CREW CENTRE OF EXPERTISE FOR WATERS

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

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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).

Contents

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 6.5 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 watercourses which are episodically flooded.

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

Habitat. Either the area and resources used by a particular species (the habitat of a species) or a community of animals and plants together with their abiotic environment.

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 habitat immediately adjacent to a raised bog separating it from the mineral substrates.

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

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.

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

Minerotrophic. Where nutrient supply is derived from mineral groundwater.

Mire. A peatland habitat where peat is being formed and accumulated.

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 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) and are confined to the lowlands and 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 the mineral. 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. Upper surface of the groundwater below which the ground is saturated.

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.

Executive Summary

Aim, Research Questions & Key Findings

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. We used an interdisciplinary approach and synthesised information from the available literature (published and grey), expert opinion, indicator data analysis, mapping visualisation methods, climate change scenario modelling and workshop participation for responding to the overall objective. The four research questions (RQs) posed, and our key findings (KFs), 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.**
    - o The main buffering capacity mechanisms are the storage of water and the delayed movement of water out of a wetland.
    - o 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.
    - o Seasonal variability of used and free water storage capacity is key to buffering.
    - o 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.
    - o 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.
- **KF1.2: Buffering capacity is catchment- and wetland-specific but improving total wetland extent through restoration and appropriate management can improve buffering capacity.**
    - o 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.

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

-
    - o 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.**
    - o 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.
    - o 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.**
    - o 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 the 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).

Background

The health of wetlands is under extensive pressure from land use conversion, management, and climate change. Wetland restoration is currently being promoted by a favourable policy environment (e.g., the third Land Use Strategy, the second Scottish Climate Change Action Programme, the Climate Change Plan 2018-2032, and the Flood Risk Management (Scotland) Act 2009). This focuses on the benefits that wetland restoration provides in terms of net carbon emissions savings, and on flood risk management. There is a particular focus on blanket bog and other peatlands (e.g., through the Peatland Action Programme). What has been missing up to now is an assessment of a broad range of wetlands with respect to their buffering capacities for both high *and* low flows. To improve wetland resilience, we need to better understand the various impacts on such capacities, as well on their biodiversity.

Research undertaken

The interdisciplinary (hydrology, climatology, and ecology) research undertaken involved comprehensive literature reviews on wetland characteristics, health, water holding capacity, buffering capacities, wetland biodiversity and on the impacts of land use conversion, management, and climate change. Due to the dispersed and incomplete nature of this literature, we carried out additional new research: the mapping of likely wetland areas in Scotland; analysis and mapping of an ensemble of 12 climate projections; engagement with external experts on the potential future health of wetlands; indicator-based analyses to i) understand the risks to plant biodiversity from extremes of water availability and ii) provide supporting evidence for rating the buffering capacities of wetlands. The analysis of wetland buffering capacity ratings, future wetland health, and impacts of projected climate change scenarios on that health and buffering capacity were based on our own final assessments, through the interpretation of the available literature and new research.

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.

1. Introduction

The estimated two million hectares of Scotland's wetlands (Lindsay and Clough, 2017) are suppliers of ecosystem services, providing multi-functional water storage infrastructure across catchments. When in good health, these wetlands can have capacity to buffer both high and low flows, mitigating flood and drought risks respectively, both individually and in combination. Their maintenance and restoration can be considered a Nature-Based Solution to these problems. The potential beneficiaries of this are downstream communities, businesses, and built infrastructure, as well as the diverse animal and plant species that live in wetlands. Buffering capacity is dependent on, for example, a large available water holding capacity, connectivity to the catchment's hydrological system, wetland vegetation, surface roughness and seasonal variability in their storage capacity. This seasonal variability, when present, allows wetlands at certain times to provide buffering: attenuating high flows in times of flood and providing water in times of drought (Bullock and Acreman, 2003; Wilkinson et al, 2019; Wilkinson, 2019).

Wetlands have been and continue to be under extensive pressure from land use and climate change. This pressure can impact on their health and change their buffering capacity. Best practices and future options for water and land management activities and plans – including drought plans – for wetlands need to be discussed with a wide audience to inform future joint actions and approaches.

