at Mortlach Moss (red = earlier, green = no change).

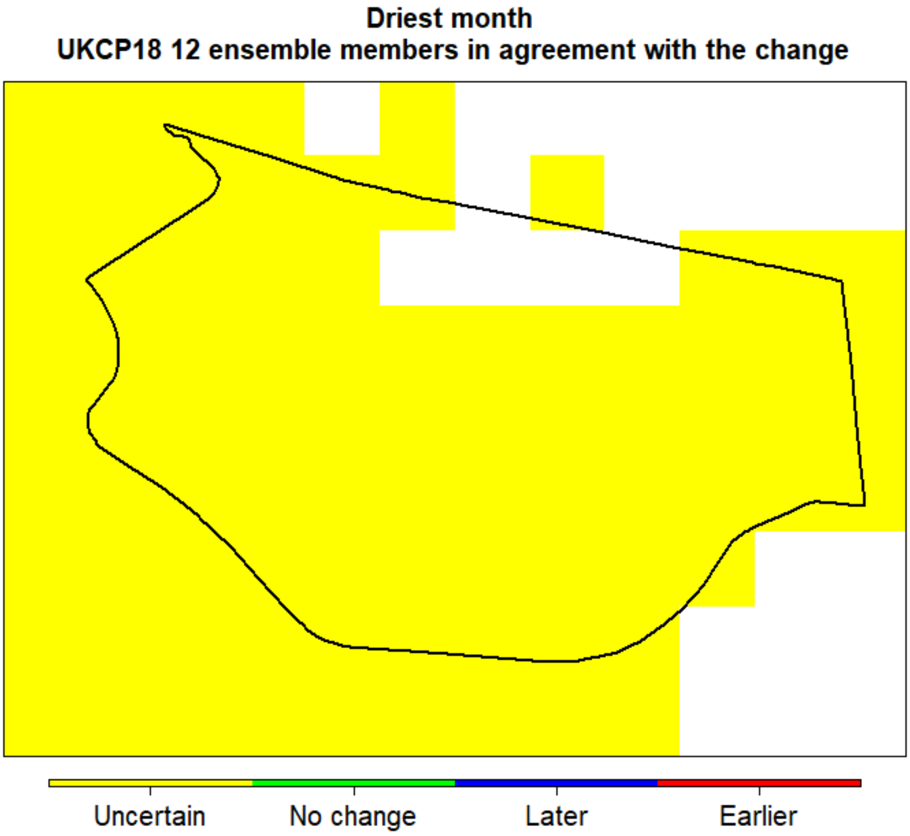


Figure 74. UKCP18 ensemble members in agreement with the sign of their change in the driest month at Mortlach Moss (yellow = no agreement).

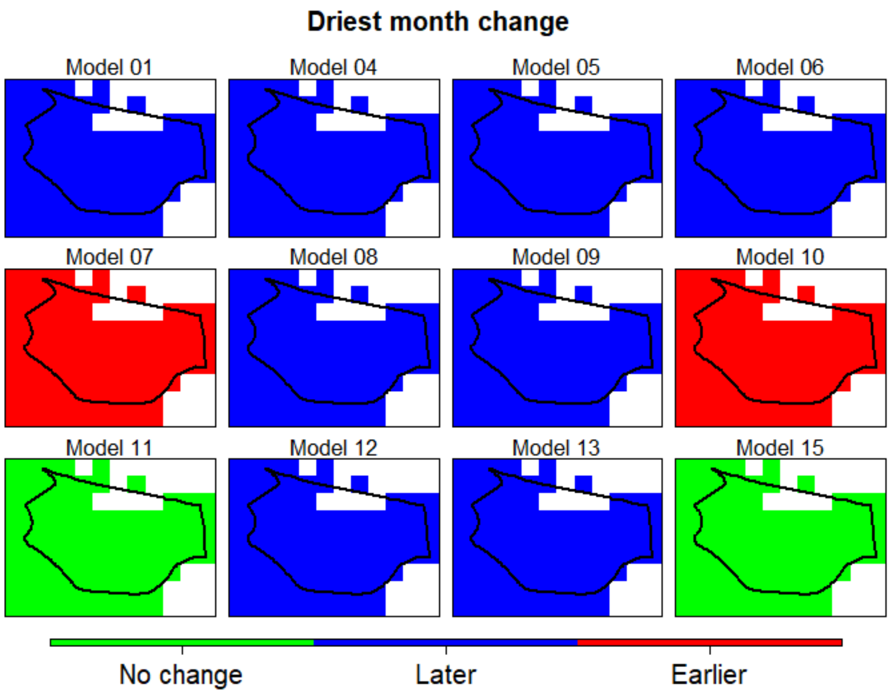


Figure 75. Variation between ensemble members in the driest month at Mortlach Moss (red = earlier, blue = later, green = no change).

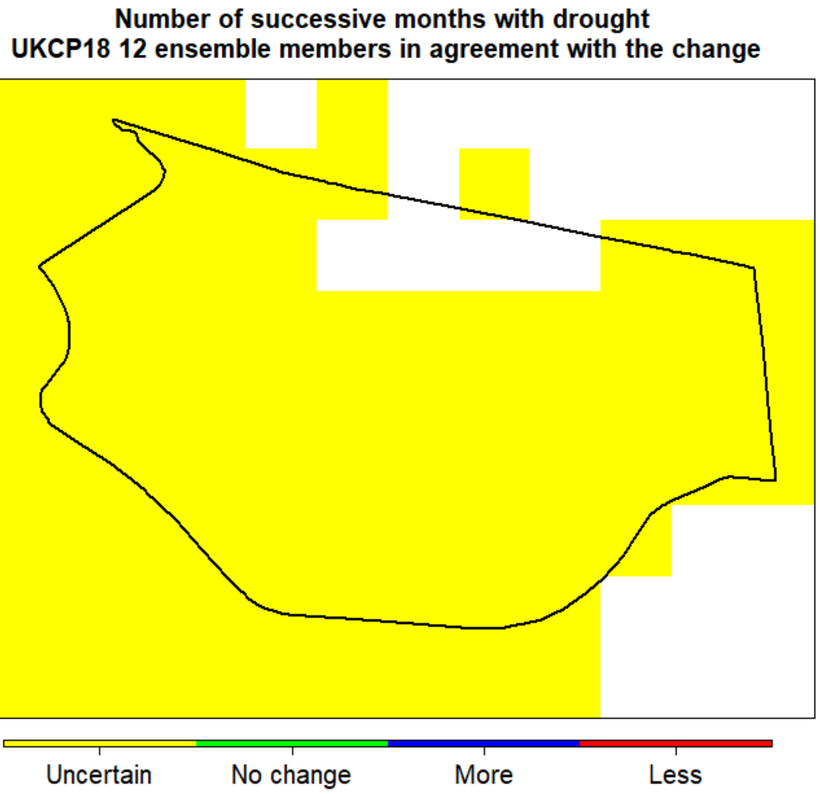


Figure 76. UKCP18 ensemble members in agreement with the sign of their change in the number of successive dry months at Mortlach Moss (yellow = no agreement).

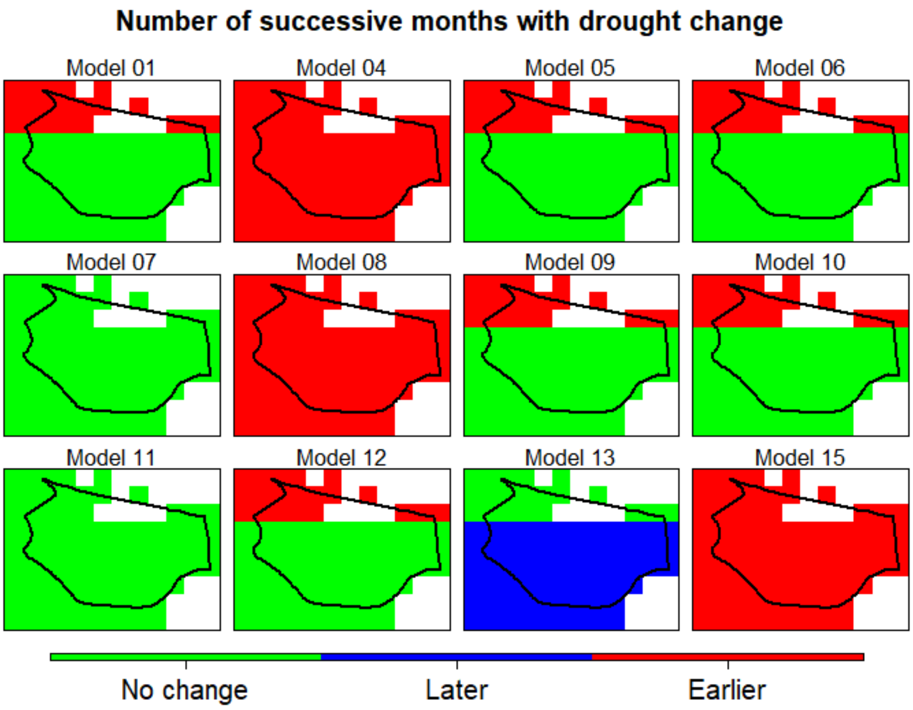


Figure 77. Variation between ensemble members in the number of successive dry months at Mortlach Moss (red = less, blue = more).

Lendalfoot Hills Complex

Location of Lendalfoot Hills Complex SAC

The Lendalfoot Hills Complex (https://sac.jncc.gov.uk/site/UK0013592) is located south of Girvan in south-west Scotland and is a Special Area of Conservation (SAC) selected because of the presence of a well-developed series of alkaline fens classified as M9 *Carex rostrata-Calliergon cuspidatum* mire and M10 *Carex dioica-Pinguicula vulgaris* mire. These have developed over base-rich serpentine rocks and occur in a range of hydrological situations such as topogenous basin fens, soligenous tracks or soakways in valley fen or wet heath and as spring-fed fens. Some of the *Carex-Pinguicula* mires have an abundance of black bog-rush *Schoenus nigricans*.

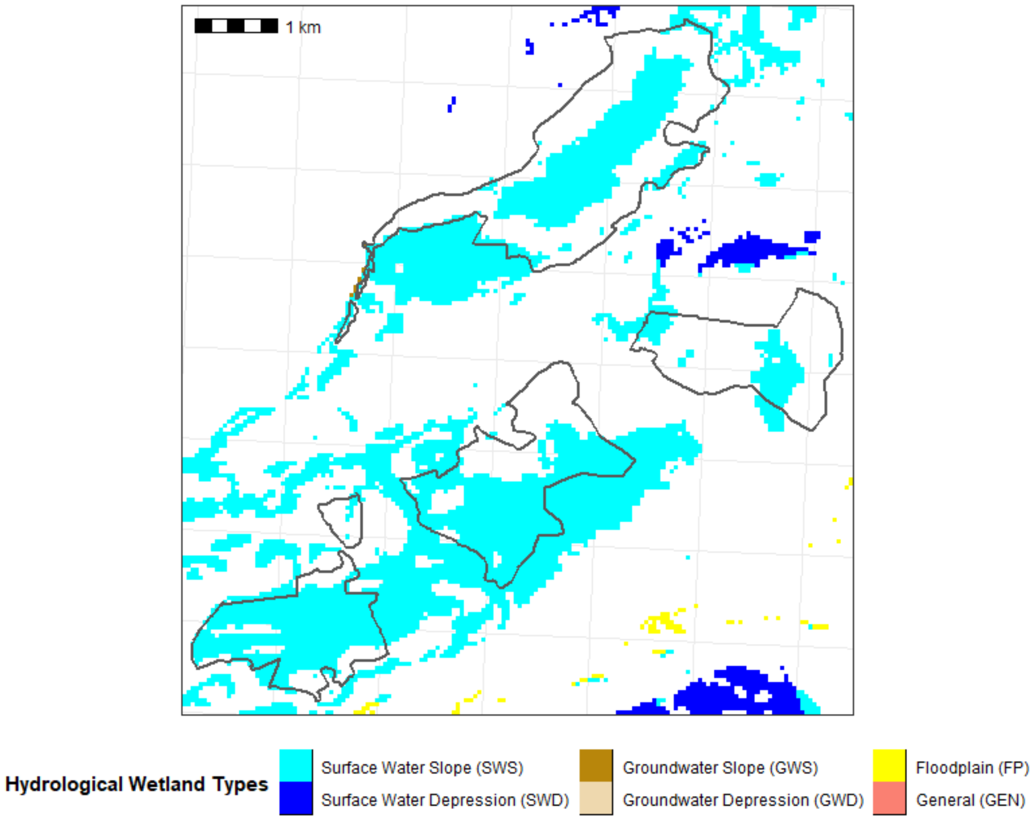


Figure 78. Wetland classes map at Lendalfoot Hills Complex.

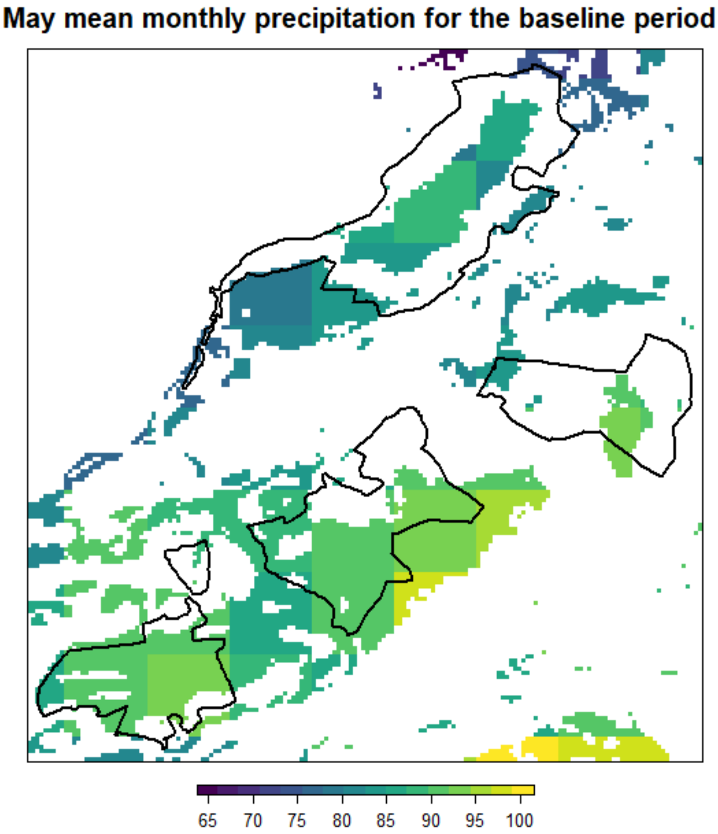


Figure 79. Observed May mean monthly precipitation (mm) at Lendalfoot Hills Complex.

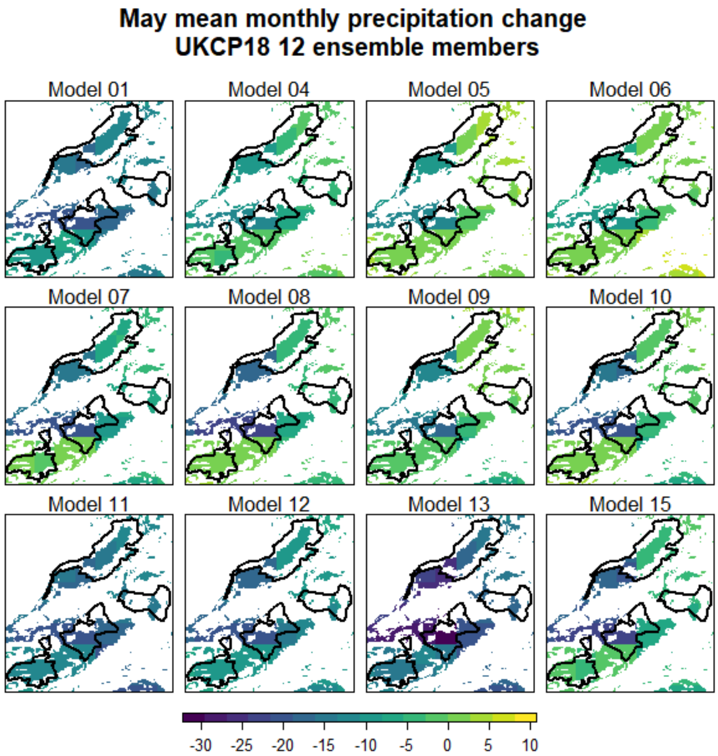


Figure 80. Projected change in May mean monthly precipitation (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Lendalfoot Hills Complex.

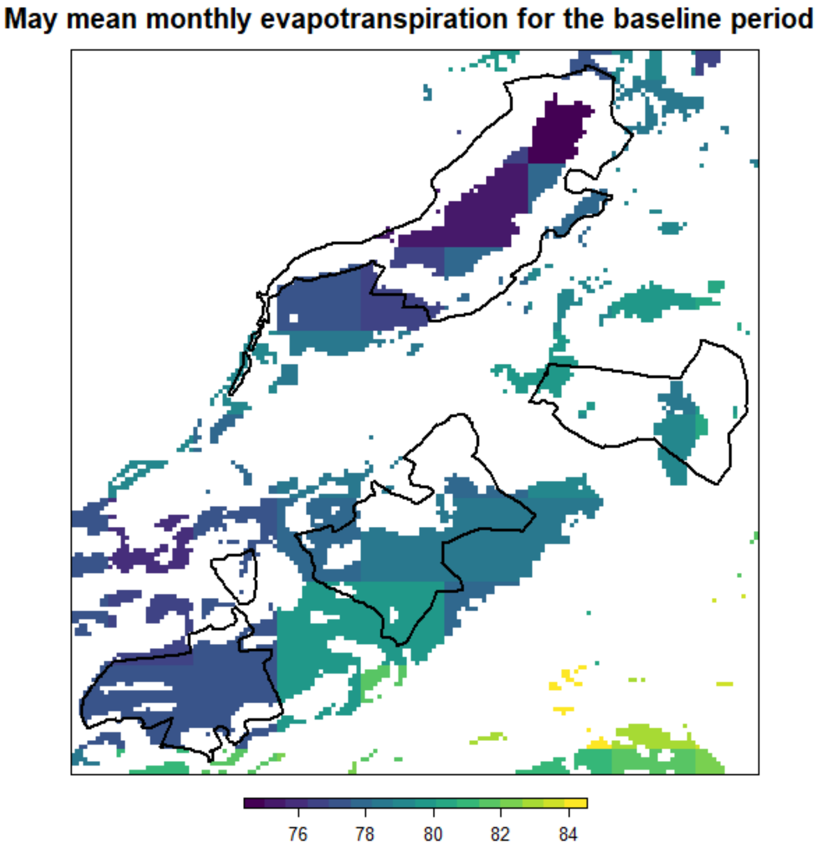


Figure 81. Observed May mean monthly evapotranspiration (mm) at Lendalfoot Hills Complex.

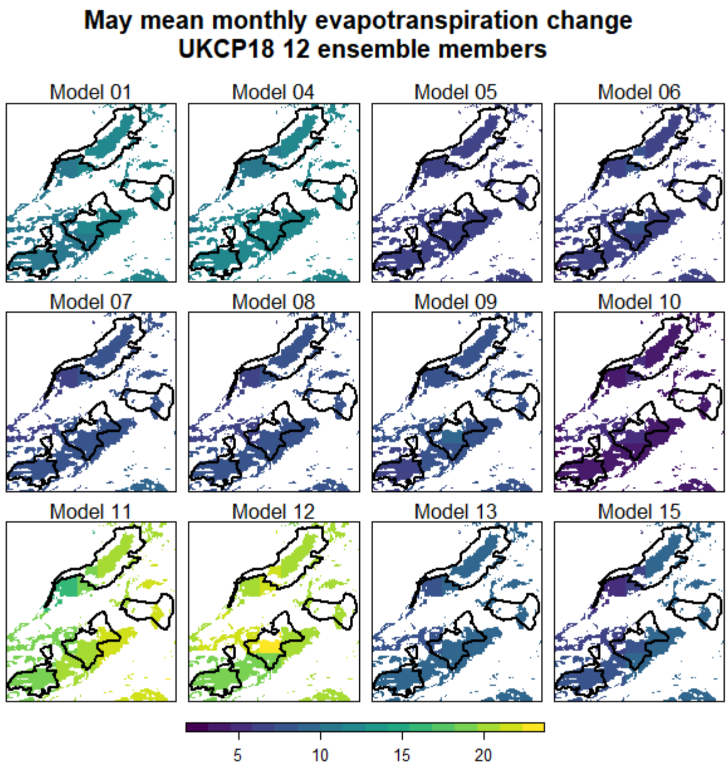


Figure 82. Projected change in May mean monthly evapotranspiration (mm) by 2030-2059 in comparison to the baseline (1994-2014) for the 12 climate model ensemble members at Lendalfoot Hills Complex.

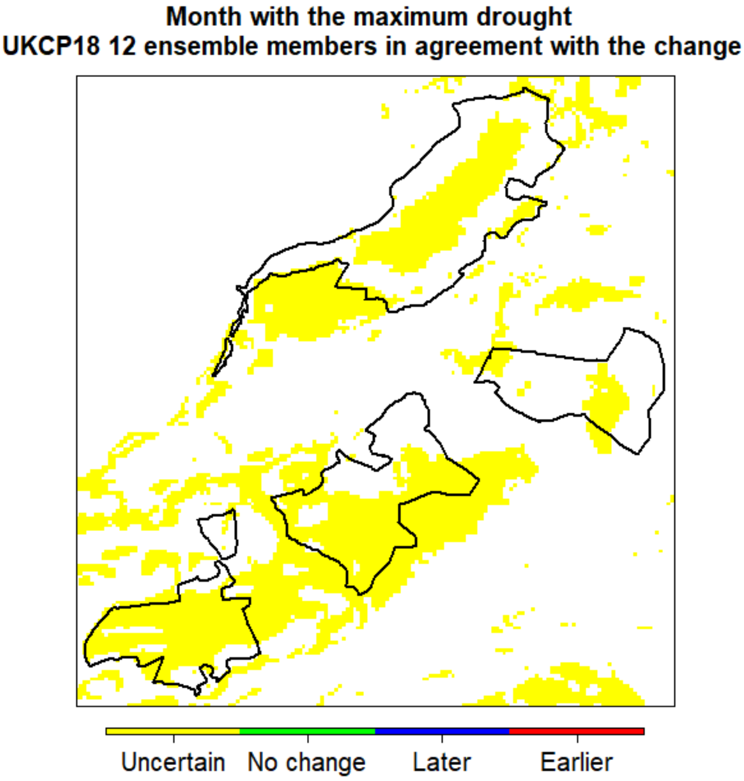


Figure 83. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum drought occurs at Lendalfoot Hills Complex (yellow = no agreement).

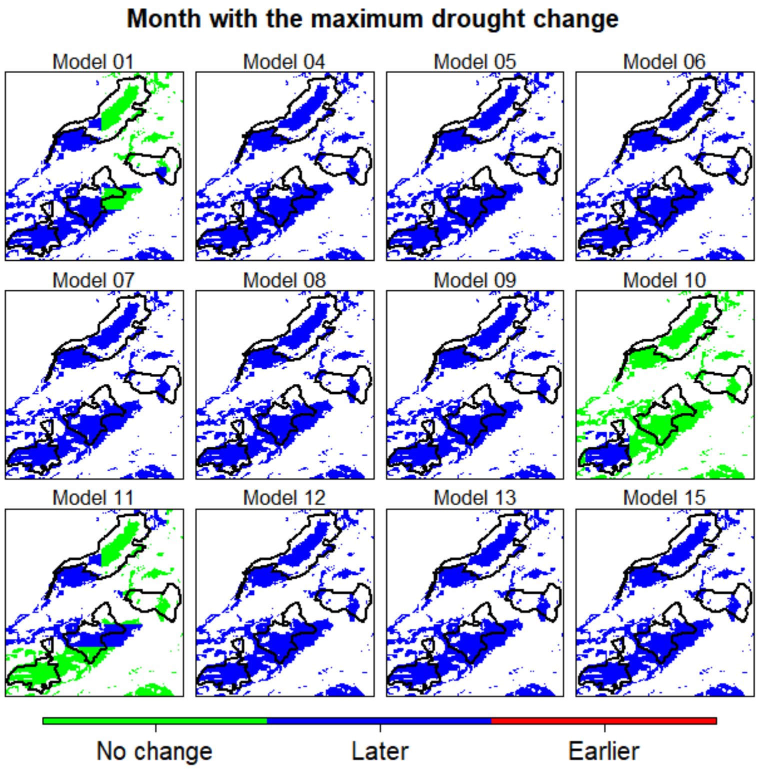


Figure 84. Variation between ensemble members in the month when the maximum drought occurs at Lendalfoot Hills Complex (blue = later).

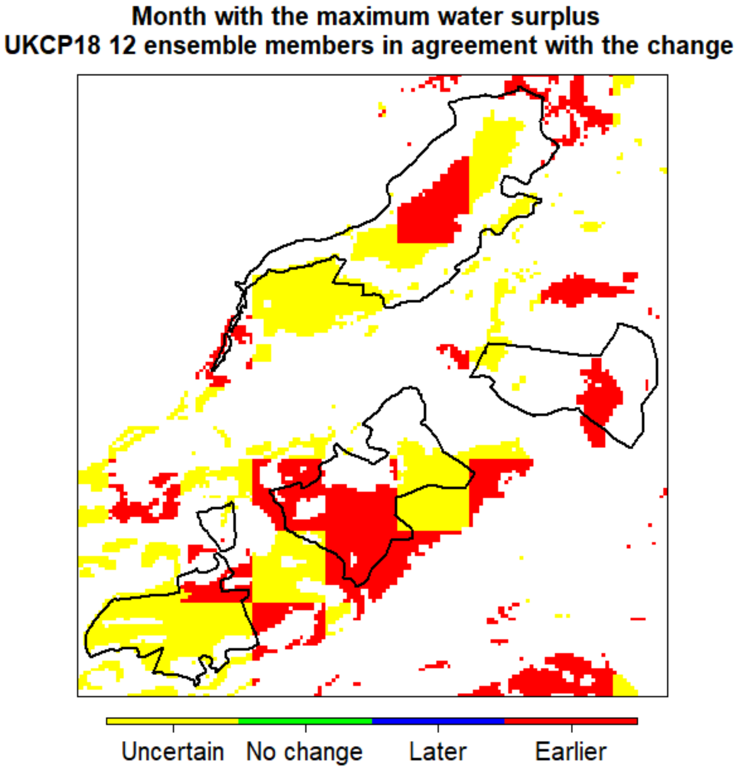


Figure 85. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum water surplus occurs at Lendalfoot Hills Complex (red = earlier).

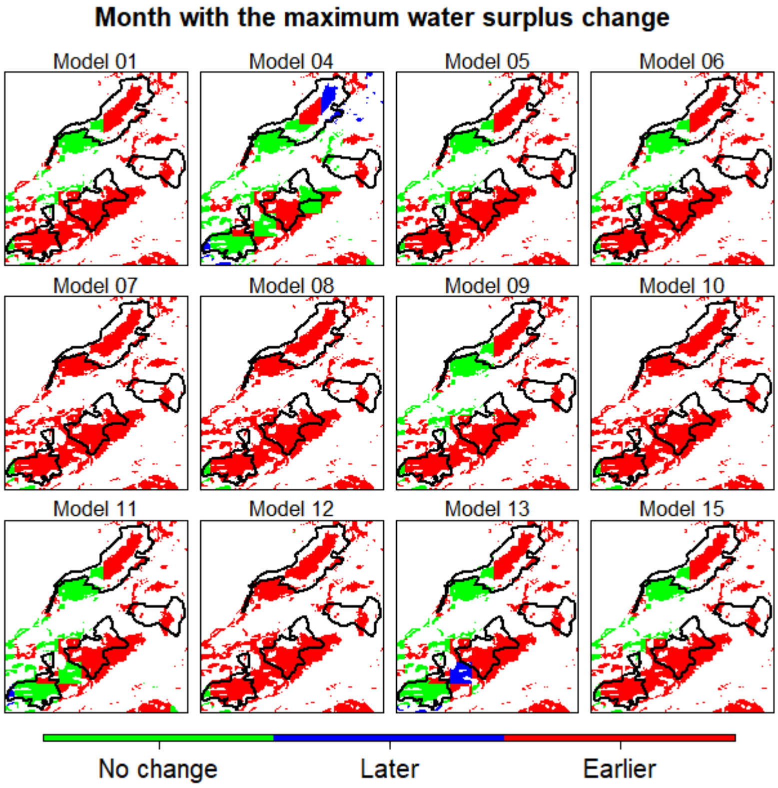


Figure 86. Variation between ensemble members in the month when the maximum water surplus occurs at Lendalfoot Hills Complex (blue = later, red = earlier, green = no change).