Wetland restoration is currently being promoted by a favourable policy environment represented, among others, by the third Land Use Strategy, the second Scottish Climate Change Action Programme, the Climate Change Plan 2018-2032, the Scottish Biodiversity Strategy, and the Flood Risk Management (Scotland) Act 2009, and River Basin Management Plan requirements. Apart from the latter, which focuses on improving water quality, flows and condition of water bodies in general, these policies focus on the benefits that wetland restoration could provide in terms of net carbon emissions savings, biodiversity and on flood risk management. There is also a particular focus on blanket bog and other peatlands. Since 2012, over 26,000 hectares of peatlands in Scotland have been put on the road to recovery through restoration enacted through the Peatland Action Programme, funded by the Scottish Government (Scottish Government, 2020).

This focus has been reflected in research, with its emphasis on particular types of wetlands, such as Scotland's most common form, the blanket bog. However, the research is dispersed and incomplete on the *broad range* of wetland habitats that call Scotland home. Furthermore, previous wetland research has lacked a specific and cohesive focus on factors influencing their health, condition, extent of buffering capacity, and response to different pressures of land use and a changing climate at a national scale. This holistic picture and improved understanding could inform wetland management practices, restoration priorities and expand the role of a broader range of wetlands in policies related to climate adaptation/mitigation strategies, the protection of biodiversity and to the buffering of downstream communities from the hydrological extremes of *both low and high flows*.

The project aim was therefore to integrate new and existing evidence on the role of functioning wetlands in moderating or "buffering" extremes of water availability in a Scottish context by answering the following key research questions in relation to a broad range of 18 types of wetland habitat (see Section 2 for list):

- *RQ 1: 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?*
- *RQ2: How is this buffering capability compromised when wetlands are degraded due to land use conversion or climate change?*
- *RQ3: What are the impacts, caused by extremes of water availability, on the biodiversity of Scottish wetlands?*
- *RQ4: Are there opportunities or potential changes in land or water management, which could enhance the buffering capability of wetlands in Scotland?*

1.1 Report structure

This main report has been structured into eight parts and framed around answering the key research questions.

In this report, we have synthesised and summarised the results of 8 interdisciplinary technical appendices about 18 wetland habitats (see Box 1.1). These have been combined and published on the CREW website as a standalone project output for those needing more information about the research approaches used and evidence-base supporting our overall conclusions. In Section 2, we introduce key working definitions related to wetland types and how we categorise and characterise the 18 wetland habitats of interest. In Sections 3-6 we present key findings that answer the research questions on a section-by-section basis. In each case, we refer to the technical outputs where appropriate. There are many knowledge gaps still to be filled and, in Section 7, we identify where these gaps are. We conclude the report in Section 8 with a summary of our key messages and recommendations.

Box 1.1 The 8 technical appendices combined and published as a standalone project output.

- **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

1.2 Research undertaken

Available knowledge was collated on key topics: water-holding and buffering capacity, wetland health and biodiversity, impacts of land use conversion and management, and climate change impacts. The result of the literature reviews[1] are given in the eight associated technical appendices. Due to incomplete knowledge and data in the literature, we also carried out new research, including:

- Hydrology of Soil Types - Digital Soil Mapping (HOST-DSM) of areas in Scotland that are likely to be wetlands;
- Analysis and mapping of past climate trends as well as UKCP 18 climate change projections;
- Indicator-based analysis of risks to plant biodiversity;
- Engagement with external experts and use of grey literature sources for supporting our own expert assessment of future wetland health.

Finally, given the complexity and interdisciplinary nature of the research questions being asked, in order to integrate all this information and answer these questions, additional research was needed for completing the main report. This involved:

- Indicator-based analysis, using the HOST-DSM map, above, to assess base flow and runoff rates related to wetland buffering capacities;
- Our own expert judgement, based on the literature and such analysis, to rate wetland buffering capacities for each of the 18 types, and assess possible impacts of projected climate scenarios on those capacities.

1 This was not a systematic review of evidence.

2. Defining wetlands and their key characteristics

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"*
>
> (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 underlying soil substratum for all or part of the year. Waterlogging occurs either when water movement is impeded by impermeable soil/rock layers or when an underlying aquifer forces it to rise (Acreman et al., 2011). 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 also influences ecological aspects of wetland ecosystems – e.g., 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 hydrology of the wetland.

2.1 Introduction to the broad range of wetlands of interest

This section introduces the broad range of 18 categories of wetland habitats that are the focus of this report.