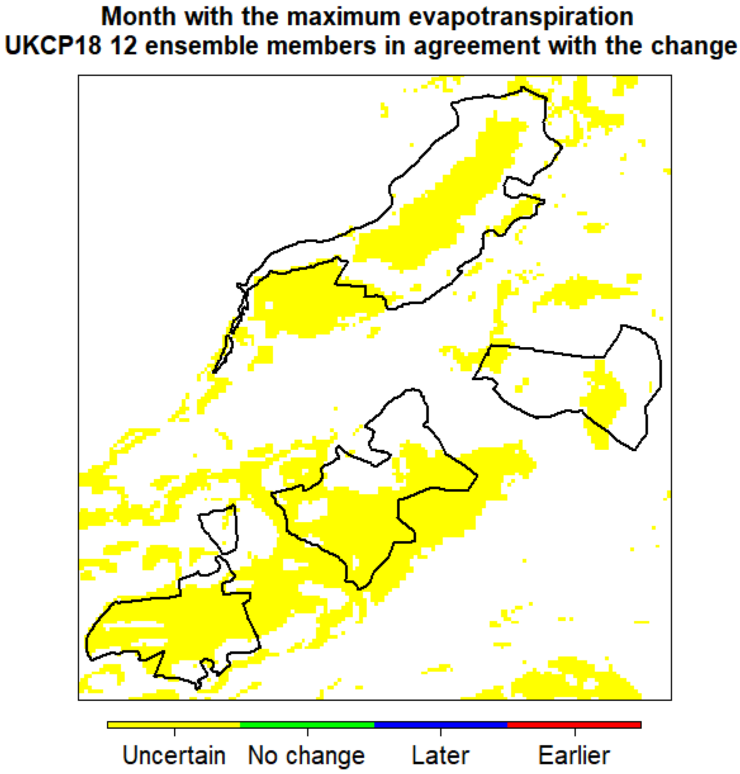


Figure 87. UKCP18 ensemble members in agreement with the sign of their change in the month when the maximum evapotranspiration occurs at Lendalfoot Hills Complex (yellow = no agreement).

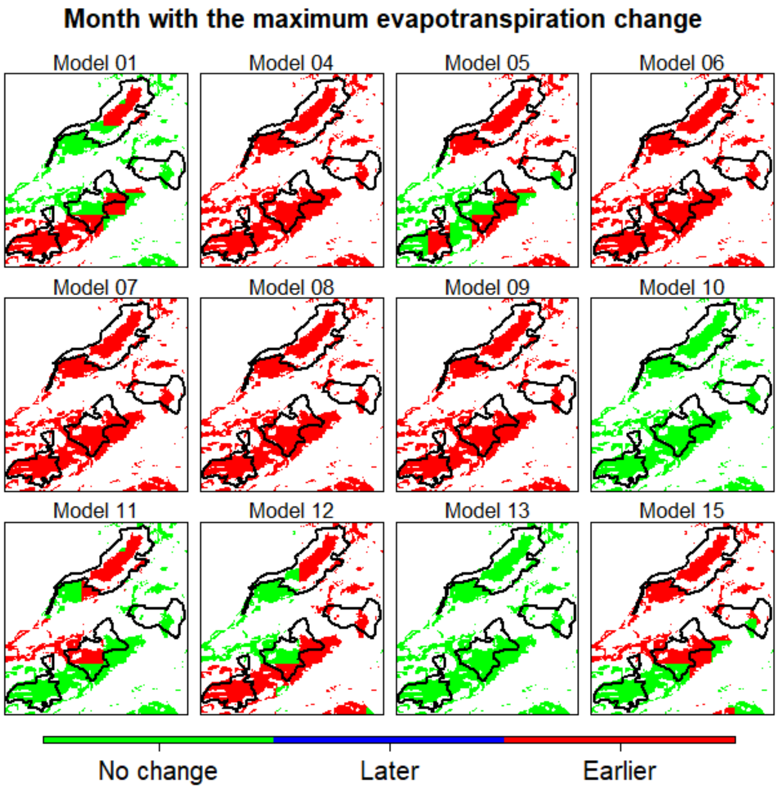


Figure 88. Variation between ensemble members in the month when the maximum evapotranspiration occurs at Lendalfoot Hills Complex (red = earlier, green = no change).

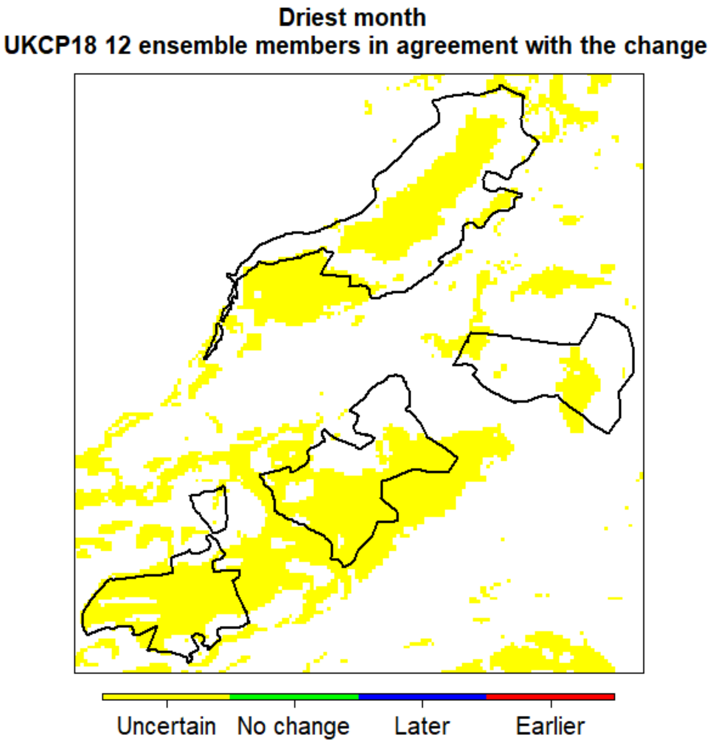


Figure 89. UKCP18 ensemble members in agreement with the sign of their change in the driest month at Lendalfoot Hills Complex (yellow = no agreement).

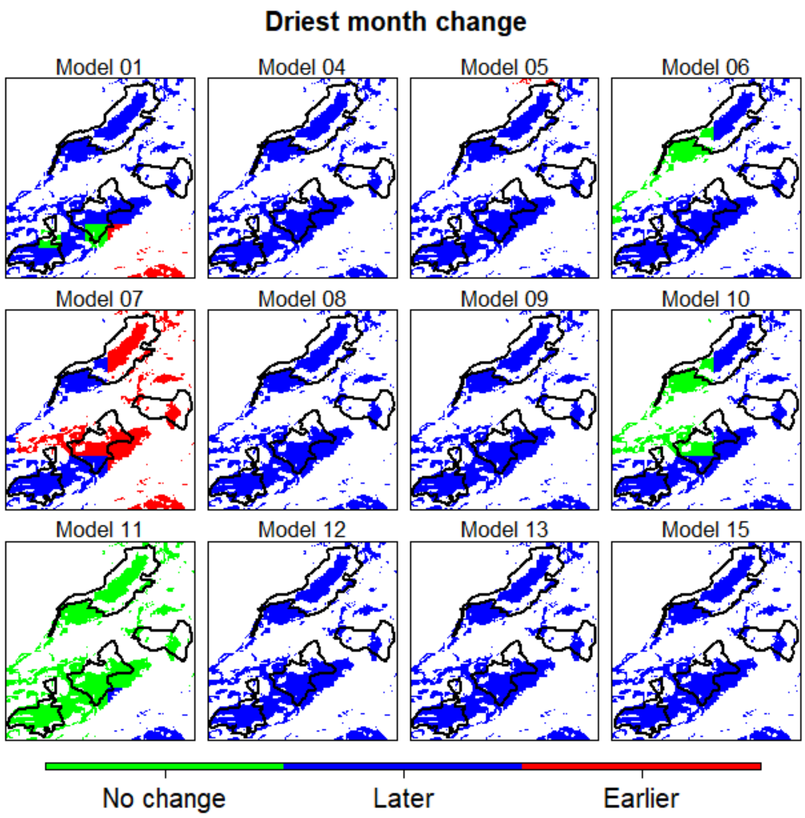


Figure 90. Variation between ensemble members in the driest month at Lendalfoot Hills Complex (red = earlier, blue = later).

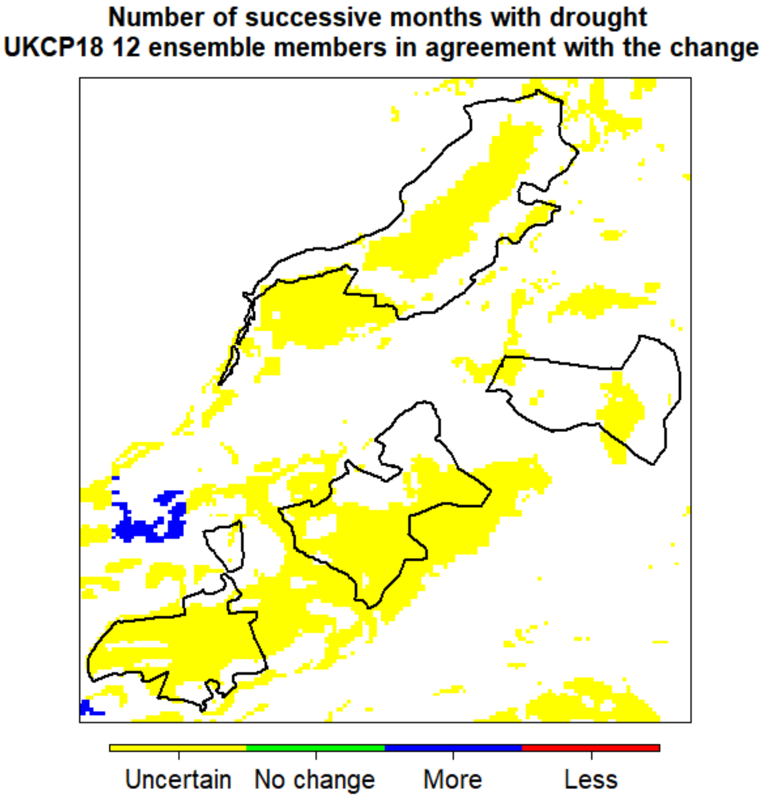


Figure 91. UKCP18 ensemble members in agreement with the sign of their change in the number of successive dry months at Lendalfoot Hills Complex (blue = more).

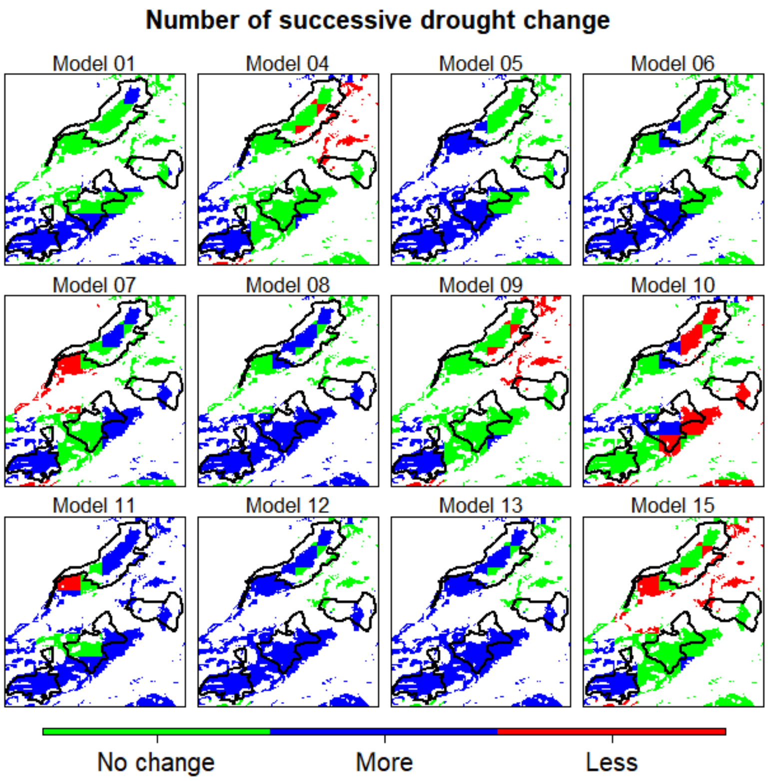


Figure 92. Variation between ensemble members in the number of successive dry months at Lendalfoot Hills Complex (red = less, blue = more).

Appendix B: Agrometeorological Indicators

The following are a set of agrometeorological indicators estimated using spatially interpolated observed weather data (1961-2018) and the same bias corrected UKCP18 climate projections (1km resolution) for RCP8.5 (high emissions pathway) used in the wetlands climate change impacts assessment. It is worth noting that in terms of estimated global temperature rises, there is little difference between the IPCC emissions scenarios up to c. 2050.

Four time periods are shown: 1961-1990, 1991-2018, 2019-2050 and 2051-280. The two historical periods show observed change, whilst the two future periods indicate projected changes. The maps for the future periods shown are generated using the mean of the 12 climate model ensembles. As such they indicate a general change in condition but do not reflect changes in inter-annual variability or extreme events.

Full details of these indicators are available in Matthews et al. (2008) and Rivington et al. (2013).

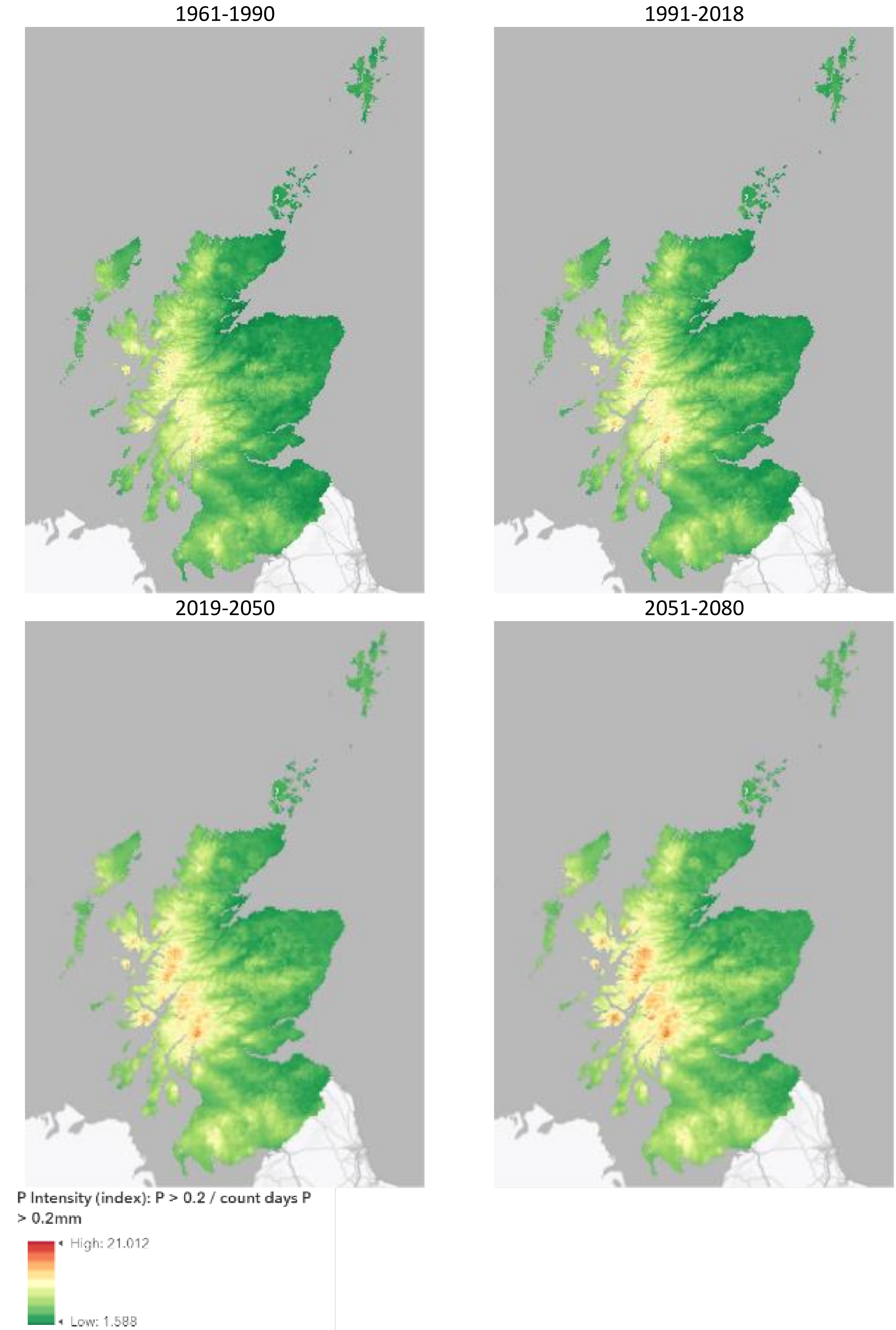


Figure 93. Precipitation (P) Intensity Indicator.

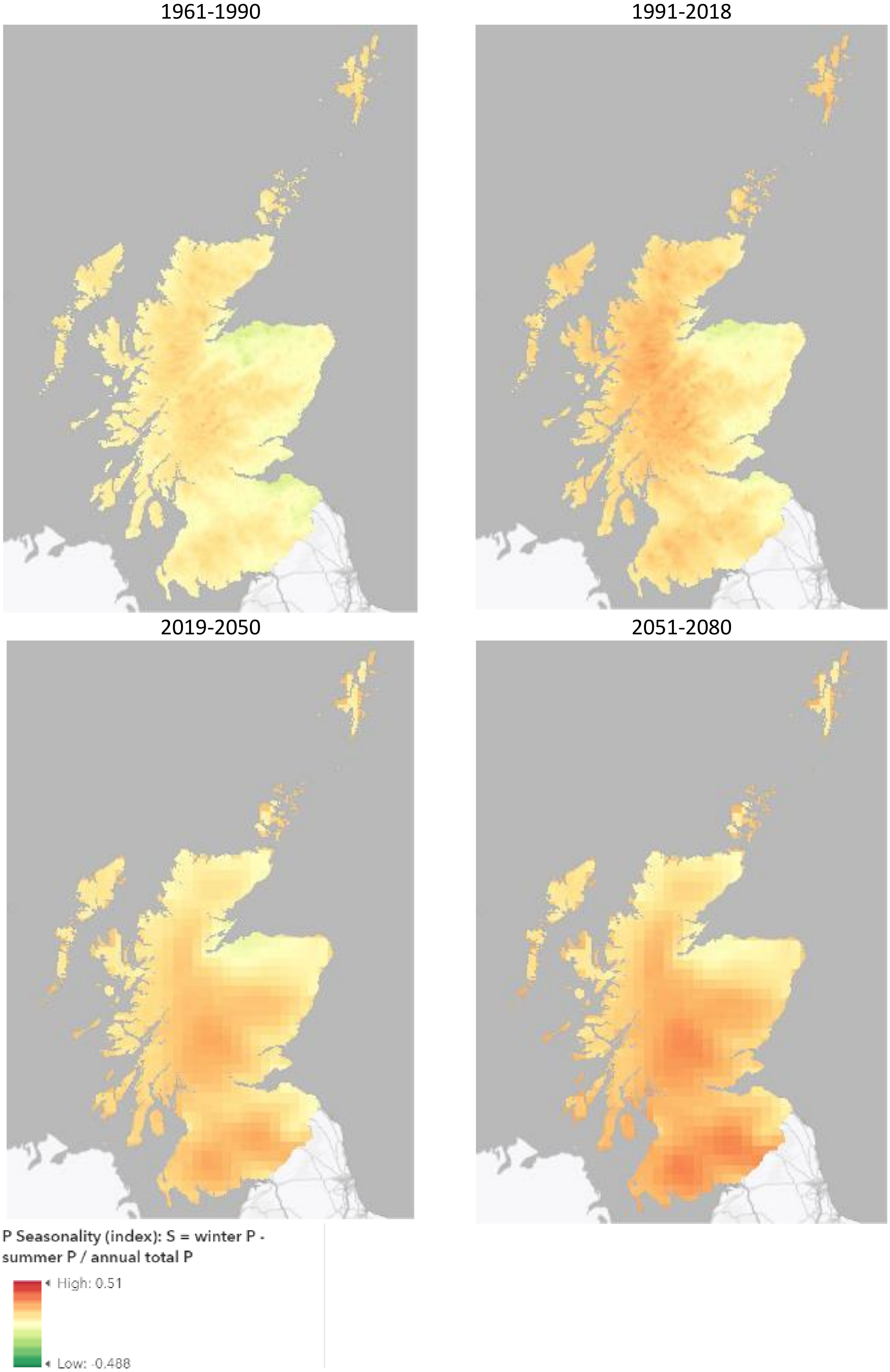


Figure 94. Precipitation (P) Seasonality Indicator.

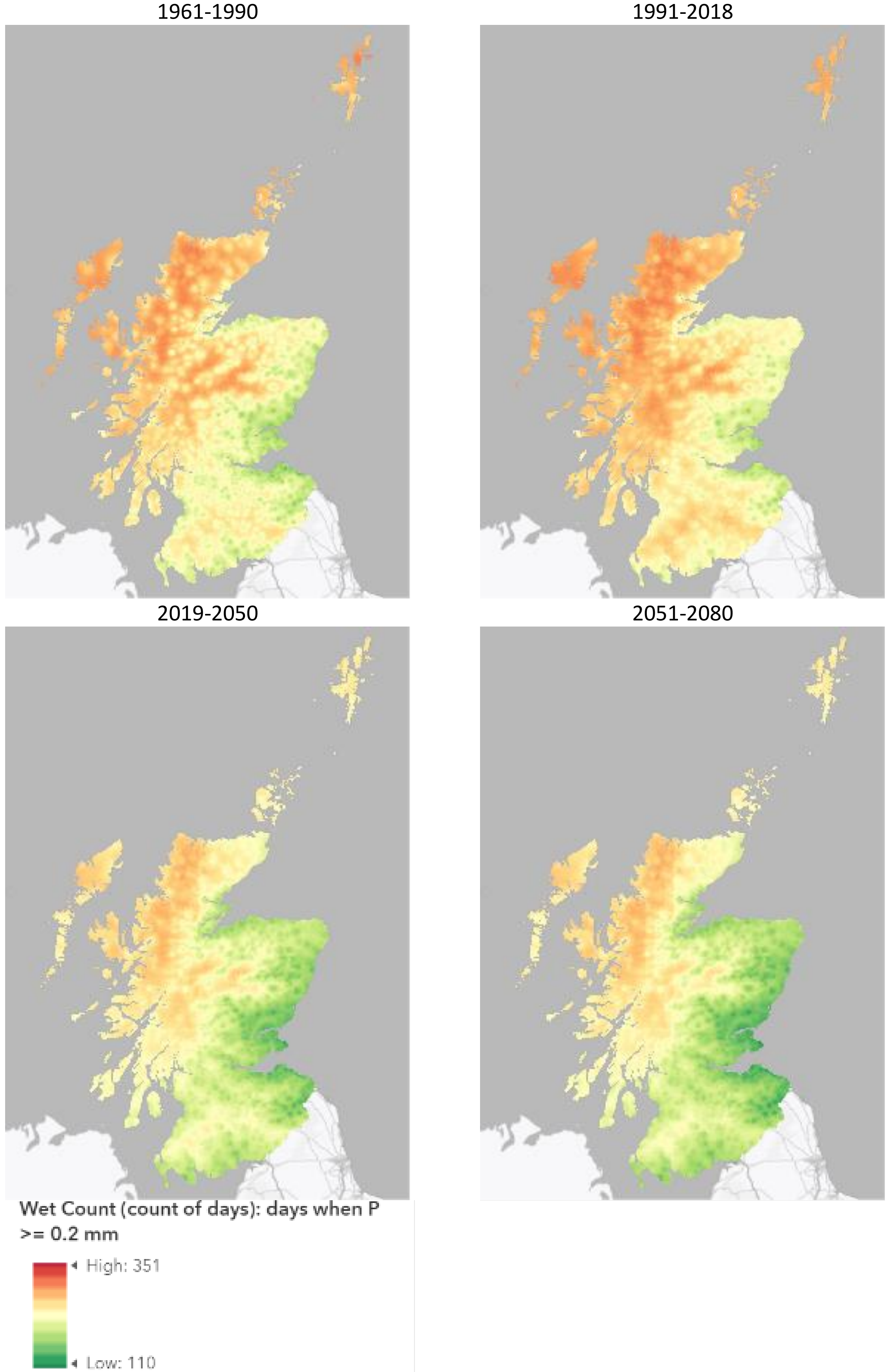


Figure 95. Count of Wet Days.

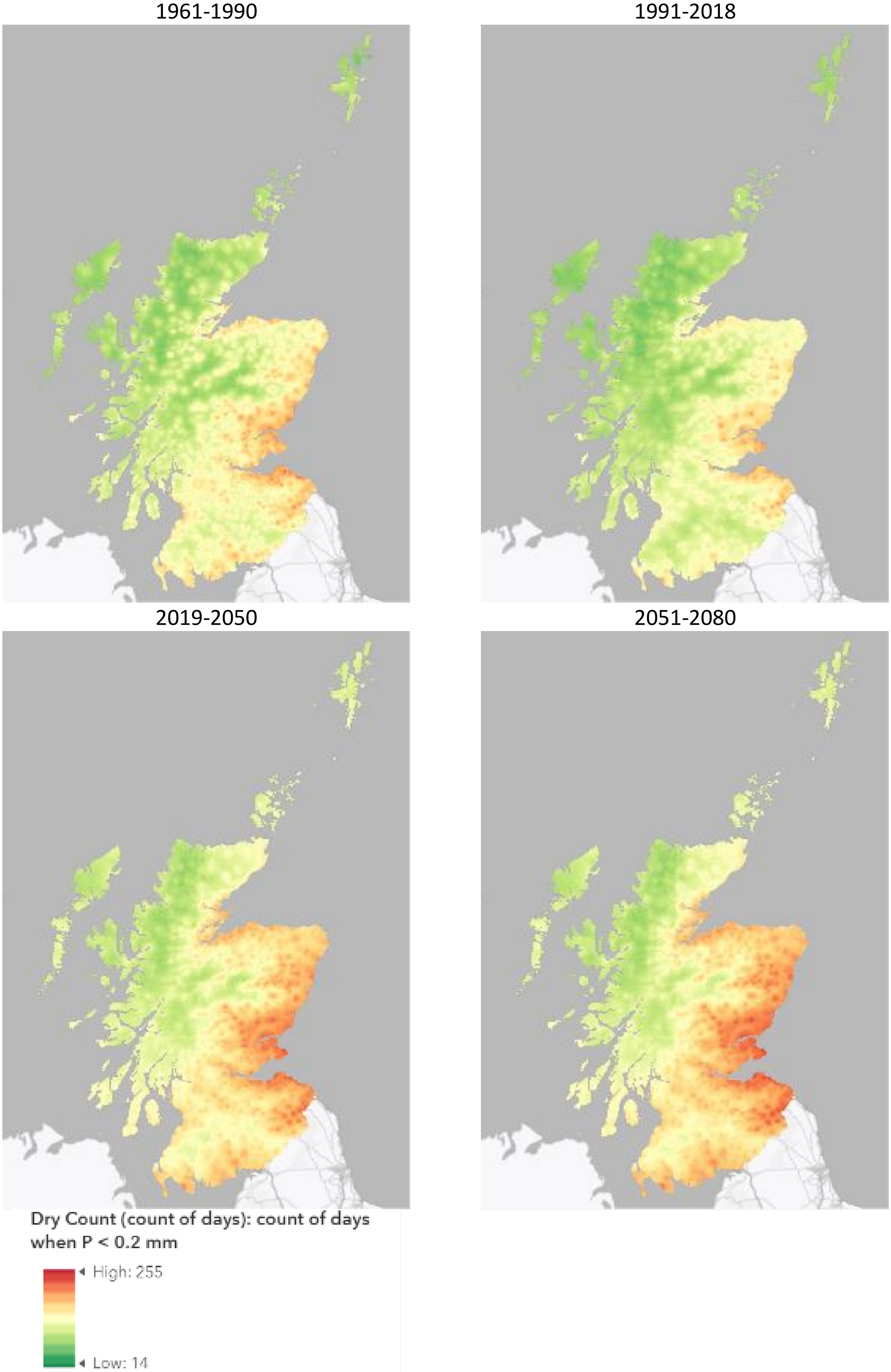


Figure 95. Count of Dry Days Indicator.