To make findings on these wetlands easier to access in this report, the habitats are primarily categorised and presented according to whether they are to be found in uplands, lowlands, wet woodlands, or wet grassland/ floodplain meadows. Additionally, due to the importance of hydrology for the functioning of wetlands as buffers of extreme water availability, the 18 wetlands are secondarily grouped throughout this report according to the five hydrological wetland types of Bullock and Acreman (2003), i.e. *surface water slope, surface water depression, groundwater slope, groundwater depression,* and *floodplain*. For now, the following important difference to note is the difference in hydrological connectivity between each type (see Figure 2.1, blue and green arrows):

- whether they have groundwater connectivity;
- their outflow connectivity, if any, to surface water bodies/courses (e.g. rivers, lochs); and
- the sources of water upon which they are dependent.

As will be explained in Section 3, hydrological connectivity and extent can make a difference to the wetland's capacity to buffer extremes of water availability. Table 2.1 provides an overview of our categorization of the target wetlands in this respect. More detailed information on these wetlands, and other key characteristics, can be found in Appendix I which provides the findings of the literature review. This review looked at approximately 100 source documents including both academic articles and expert reports, such as the SEPA-commissioned report on water supply mechanisms (SNIFFER, 2014).

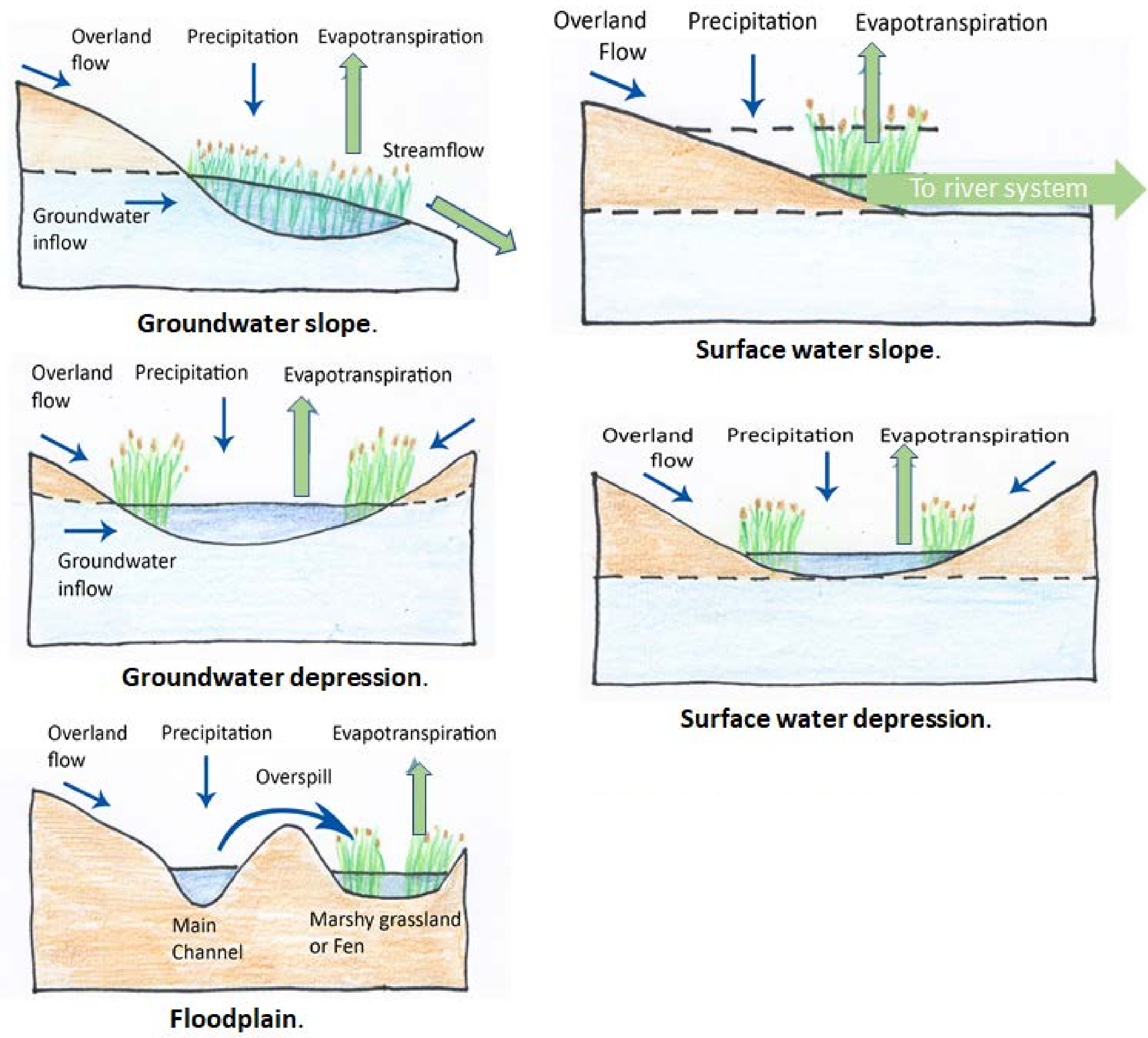

Figure 2.1 The five hydrological wetland types based on Bullock and Acreman (2003) used in this study. Blue arrows show source of water (inflows). Green arrows show connectivity (outflows) to the hydrological system (S. Donaldson-Selby, adapted from Cooper and Merritt (2012)).

Table 2.1 A comparison of key characteristics of each of the 18 wetland habitats.

Wetland Habitat	Primary Category	Secondary category: Hydrological wetland type	Hydrological connectivity: Groundwater connectivity	Hydrological connectivity: Outflow connectivity to water courses	Dependent water source	Other information
Blanket bog	Upland; lowland	Surface Water Slope	Yes	Yes	Rainfall	The most common form of upland peatland in Scotland
Wet heath	Upland; lowland	Surface Water Slope	Yes	Yes	Rainfall	*Erica tetralix* tends to be the dominant dwarf shrub species, rather than heather (found in dry heath)
Depressions on peat substrates of the *Rhynchosporion*	Upland	Surface Water Depression	Yes	No	Other wetland habitats	This is a rare habitat that occurs as a part of a wetland mosaic, on humid, exposed peat on or on the edge of other habitats, e.g., bog pools and hollows in wet heath and raised/blanket bogs
Base Rich/ Alkaline fens	Upland; lowland	Groundwater slope	Yes	Yes	Groundwater or surface flows	An extremely species-rich habitat, accounting for a third of UK native flora, greater than a half of UK dragonfly species, thousands of other insect species, and an important habitat for aquatic beetles
Raised bogs	Lowland	Surface water depression	Yes	No	Precipitation (Lagg fens at edges of raised bogs can be groundwater fed)	The bog eventually forms a dome (becomes raised) due to the different growth rate of vegetation (higher in the centre, lower on the edges) and the entire surface becomes exclusively rainfed
Transition mires and quaking bogs	Lowland	Groundwater slope	Yes	Yes	Very wet groundwater or surface water-fed basins	Associated with static open waters. Vegetation and ecology are transitional between fen and bog, and surface conditions can range from acid bog to base-rich fen
Open-water transition fens	Upland; lowland	Groundwater slope	Yes	Yes	Adjacent lake or river (primarily)	Upland open-water transition fens are generally base-poor, while those in lower catchments may be base-rich
Reedbeds	Lowland	Groundwater depressions/ Groundwater slope	Yes	Yes	Standing water, from groundwater or surface water flow	The dominant species is the common reed *Phragmites australis*. Reedbeds provide a hydro-morphological function by absorbing wave energy and protecting the river banks from erosion
Swamps	Upland; lowland	Groundwater depressions/ Groundwater slope	Yes	Yes	Adjacent water bodies, or else groundwater	Upland swamps are restricted to narrow margins surrounding lochs. Lowland swamps are found in flat to gentle slopes along streams, lochs, open water or in coastal settings