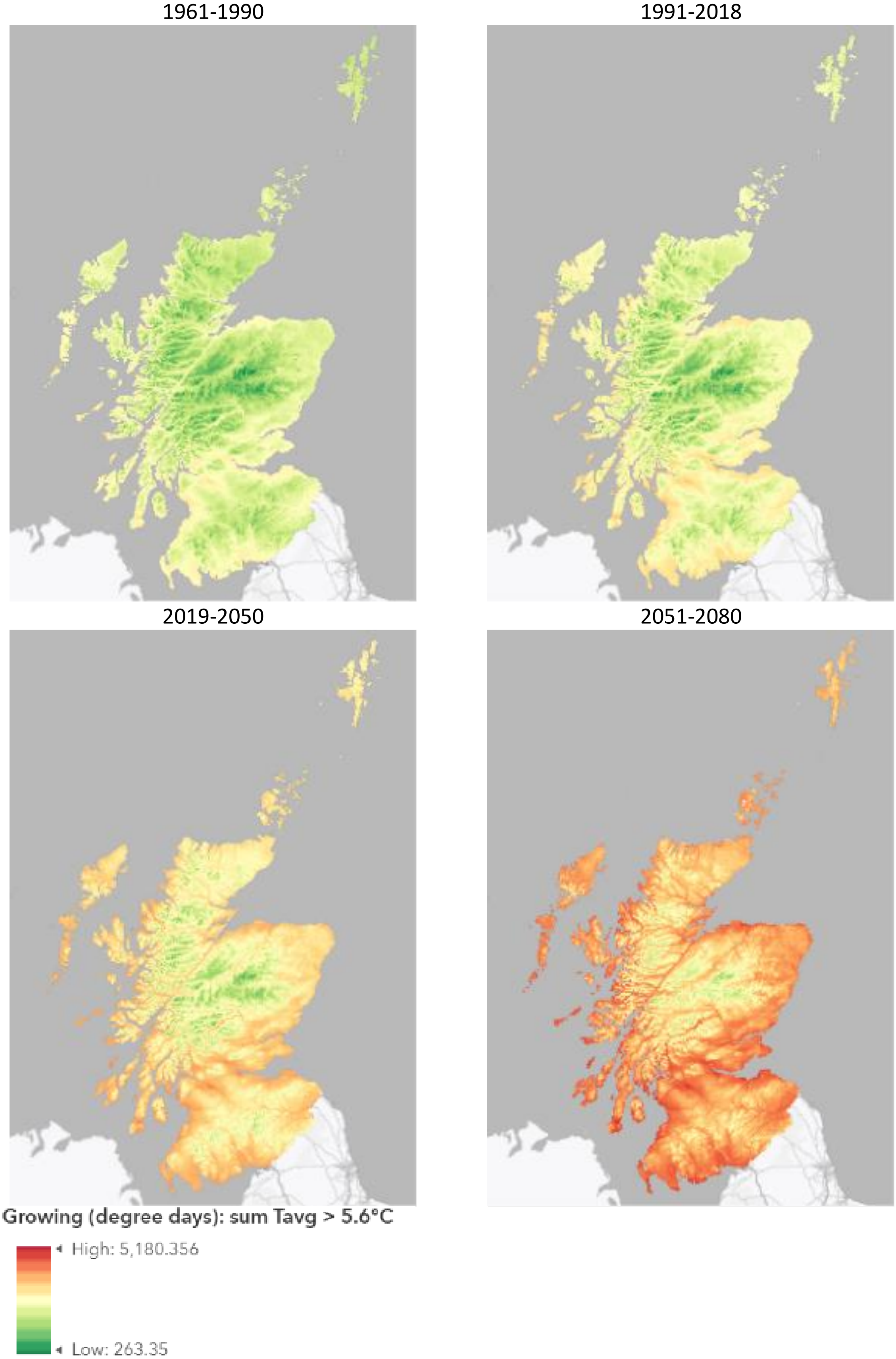


Figure 96. Thermal Time Accumulation Indicator (Growing Degree Days).

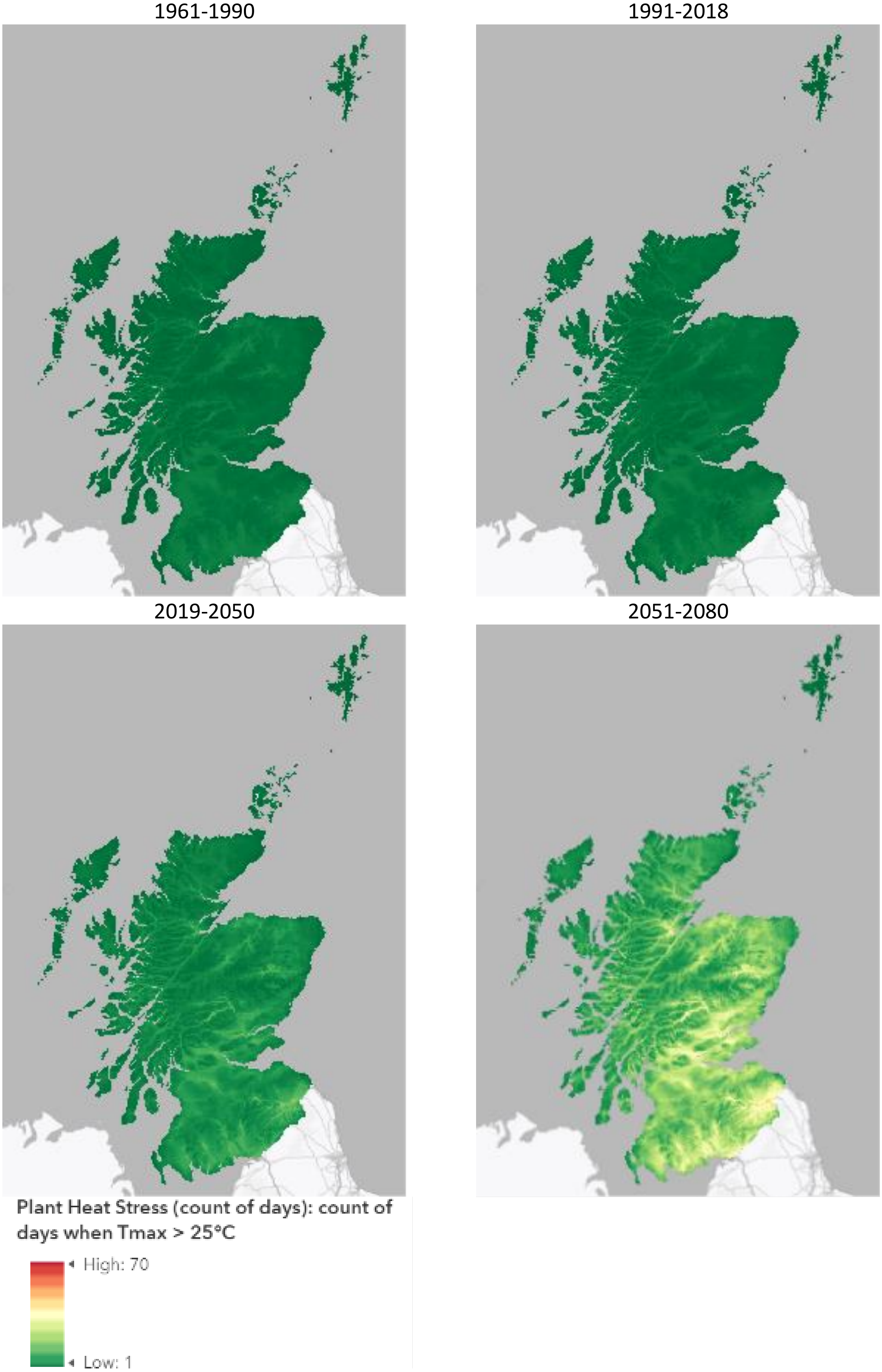


Figure 97. Plant Heat Stress.

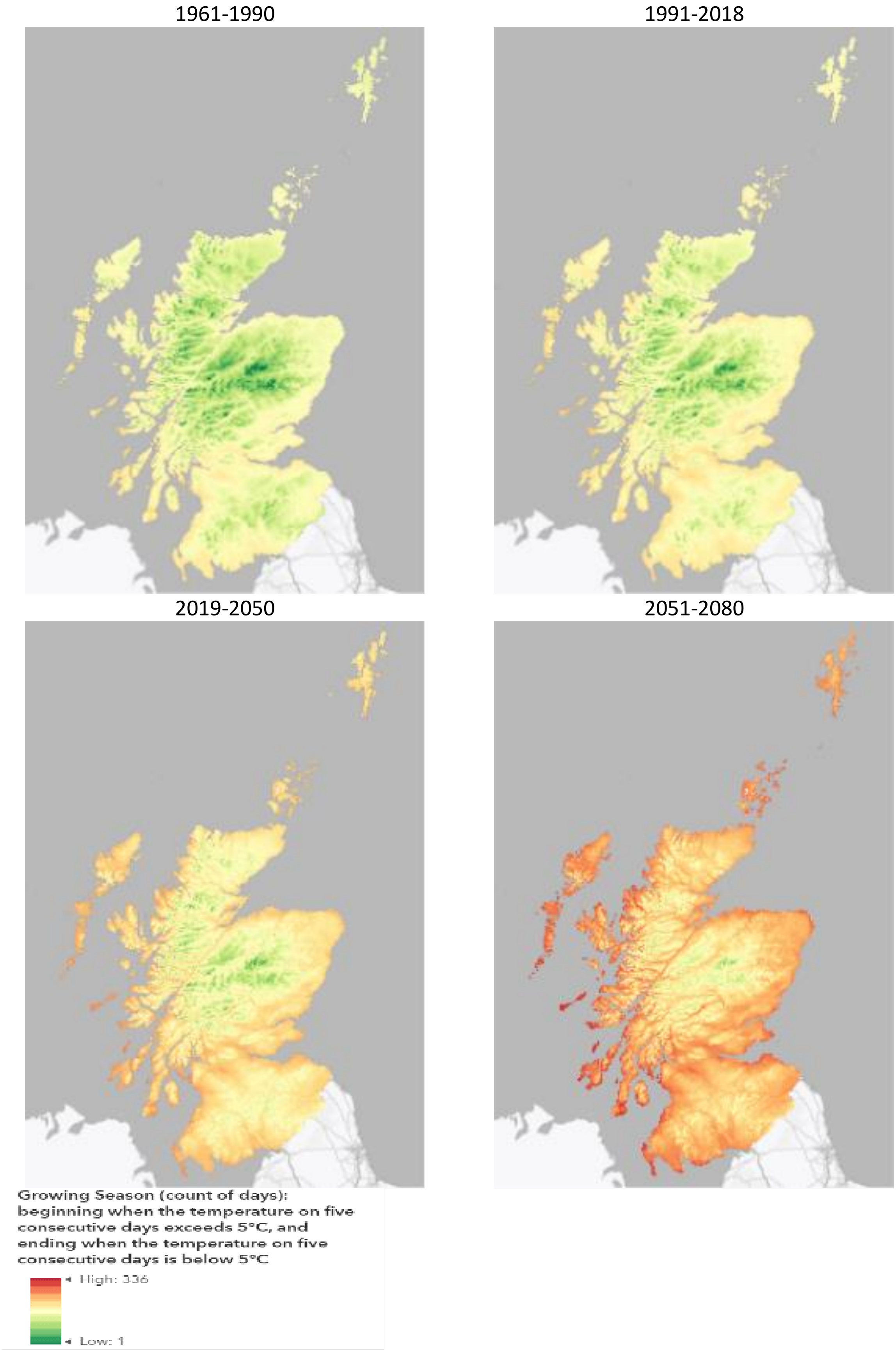
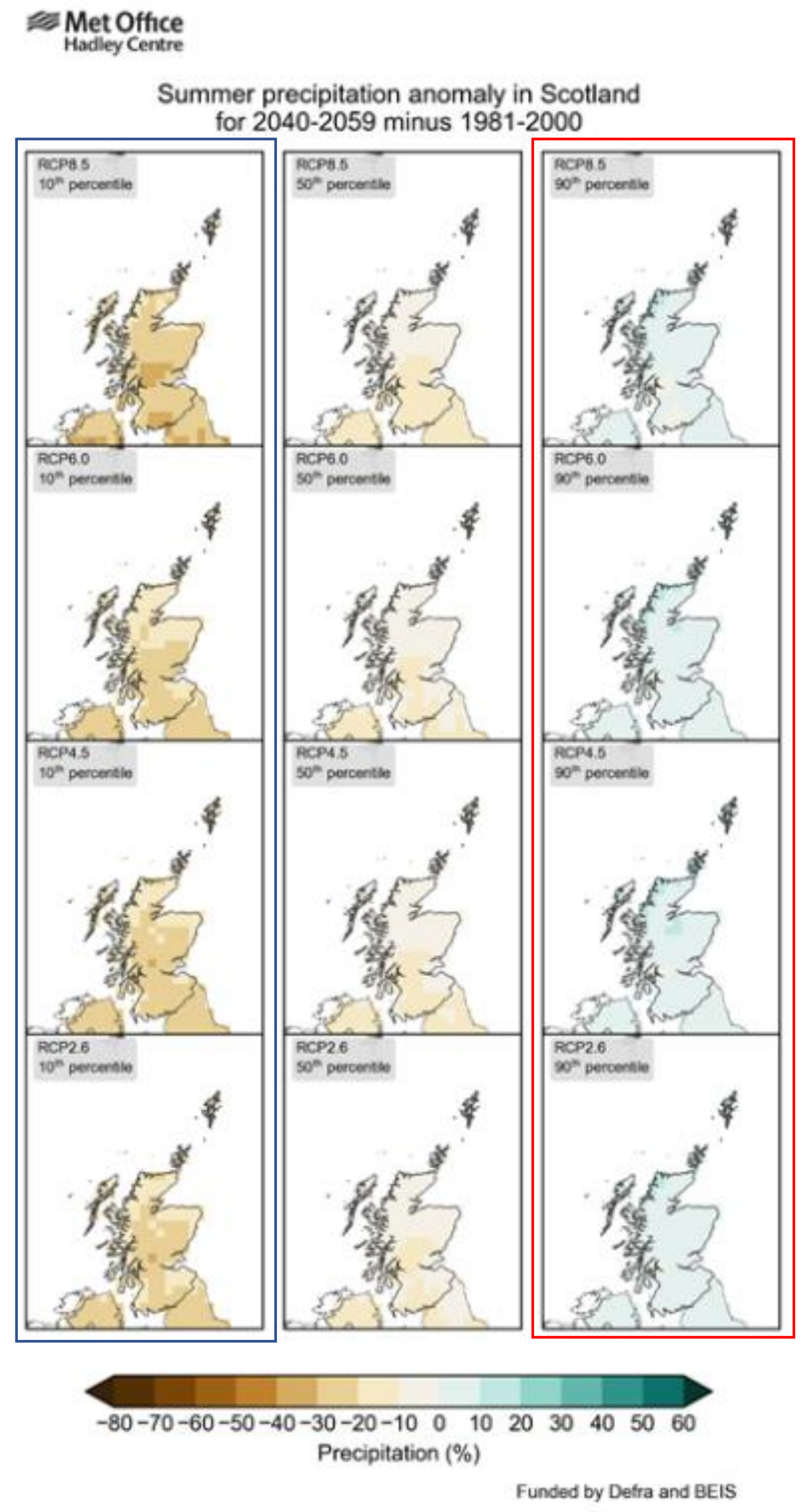


Figure 98. Growing Season Indicator.

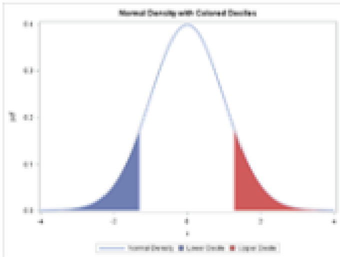
Appendix C: Probabilistic Climate Projections

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

The UKCP18 uses probability projections rather than absolute predictions. Figure 116 illustrates the range of possible summer precipitation for three points on a probability distribution (see inset figure). These three points are the low levels of probability (10^{th} percentile, blue part of the inset figure representing likelihood of precipitation lower than the observed period, and the 90^{th} percentile, red, representing the likelihood of increased precipitation), and the mid-range (50^{th} percentile, white part). The way to interpret this information is that the greater probability is the 50^{th} percentile mid-range amount, whilst the other two are possible but less likely.



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



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

Figure 99. Scottish summer precipitation anomaly (%) for 2040-2059 minus 1981-2000 for RCP8.5, 6.0, 4.5 and 2.6 for the 10th, 50th and 90th percentiles (probability levels).

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

7. Appendix VII: Biodiversity Impacts

by Robin Pakeman

0.1 Research questions

The key research question that this appendix sought to answer was:

- *What is the nature of wetland biodiversity that might be impacted by extremes of water availability?*

0.2 Objective

Review the impacts on key aspects of biodiversity intrinsic to wetlands, migratory communities and areas downstream of both flooding and water scarcity (high and low flows, respectively).

This work builds on Appendix I which explored the potential change trajectories and causes of change for the habitat attributes of different wetland types.

1. Introduction to the approach

The occurrence of a species at a site indicates that conditions are at least adequate, and that the environment of that site falls within the niche of the species. However, without detailed information about both the site and the ecology of the species, we are unable to predict if the species might be positively or negatively affected by a change in conditions as we do not know where that site sits within that species' niche as we lack both detailed information on individual species' niches and detailed recording or wetland environmental conditions.

One potential way to assess how a change in the hydrological regime affects individual species or groups of species is to model their hydrological niches, so that predictions can be made for those species given just information on changes in the environment. Such hydrological niches have been calculated for wet grassland species (Silvertown et al., 1999) and have been used to make predictions as to the impacts of climate change (Thompson et al., 2009) and of water level management (Swetnam, et al. 1998). These approaches mainly focus on plant species, but also cover the potential impacts on birds (Thompson et al., 2009). However, what all these approaches share, is that they are tied to making predictions based on site-specific information which is not generally available.

Ellenberg indicator values

An alternative to such a detailed programme is to compare existing data on species and their attributes, traits or environmental preferences. In effect, this simplifies the hydrological niche approach outlined in the previous paragraph. This combination exists for vascular plants and bryophytes as a range of quadrat data exists for different communities and these groups have been characterised in terms of their environmental preferences through the use of indicator values, specifically Ellenberg Indicator Values (Ellenberg, 1988, Hill et al., 2004, Hill et al., 2007).

As yet, this approach is not possible with other groups of species.

Ellenberg (1988) sets out indicator values for light (L), temperature (T), continentality (K), water (F), reaction (R), nitrogen (N) and salt (S).

Water indicator values run on a scale of 1 to 12:

1. Indicators of extreme dryness, often restricted to places that dry out completely

2. Between 1 and 3
3. Dry site indicators, more often found on dry ground than moist places, not found on damp soil
4. Between 3 and 5
5. Moist-site indicators, mainly on soils of average dampness, absent from both wet ground and places which may dry out
6. Between 5 and 7
7. Damp-site indicators, mainly on constantly damp, but not wet, soils
8. Between 7 and 9
9. Wet-site indicators, often in water-saturated, badly aerated soils
10. Indicators of sites occasionally flooded but free from surface water for long periods
11. Plants rooting under water but at least for a time exposed above or floating on the surface
12. Submerged plants, permanently or almost constantly under water.

Linking Ellenberg indicator values for water (EIV-F) to risk from low and high flows

These Ellenberg indicator values can then be linked to a species list for a habitat and used to identify species with outlying hydrological preferences compared to the mean preference. So, *if species X had a much lower Ellenberg indicator value for water (EIV-F) than the sample's average it can be assumed that this species would be at risk of a reduction in abundance or loss if there was a reduction in the depth to the water table or increased flooding. Similarly, if species Y has a much higher EIV-F than average it is clearly more at risk from drought than the average species from that sample.*

A site-specific approach to assessing the impacts of hydrological change could be taken, but this would require detailed vegetation data. Instead, a generic approach using the community descriptions in the National Vegetation Classification was taken (NVC, Rodwell, 1991a, 1991b, 1992, 1995, 2000). The NVC is a comprehensive attempt to identify and describe vegetation communities across Great Britain and contains information about which vascular plant, bryophyte and lichen species are found in each community. The community descriptions were downloaded from the JNCC website (https://hub.jncc.gov.uk/assets/a407ebfc-2859-49cf-9710-1bde9c8e28c7#NVC-floristic-tables.xls). Approximate cover values for each species were calculated by converting the constancy and Domin scores using the transformation approach of Currall (1987), which provides a more realistic value than the midpoint, as values are more likely to lie below the midpoint in any range, and then multiplying the two. The community-weighted mean EIV-F score was then calculated for each wetland community and species identified if they differed by ± 1 (moderate risk) or ± 2 units (severe risk) from the mean (Table 1). As values for species are whole numbers, then these are minimum differences.

The calculation of community-weighted mean EIV-F scores means that the species identified by this approach, are by definition, not the community constants or dominant species, as the calculated weighted means would fall near to the EIV-F values for these abundant species. Hence the species identified are likely to be less frequent and/or subordinate species in each community. Species listed on the Scottish Biodiversity List, as either "Conservation action needed" or "Avoid negative impacts", or listed in the NVC as rare species were identified for each community where they contributed to the species highlighted as at risk of hydrological changes in the above analysis. It should be noted that the NVC is based on sample data and, hence, rare species are not usually listed in the associated tables for each community. As a consequence, this analysis will pick out relatively few species.

Also, the approach is identifying species at risk, and does not assess the likely ecological impacts of change, for instance the shift in dominance from *Sphagnum* species to sedges in a drying bog surface and the resultant impacts on ecosystem function. We lack the necessary information on most wetland communities to attempt to this sort of detailed assessment of the impacts of changed hydrological regimes.

What this approach does not cover

Without detailed hydrological data for sites or comprehensive information on ecological preferences for many species groups, including migratory species, it is not possible to extend this analysis beyond the vascular plants and bryophytes covered below. Most of the information available for individual species is very coarse-grained, i.e., they are wetland specialist, but this cannot be used to say what might happen under different scenarios unless there is a complete loss of wetland habitats.

2. Potential Impacts

Table 1 shows the proportion of species in each National Vegetation Classification (NVC) community at risk of either increased wetness or dryness. Given that the calculation of the mean indicator value for each community is weighted, then the highlighted species are not the community dominants, as these will have Ellenberg F scores close to the mean.

Across the many wetland communities described in the NVC it appears that many mires (M) and swamps (S) harbour species that are at risk of increased wetness as their habitat preferences are for conditions much drier than the average species in that community (Table 1). It is likely that these species are found in drier microsites within these communities. There are exceptions to this, as the M4 *Carex rostrata-Sphagnum recurvum* mire, M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire, M10 *Carex dioica-Pinguicula vulgaris* mire all have more species at risk if the habitat dries out.

The mesotrophic grasslands are more varied in the patterns of their data. More species are at risk from increased dryness in MG9 *Holcus lanatus-Deschampsia cespitosa*, MG11 *Festuca rubra-Agrostis stolonifera-Potentilla anserina* and MG13 *Agrostis stolonifera-Alopecurus geniculatus* grasslands, whilst there is a more even balance in species at risk of increased wetness and dryness in the other communities. This risk to increased dryness suggests many species are restricted to damper microsites than average in these wet grasslands.

More species are at risk of increased wetness in W3 *Salix pentandra-Carex rostrata* and *W4 Betula pubescens-Molinia caerulea* woodland, whilst more species are at risk of increased dryness in W6 *Alnus glutinosa-Urtica dioica, W7 Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* and W18 *Pinus sylvestris-Hylocomium splendens* woodland.

Mosaics

Many wetland habitats exist as mosaics of different communities and many species are found across different communities. As such, hydrological change at a site may result in a species decreasing in one community whilst increasing in another. It will be the outliers across the whole system that will be most at risk, i.e., the species of dry habitats in the driest community will be most at risk of increased flooding or a rise in the water table, whilst it is the species of wet habitats in the wettest community that will be most at risk of reduced water availability. The mosaic nature of many wetlands will help buffer them from species loss to a certain extent when confronted by hydrological change.

Table 1. The percentage of species listed in the floristic table for each main community in the National Vegetation Classification at severe (± 2 EIV-F, Ellenberg F indicator value units) or moderate (± 1 EIV-F) risk from an increase in site wetness or dryness. The occurrence of NVC communities across the different wetland types is shown in Table 1 and Table 10 Appendix V.

National Vegetation Community (no. of species in community)	Percentage of species at risk of increased wetness		Percentage of species at risk of increased dryness	
	Severe *± 2 EIV-F*	Moderate *± 1 EIV-F*	Moderate *± 1 EIV-F*	Severe *± 2 EIV-F*
Mires				
M1 *Sphagnum auriculatum* bog pool community (27)	3.7	29.6	0.0	3.7
M2 *Sphagnum cuspidatum/recurvum* bog pool community (31)	6.5	9.7	12.9	0.0
M3 *Eriophorum angustifolium* bog pool community (12)	25.0	50.0	0.0	0.0
M4 *Carex rostrata-Sphagnum recurvum* mire (46)	15.2	10.9	21.7	0.0
M5 *Carex rostrata-Sphagnum squarrosum* mire (47)	10.6	10.6	10.6	0.0
M6 *Carex echinata-Sphagnum recurvum/auriculatum* mire (50)	10.0	10.0	26.0	6.0
M7 *Carex curta-Sphagnum russowii* mire (54)	31.5	13.0	9.3	0.0
M8 *Carex rostrata-Sphagnum warnstorfii* mire (103)	30.1	13.6	4.9	0.0
M9 *Carex rostrata-Calliergon cuspidatum/giganteum* mire (86)	19.8	32.6	0.0	0.0
M10 *Carex dioica-Pinguicula vulgaris* mire (87)	12.6	11.5	29.9	2.3
M11 *Carex demissa-Saxifraga aizoides* mire (72)	33.3	15.3	5.6	0.0
M12 *Carex saxatilis* mire (83)	33.7	14.5	2.4	0.0
M15 *Scirpus cespitosus-Erica tetralix* wet heath (84)	19.0	20.2	13.1	3.6
M16 *Erica tetralix-Sphagnum compactum* wet heath (66)	12.1	19.7	13.6	1.5
M17 *Scirpus cespitosus-Eriophorum vaginatum* blanket mire (67)	19.4	17.9	14.9	1.5
M18 *Erica tetralix-Sphagnum papillosum* raised and blanket mire (45)	17.8	11.1	24.4	4.4
M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire (66)	3.0	22.7	22.7	9.1
M20 *Eriophorum vaginatum* blanket and raised mire (29)	34.5	20.7	6.9	0.0
M22 *Juncus subnodulosus-Cirsium palustre* fen-meadow (110)	13.6	12.7	20.0	9.1
M23 *Juncus effusus/acutiflorus-Galium palustre* rush-pasture (74)	13.5	16.2	18.9	5.4
M25 *Molinia caerulea-Potentilla erecta* mire (79)	15.5	19.0	17.9	2.4
M26 *Molinia caerulea-Crepis paludosa* mire (60)	16.5	17.7	13.9	3.8
M29 *Hypericum elodes-Potamogeton polygonifolius* soakway (54)	16.7	27.8	1.9	1.9
Mesotrophic grasslands				
MG8 *Cynosurus cristatus-Caltha palustris* grassland (64)	7.8	28.1	17.2	12.5