Hydrological connectivity						
Wetland Habitat	**Primary Category**	**Secondary category: Hydrological wetland type**	**Groundwater connectivity**	**Outflow connectivity to water courses**	**Dependent water source**	**Other information**
Basin fens	Upland; lowland	Groundwater depression	Yes	Yes	Mostly surface water flow, sometimes groundwater. May benefit from high rainfall	Basin fens may form in depressions such as kettle holes, the swales between beach ridges, and the embayments of seas or lakes
Floodplain fens	Lowland	Floodplain	Yes	Yes	Periodic inundation from adjacent streams and rivers but can also be influential groundwater inputs	Floodplain fens are some of the largest fen complexes in the UK often supporting shallow lakes and pools
Fen woodland	Wet woodlands	Groundwater depression/ Floodplain	Yes	Yes	Adjacent water bodies, or else groundwater	Also known as fen-carr, are mainly found on lowland flood-plain fens, open water transition fens and basin fens
Alder woodland	Wet woodlands	Groundwater slope/ Groundwater depression/ Floodplain	Yes	Yes	Floodplains	
Bog woodland	Wet woodlands	Surface water slope/ Surface water depression	Yes	Yes	Rainfall	Bog woodland is fairly rare and consists of mature Scots Pine. It is a conservation priority habitat type under the EU Habitats Directive
Fen meadow	Wet grassland/ floodplain meadow	Groundwater slope/ Floodplain	Yes	Yes	Slow groundwater flow	Since the Middle Ages many fens have been partially drained, forming fen meadows which require some form of management
Wet meadows/ marshy grassland	Wet grassland/ floodplain meadow	Floodplain	Yes	Yes	Seasonally saturated	Marshy grassland has a high proportion of rush, sedge or meadowsweet species; and wet meadows support communities of marsh marigold and valerian
Transition grassland	Wet grassland/ floodplain meadow	Floodplain	Unknown	Unknown		Clear definitions are lacking. Their vegetation and hydrology are intermediate between wet meadows/ marshy grasslands described above and drier, rough grassland
Transition saltmarsh	Wet grassland/ floodplain meadow	Floodplain	Unknown	Unknown	Associated with true saltmarshes, but have a lower inundation regime	Vegetation communities are intermediate between true saltmarshes and those vegetation communities that are adapted to saline environments, e.g., reedbeds

3. RQ 1: 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?

To answer this question, we carried out a second literature review on water holding and buffering capacities of each of the wetland habitats covering over 105 source documents (see Appendices II and III for more details).

The buffering capacity of a wetland is primarily dependent on its available water holding capacity (Figure 3.1). There are several mechanisms by which water is stored. Above the ground, surface water is stored as open water where it collects in topographical features such as hollows and channels or runs off where the saturation or infiltration capacity of the underlying soil is exceeded. 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). Water can also be stored thanks to mechanisms provided by the overlying vegetation for example interception of rainfall within tree canopies or as moisture within *Sphagnum* mosses. An additional hydrological mechanism that wetlands offer is through the surface hydraulic roughness provided by overlying vegetation and topographical irregularities that slow surface runoff. All mechanisms are important, and their relative importance varies temporally and spatially depending on the functioning of a specific wetland.

3.1 The buffering capacity of wetlands explained

The water holding capacity of a wetland can be divided into two types (Figure 3.1): used water storage and available free storage with the balance between the two varying (McCartney and Acreman, 2009). Compared to other terrestrial landscape features, when all available storage is used wetlands have the potential to hold considerable quantities of water both above and beneath the ground surface. The variable nature of available storage as determined by the water balance and hydrological connectivity within a catchment, determine the ability of wetlands to buffer low and high flows. The key mechanisms and their controls that determine buffering are explored further in Section 3.1.1.

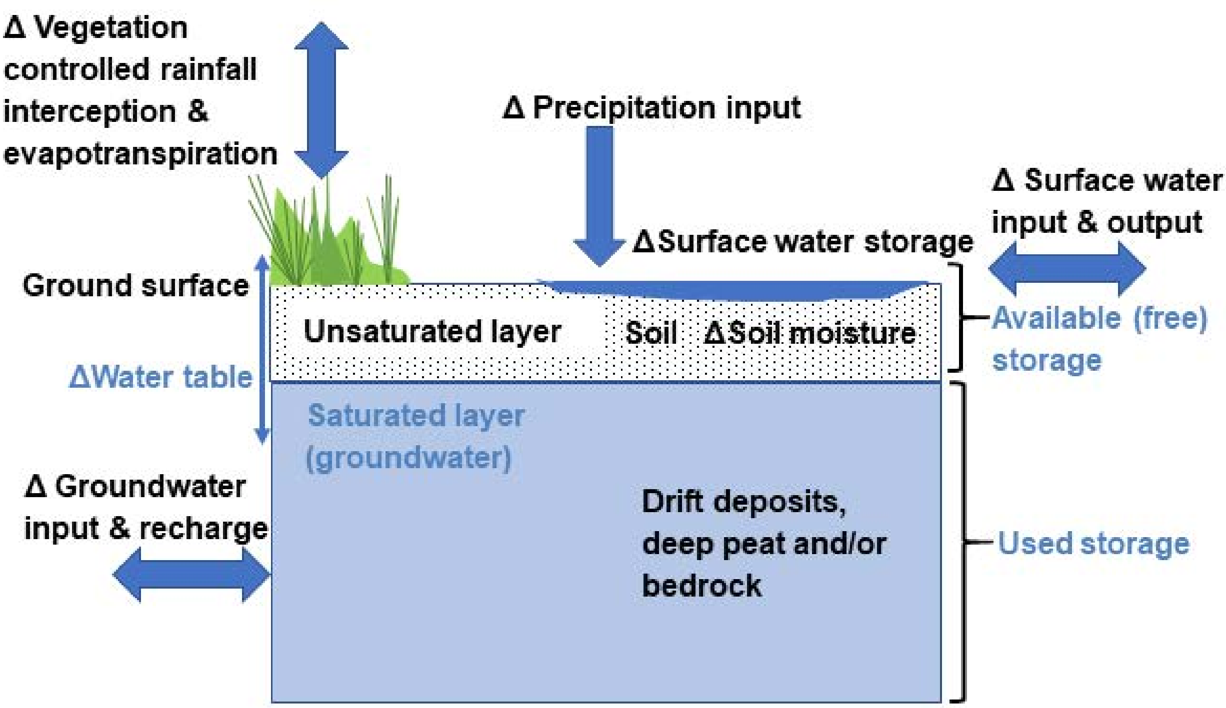

Figure 3.1 Conceptual summary of wetland water holding characteristics. Note not all wetlands are connected to groundwater and the combinations of inputs and outputs are not universal.

3.1.1 Wetland buffering of hydrological extremes

High flows

The capacity of a wetland to buffer the effects of flooding is commonly highlighted as a service that well-functioning wetlands offer. By storing excess surface water or delaying its movement, downstream flooding can be mitigated via the delay of flood peaks, attenuation of flood peak discharge or through reduced volume of runoff. Key spatial controls on these buffering mechanisms include wetland location within a catchment, its size and the distance from a receptor (e.g., downstream urban community; Larson, 2009a). The inherent roughness, topography, soil characteristics and vegetation of a wetland, as explored in Appendix III, present further controls on the precise response to a flood wave in a wetland.

Importantly, the health and extent of wetlands also represent major controls on the hydrological buffering capacity. Historically wetlands have been drained or reduced in extent as other types of land use have replaced them. Such land management actions can mean catchments have less capacity to buffer flood peaks (Appendix III). The arrangement of wetlands is also important. For example, wetlands positioned close to water courses have been predicted to play an important role in attenuating high flows that is 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, declines. However, these predictions are catchment specific; the health of wetlands, catchment topography, underlying geology and relative size of a catchment are all important additional controls.

The wetland's balance of inflows and outflows (e.g., Figure 2.1; see also Table 2.1, Section 2) is an important control on water holding capacity (Baker et al., 2009) and in turn ability to buffer hydrological extremes. The nature of its storage (i.e., duration, or storage type: on the surface, in the soil as moisture or as groundwater) importantly can determine when it is persistently saturated with no available spare capacity or able to offer spare capacity to hold additional water. Linked to this is whether the wetland is sloping or in a depression (basin). In general, sloping wetlands have lower water storage capacity than those situated in depressions.

It is worth noting, though, that certain wetlands even when in healthy condition, may function as net contributors to flooding (Bullock and Acreman, 2003). In temperate regions, wetlands hydrologically connected to headwater streams in upland areas such as blanket bog and wet heath tend to be flood generating during precipitation or snowmelt events as soils are often saturated. This reflects high rainfall input and poor drainage due to moisture retaining organic soils leading to rapid overland runoff (Bullock and Acreman, 2003). In contrast, some may have no effect on flood generation (or on buffering floods either) because they are isolated from stream networks (Larson, 2009b).

The hydrological functioning and thus buffering capacity of wetlands also varies temporally. Long term (e.g. decadal), seasonal and event scale temporal factors result in important changes. For example, a high rainfall or snowmelt event or period of drought over a longer timescale, can create antecedent conditions of limited available free storage and freely available capacity respectively.