MG9 *Holcus lanatus-Deschampsia cespitosa* grassland (73)	0.0	11.0	13.7	17.8
MG10 *Holcus lanatus-Juncus effusus* rush-pasture (50)	0.0	28.0	18.0	16.0
MG11 *Festuca rubra-Agrostis stolonifera-Potentilla anserina* grassland (50)	2.0	8.0	12.0	8.0
MG12 *Festuca arundinacea* grassland (44)	4.5	27.3	13.6	13.6
MG13 *Agrostis stolonifera-Alopecurus geniculatus* grassland (37)	5.4	10.8	16.2	21.6
Other vegetation				
OV28 *Agrostis stolonifera-Ranunculus repens* community (26)	3.8	42.3	7.7	11.5
Swamps				
S3 *Carex paniculata* swamp (33)	18.2	3.0	15.2	3.0
S4 *Phragmites australis* swamp and reed-beds (23)	8.7	30.4	4.3	0.0
S5 *Glyceria maxima* swamp (41)	29.3	26.8	4.9	0.0
S9 *Carex rostrata* swamp (26)	7.7	26.9	7.7	3.8
S10 *Equisetum fluviatile* swamp (15)	0.0	26.7	6.7	0.0
S11 *Carex vesicaria* swamp (28)	21.4	25.0	0.0	0.0
S12 *Typha latifolia* swamp (43)	16.3	20.9	4.7	2.3
S14 *Sparganium erectum* swamp (45)	17.8	20.0	15.6	4.4
S19 *Eleocharis palustris* swamp (41)	34.1	12.2	2.4	9.8
S26 *Phragmites australis-Urtica dioica* tall-herb fen (57)	33.3	8.8	12.3	0.0
S28 *Phalaris arundinacea* tall-herb fen (26)	30.8	7.7	15.4	0.0
Woodland				
W1 *Salix cinerea-Galium palustre* woodland (61)	14.8	13.1	21.3	9.8
W3 *Salix pentandra-Carex rostrata* woodland (101)	22.8	14.9	8.9	1.0
W4 *Betula pubescens-Molinia caerulea* woodland (91)	22.0	25.3	12.1	4.4
W6 *Alnus glutinosa-Urtica dioica* woodland (81)	0.0	19.8	17.3	14.8
W7 *Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum* woodland (117)	0.9	20.5	19.7	12.8
W18 *Pinus sylvestris-Hylocomium splendens* woodland (57)	0.0	1.8	14.0	7.0

Caveat

The above analysis takes no account of the conservation value of the individual species, and it is possible that risks at the community level are not the same risk if assessed in terms of rare species. From the above analysis species listed as rare in the National Vegetation Classification (Table 10 in Appendix V) and plant species in the Scottish Biodiversity List (in categories "Conservation action needed" and "Avoid negative impact") were extracted from the data. A number of rare species do not occur in the community descriptions of the NVC or have never been allocated Ellenberg indicator values, so there is a limit on how comprehensive this analysis is.

Impact on rare species

The analysis on rare species, in Table 2 below, shows a slight preponderance of species presences in habitats at risk of increased drying of habitats (11) compared to increased wetting (8). Interestingly, whilst *Pyrola rotundifolia* (round-leaved wintergreen) was at risk of increased wetness in M9 *Carex* *rostrata-Calliergon cuspidatum/giganteum* mire and W3 *Salix pentandra-Carex rostrata* woodland, *Pyrola rotundifolia* was also deemed at risk of increased dryness in W18 *Pinus sylvestris-Hylocomium splendens* woodland. In contrast, the sedge *Carex vaginata* (sheathed sedge) and the moss *Campylopus setifolius* (silky swan-neck moss) were consistent in terms of their risk across habitats, i.e., with *C. virginata* at risk of increased wetness and *C. setifolius* at risk of increased dryness.

Only two species on the Scottish Biodiversity List were identified in this analysis (Table 2). *Oenanthe fistulosa* (tubular water dropwort) was identified as at severe risk if MG13 *Agrostis stolonifera-Alopecurus geniculatus* grasslands dried out and *Anagallis arvensis* (scarlet pimpernel) was seen as at severe risk if the OV28 *Agrostis stolonifera-Ranunculus repens* community increased in wetness. *Oenanthe fistulosa* is also found in other communities, but without good information on its distribution amongst these communities, it is difficult to quantify the impact of its loss from this habitat. *Anagallis arvensis* is a species typical of dry disturbed habitats and arable fields, so its loss from OV28 communities would not seriously impact its conservation.

Table 2. Rare species identified in the National Vegetation Classification or plant species listed in the Scottish Biodiversity List at severe (± 2 EIV-F units) or moderate (± 1 EIV-F) risk from an increase in site wetness or dryness. The occurrence of NVC communities across the different wetland types is shown in Table 1 and Table 10 of Appendix V.

			Increased wetness		Increased dryness	
National Vegetation Community	Wetland type	Species Name	Severe	Moderate	Moderate	Severe
		NVC rare species				
M2 *Sphagnum cuspidatum/recurvum* bog pool community	Raised bog/Depressions on peat/Blanket bog	*Sphagnum pulchrum*			X	
M9 *Carex rostrata-Calliergon cuspidatum/giganteum* mire	Transition mires and quaking bogs	*Potamogeton coloratus*			X	
		Pyrola rotundifolia	X			
M10 *Carex dioica-Pinguicula vulgaris* mire	Fens: Base-rich fens, alkaline fens	*Minuartia verna*	X			
		Schoenus ferrugineus			X	
		Carex capillaris		X		
M11 *Carex demissa-Saxifraga aizoides* mire	Fens: Base-rich fens, alkaline fens	*Carex vaginata*	X			
M12 *Carex saxatilis* mire	Fens: Base-rich fens, alkaline fens	*Carex vaginata*	X			
M15 *Scirpus cespitosus-Erica tetralix* wet heath	Raised bog/Depressions on peat/Blanket bog/Wet heath	*Campylopus setifolius*			X	
M16 *Erica tetralix-Sphagnum compactum* wet heath	Raised bog/Depressions on peat/Blanket bog/Wet heath	*Rhynchospora fusca*			X	
M17 *Scirpus cespitosus-Eriophorum vaginatum* blanket mire	Raised bog/Depressions on peat/Blanket bog/Wet heath/Bog woodland	*Campylopus shawii*			X	
		Campylopus setifolius			X	

M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire	Raised bog/Depressions on peat/Blanket bog/Wet heath/Bog woodland	*Betula nana*			X	
S14 *Sparganium erectum* swamp	Reedbeds and swamps/Open water transition fens	*Wolffia arrhiza*			X	
W3 *Salix pentandra-Carex rostrata* woodland	Fen woodland, alder woodland, wet woodland	*Pyrola rotundifolia*		X		
		Corallorhiza trifida	X			
W18 *Pinus sylvestris-Hylocomium splendens* woodland	Bog woodland	*Pyrola rotundifolia*			X	
		Scottish Biodiversity List				
MG13 *Agrostis stolonifera-Alopecurus geniculatus* grassland	Wet meadows, marshy grassland, Fen meadow	*Oenanthe fistulosa*				X
OV28 *Agrostis stolonifera-Ranunculus repens* community	Wet meadows, marshy grassland, Fen meadow	*Anagallis arvensis*	X			

A Way Forward

The ability to predict the consequences of environmental change on biodiversity is intrinsically difficult. It is harder still when that environmental change acts at a range of scales, with hydrological conditions being influenced by regional rainfall patterns interacting with site characteristics.

To make effective predictions at a site level one needs information of species preferences and hydrological preferences. This has been done (e.g., Swetnam et al., 1998, Thompson et al., 2009) but it is necessary to properly monitor the hydrological regime and model species distribution along hydrological gradients to achieve this. This approach would be resource intensive if multiple sites were to be assessed, with a need for hydrological monitoring and the development of appropriate species distribution models that take into account other parameters such as nutrient supply and successional age. This would be the only way forward where proxies for habitat requirements do not exist, in other words, for all species groups other than vascular plants and bryophytes.

The method using indicators as employed here can be employed at a site level using sample information from the habitats present at a site. It could then be used to risk assess which species might be threatened by a change in hydrological regime. Scaling-up to a regional or national level could be achieved if enough vegetation samples were available from a cross-section of sites. However, these indicators only exist for vascular plants and bryophytes, so at present we cannot say what the impacts are likely to be on other species groups. Extending it to other taxa would be possible if detailed habitat associations became available or where there were specific species requirements for specific plant species, i.e., butterflies and moths with a narrow caterpillar feeding range.

3. Conclusions

The above analysis clearly shows that the risks to the diversity of wetland communities due to increased or decreased water availability is dependent on the identity of the community.

Many communities harbour species at increased risk of loss if there is an increase in wetness, including many mires and swamps. However, there are clear exceptions to this with some mires having higher numbers of species at risk if there is more drying out of these communities.

These impacts will likely be buffered since many wetlands are a mosaic of different habitats which share many species. Managing or restoring wetlands to keep a mosaic of communities will improve their resilience. This heterogeneity both provides a greater breadth of niches for species but will also provide resilience as a more diverse site will contain more species capable of maintaining wetland functioning under different scenarios of change.

The species of dry microsites in the driest community will be most at risk of increased flooding or a rise in the water table, whilst it is the species of wetter microsites in the wettest community that will be most at risk of reduced water availability. Two species on the Scottish Biodiversity List could be affected in this way, one from each scenario.

However, climate projections suggest increased frequency of both storms and droughts, and modelling studies suggest that this will have disproportionate impacts on rare species with narrow ecological ranges (Bartholomeus et al., 2011).

Identifying rare species at risk in this analysis was problematic as they either have no Ellenberg indicator values or they have not been recorded during the production of the National Vegetation Classification. Roughly similar numbers of species were at risk of increased wetness and dryness.

This type of analysis could be applied to inventory data from specific wetlands to identify plant species at risk from different scenarios of change.

The systematic analysis provided here is relatively restricted in scope for a number of reasons, including:

- A lack of baseline information on the distribution and abundance of wetland species,
- A lack of systematic information describing ecological preferences of species beyond vascular plans and bryophytes. Even for these groups, systematic information is only available on the coarse-grained Ellenberg indicator scale and rare species have often not been included in this data,
- A lack of basic vegetation science focussed on the zonation and driving variables behind the distribution of both species and communities in wetlands,
- Complex relationships between classifications based on hydrology and those based on vegetation leading to difficulties identifying how hydrological changes might impacts species.

As noted in a review of hydrological niches and community assembly (Silvertown et al., 2015), this is a field that needs "the characterisation of the realised hydrological niche of species" and their integration into "process-based models" to develop "an integrated programme linked to global change research".

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8. Appendix VIII: HOST-DSM of Wetlands in Scotland

by Zisis Gagkas and Allan Lilly

1. Introduction

1.1 Research questions

This deliverable contributes to answering questions related to:

- Climate change impacts on wetlands' ability to moderate extremes of drought and excess rainfall (Appendix VI).
- Assessment of wetland health (Appendix IV).

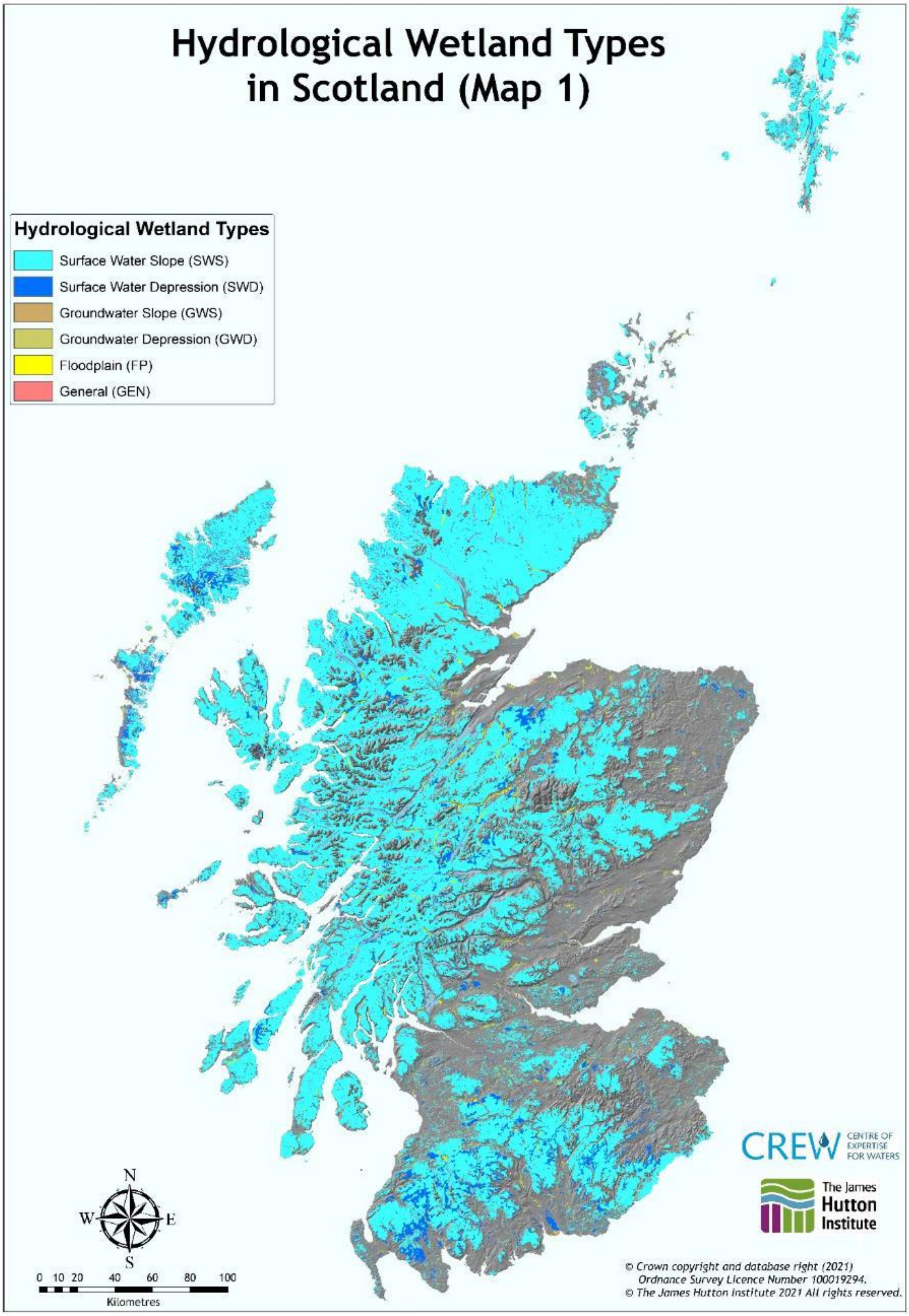
1.2 The deliverables

The deliverable consists of two versions of a national map at 50m grid cell resolution (Map 1 and Map 2) of areas that are most likely to be wetlands classified into the hydrological wetland typology of Bullock and Acreman (2003). The hydrological wetland type maps are available as image files in jpeg format and as spatial (GIS) layers in Geotiff format. The deliverable also includes a MS Excel file that gives a) the classification of Scottish landforms into hydrological wetland types and b) linkages between hydrological wetland types and the occurrence of specific wetland habitat and vegetation communities.

2. Overview of deliverables

2.1 What do the data show?

The map shows the hydrological wetland types based on the Bullock and Acreman (2003) typology for the areas in Scotland most likely to be wetlands at a 50m grid cell resolution and was created by combining information on landform, soil hydrological characteristics and land use types (Map 1) or wetland habitat types (Map 2). The Bullock and Acreman typology (2003) categorises wetlands into headwater or floodplain wetland types (plus general wetlands when wetland type cannot be specified). Inputs to floodplain wetlands (FP) are assumed to be predominantly upstream river flows. Headwater wetland types are further subdivided to four (4) classes: a) Surface water depression (SWD); b) Surface water slope (SWS); Groundwater depression (GWD); and d) Groundwater slope (GWS). These classes are determined depending on the presence/absence of hydraulic connectivity with groundwater or direct outlet connectivity with the river network; the excel file that accompanies the hydrological wetland types map shows how each headwater hydrological wetland type is determined.


Hydrological Wetland Types
in Scotland (Map 1)
Hydrological Wetland Types
Surface Water Slope (SWS)
Surface Water Depression (SWD)
Groundwater Slope (GWS)
Groundwater Depression (GWD)
Floodplain (FP)
General (GEN)
N
W
E
S
0 10 20 40 60 80 100
Kilometres
CREW CENTRE OF EXPERTISE FOR WATERS
The James Hutton Institute
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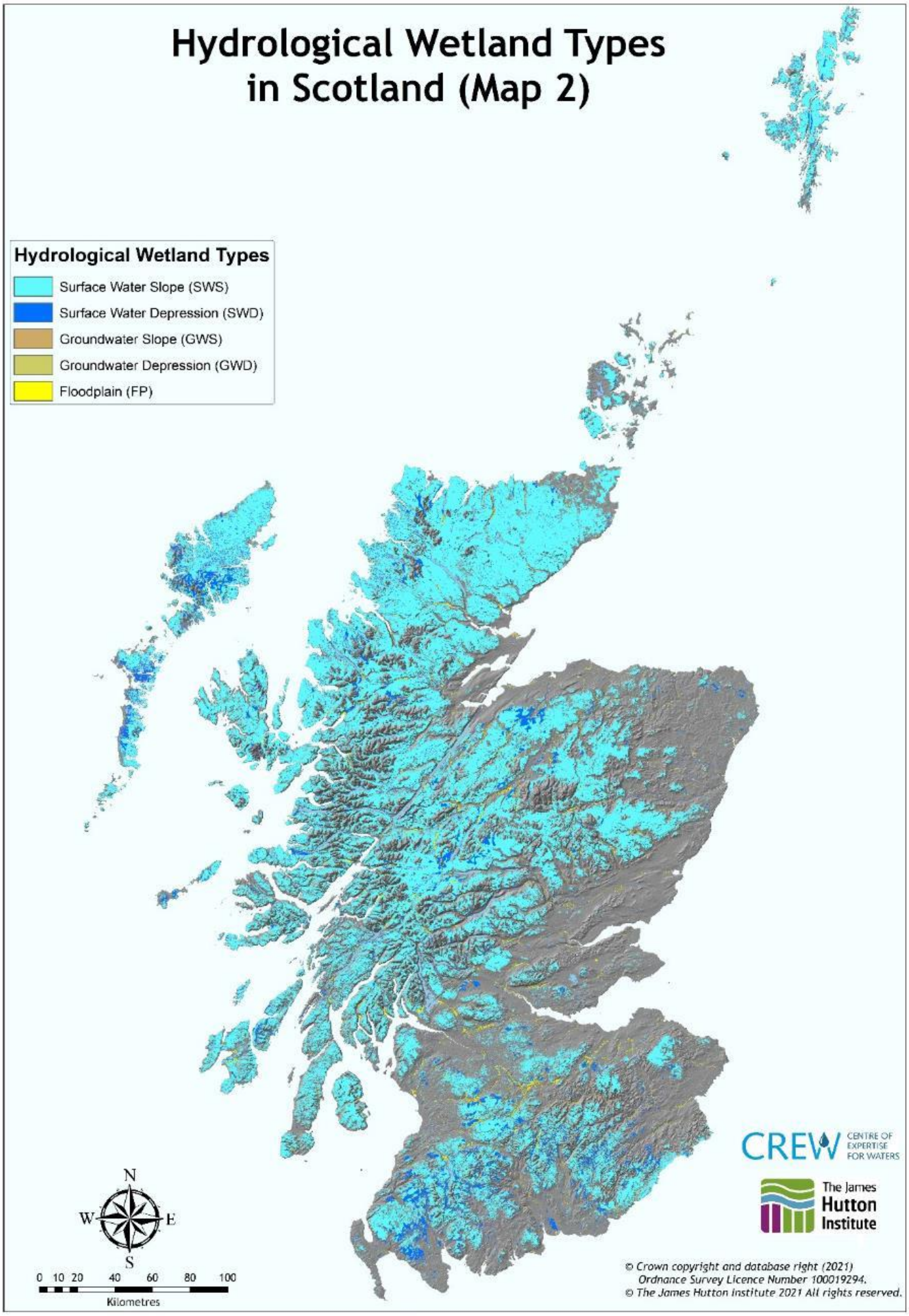
Hydrological Wetland Types in Scotland (Map 2)
Hydrological Wetland Types
Surface Water Slope (SWS)
Surface Water Depression (SWD)
Groundwater Slope (GWS)
Groundwater Depression (GWD)
Floodplain (FP)
N
W
E
S
0 10 20 40 60 80 100
Kilometres
CREW CENTRE OF EXPERTISE FOR WATERS
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2.2 How was the data produced?

We produced the hydrological wetland type map by combining information on:

a. Landform types from the National Soil Map of Scotland at 1:250,000 scale (Soil Survey of Scotland Staff, 1981).
b. Hydrology of Soil Types (HOST) classes, which describe key features of soil hydrology (Boorman et al., 1995), from a digital soil series map (Gagkas and Lilly, 2019), and
c. Land cover from the Land Cover of Scotland 1988 (LCS88, for Map 1) map at 1:25,000 scale (MLURI, 1993) (Map 1) and wetland habitats at EUNIS level 2 at 20m grid cell resolution from the Scotland Habitat and Land Cover Map 2000 (SLAM) created by Space Intelligence in partnership with NatureScot (for Map 2).

We produced a second version of the hydrological wetland map (Map 2) when the SLAM map became available at a later stage of the project because it can provide the hydrological wetland type and wetland habitat type areal combinations that are needed in Appendix IV.

The hydrological wetland typology is based on broad, landscape-scale hydrological features. Therefore, we classified the landform types of the National Soil Map units into hydrological wetland types using available descriptions of landform characteristics such as slope, relative landscape position and topography. The advantage of this approach was that it enabled us to establish a 1:1 relationship between landform and hydrological wetland types necessary for mapping purposes.

Wetlands occur where soils are permanently or seasonally wet due to climatic, topographical and soil hydrological conditions and characteristics, but many of the National Soil Map units contain a mixture of both dry and wet soils, whose exact location within the polygon is often unknown. In order to identify the location of individual soil types within the map units, we used an available digitally-derived map of soil type (series) at a 50m grid cell resolution, which we have previously generated by disaggregating the same National Soil Map units using a predictive soil modelling technique to derive a digital soil map (Gagkas and Lilly, 2019). We then mapped the areas of wet soils by selecting soils assigned to HOST classes 7, 8, 9 and 10 (potentially wet or waterlogged alluvial soils), HOST class 12 (basin peat and some peaty gleys), HOST classes 14 and 24 (mainly noncalcareous gleys), HOST class 15 (peaty podzols, peaty gleyed podzols and peaty gleys), HOST classes 26 and 27 (peaty soils, mainly peaty rankers) and HOST classes 28 and 29 (upland blanket peats).

The final step was to exclude areas mapped as wet soils that are less likely to be wetlands due to their land use (Map 1) or habitat type (Map 2).

For the generation of Map 1 we excluded areas belonging to the arable, improved grasslands and built-up classes from the LCS88 map and kept areas covered by all types of seminatural vegetation, including areas of wet soils converted to commercial forestry. To ensure the inclusion of more recently established conifer plantations, we updated the LCS88 map using information from the National Forest Information (NFI) digital map from Forest Research.

Regarding the production of Map 2, we selected areas of wetland habitats classified in the SLAM map as: C Surface standing and running waters; D1 Raised and blanket bogs; D2 Valley mires, poor fens, and transition mires; D4 Base-rich fens and calcareous spring mires; E3 Seasonally wet and wet grasslands; F4 Temperate shrub heathland and F9 Riverine and fen scrubs, plus G3 Coniferous woodland. Because G3 Coniferous woodland included all land covered by conifers, we used information from the Caledonian Pinewood Inventory map (available from Scottish Forestry Open Data) to identify areas covered by native pinewoods. In addition, for floodplain areas only, we included the G1 Broadleaved deciduous woodland and G4 Mixed deciduous and coniferous woodland classes in the SLAM map to include wetland areas of bog woodlands, fen woodlands, alder woodlands and other wet woodlands.

Hydrological wetland type Maps 1 and 2 provide different overall areal coverage (37,982 km^2 and 31,217 km^2, respectively) but provide the same classification of hydrological wetland types within the mapped area common to both maps, which accounts for around 95% of Map 1. Based on Table 1, surface water slope, which includes all types of blanket bog, wet heath and bog woodlands, is by far the dominant hydrological wetland type in Scotland for both Maps 1 and 2.

Table 1. Areas and proportions of hydrological wetland types for Maps 1 and 2.

Hydrological Wetland Types	Code	Map 1		Map 2	
		Area (in km^2)	Cover (%)	Area (in km^2)	Cover (%)
Surface Water Slope	SWS	35,260	92.9	28,898	92.6
Surface Water Depression	SWD	2,148	5.7	1,774	5.7
Groundwater Slope	GWS	5	0.0	2	0.0
Groundwater Depression	GWD	135	0.4	59	0.2
Floodplain	FP	422	1.1	485	1.6
General wetland (not specified)	GEN	11	0.0	0	0.0

2.3 What do the data not show?

Areas mapped in the LCS88 map as either arable land or improved grasslands were unlikely to be wetlands due to management effects (i.e., artificial drainage) and were excluded from the analysis and are not shown in the map. Similarly, areas mapped as cultivated land or as dry habitats in the SLAM map were also excluded from the analysis. However, areas of wet soils (e.g., peatlands) that have been converted to commercial forestry are included and shown in both maps as candidate areas for restoration. Due to the hydrological wetland type map's resolution, linear features of less than 50 m width and wetland areas of less than 0.25 ha could not be delineated on the map.

2.4 How accurate are the data?

We derived information on the spatial distribution of soils at a 50m grid cell resolution from a digital soil type (series) map that we have previously generated using a robust soil modelling approach (Gagkas and Lilly, 2019) that provided confidence in the accuracy of the predicted soil type information. We used landform type and land cover information derived from the National Soil Map of Scotland and the LCS88 maps, respectively. Both maps have been produced via a combination of ground surveying and aerial photo interpretation, are both of high attribute and positional accuracy and have been extensively used in various research projects with good result. The SLAM map has been produced using a combination of artificial intelligence (AI) techniques, satellite imagery from multiple sensors and ground data with the objective to be used by Nature.Scot to improve the accuracy of Scotland's annual Natural Capital Asset Index assessment, hence it is an appropriate dataset for use in this project.

2.5 Uncertainties and gaps in the data

Uncertainties in the mapping datasets used to produce the hydrological wetland types map include a) uncertainties related to the positional accuracy of individual datasets, b) uncertainties related to spatial mismatches when combining datasets of different scale/resolution, and c) uncertainties related with the modelling and mapping of soil types. Overall, we expect low uncertainties related to positional accuracy for most areas mapped; areas mapped with greater certainty include larger, more well-defined and uniform (in terms of soil type and land use) areas such as peatlands, whereas mapping of hydrological wetland types could be less certain in floodplains that are relatively narrow and have a variety of soil types. Uncertainties in the SLAM map habitat mapping can be quantified with extensive ground-truthing. In addition, we have identified and removed the limited spatial mismatches created during map production. Regarding the digital soil series map, we have used the most-probable soil series (i.e., the soil series predicted most times in every 50m grid cell), with overall high prediction certainty for most wet soils mapped. In the case of narrow floodplain areas flanked by free draining glacio-fluvial soils, we tested both the most and second-most frequently predicted soil series to ensure that only soils associated with the valley bottom wetlands were selected (i.e., wet/waterlogged alluvial soils and basin peats); visual inspection using satellite imagery combined with on-ground knowledge showed that this approach improved the detection and mapping of wetland areas within floodplains. Finally, due to the spatial resolution of the hydrological wetland map, there is less certainty in the mapping of relatively narrow riparian wetlands and of small pockets of wetlands.

3. References

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