Low flows

Wetlands also have the potential to aid buffering of droughts and low flows through mechanisms that sustain groundwater and surface outflows that in turn maintain baseflows in watercourses. 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).

The ability to buffer the effects of dry periods is dependent on the wetland type (see Section 2). Most wetlands will retain water during dry periods. However, the mechanism by which they can contribute to base flow in water courses is affected by evapotranspiration which can reduce that contribution compared to other habitats (Bullock and Acreman, 2003). The loss of water through evaporation from wetlands, is dependent on the wetland site, its vegetation and water supply (Mohamed et al., 2012). Floodplains, and the wetlands they potentially support such as floodplain fens, swamps and fen meadows, have water tables strongly coupled to the level of water flow within the adjacent watercourse (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 mechanism directs groundwater into the watercourse thus helping to sustain the baseflow of that watercourse during dry periods (Burt et al., 2002). Groundwater contained within valley bottom alluvial deposits that underlie floodplains thus represent a potentially major source of baseflow (Tetzlaff and Soulsby, 2008).

3.2 What are the buffering capacities of the different wetland habitats?

The buffering capacity of a wetland varies depending on the inherent mechanisms, wetland type, location and temporal variability of the water balance as summarised in Appendices I and II.

The assessment of the potential buffering capacity for both low and high flows for each of the 18 wetland habitats is summarised in Table 3.1. This qualitative assessment, similar to the review undertaken by Bullock and Acreman (2003), was based on a rating (Low or Good) of the buffering capacity that intact, healthy wetlands would have. The ratings give a relative measure of the buffering capacity between the different wetland types.

Confidence levels (High, Medium and Low) on these buffering ratings were then assigned based on the weight of literature evidence (Appendices II and III), Hydrology of Soil Type (HOST) classification indices where available Baseflow Index (BFI) and Standard Percentage Runoff (SPR) ratings derived from the mapping work in Appendix VIII.

Knowledge of the buffering capacities of specific wetland types is incomplete (see Section 7) and due to the complexity of mechanisms, and the multi-faceted nature of their controls, management decisions should ideally be based on site-specific hydrological assessment. Thus, the assessment of buffering capacity ratings given in Table 3.1. is cautious. Nevertheless, this summary provides a starting point to predict the level of buffering capacity offered by different wetland types and to inform strategic planning for management and restoration.

Table 3.1 Summary of buffering capacity of healthy, functional wetlands. Green cells highlight wetland types that are likely to offer good low flow or high flow buffering capacity. Assessment of buffering ratings are based on judgement informed by literature where available (Appendices II and III) and Baseflow Index (BFI) and Standard Percentage Runoff (SPR) indicators based on Hydrology of Soil Type – European Nature Information System (HOST-EUNIS) combinations from hydrological wetland habitat mapping (Table 5e in Appendix IV). Assessment is independent of the total extent of a wetland type within a catchment (i.e. buffering effectiveness is relative to wetland unit area). BFI and SPR indices give an indication of the low flow and high flow buffering capacity respectively, of the soil associated with the wetland. Water holding capacity is categorised according to whether the wetland has a Persistently High Water Table (PHWT) or a variable one.

Wetland habitat	Water holding capacity	Low flows buffering rating	HOST Base-flow index rating[1]	Confidence level / Refs[3]	High flows buffering rating	Stand-ard % runoff rating[2]	Confidence level / Refs[3]
Uplands							
Blanket bog	PHWT	Low	Low	Medium; Evans 1999; Soulsby et al., 2006; Tetzlaff et al., 2007	Low (potentially good in the short-term following dry periods in summer)	High	High; Acreman and Holden, 2013; Bullock and Acreman, 2003; Boelter and Verry, 1977; Tetzlaff et al., 2007; Scheliga et al., 2018
Wet heath	PHWT	Low	Low	Low	Low	High	Low
Depressions	PHWT	Low	-	Low; Acreman and Macartney, 2009	Low	-	Low; Acreman and Macartney, 2009
Base rich/ alkaline fens	Variable	Low	Low	Low; Soulsby et al., 2007	Low	High	Low
Lowlands							
Floodplain fens	Variable	Good	Low	Medium; Burt et al. 2002; Ameli and Creed, 2019; Macdonald et al., 2014; O Dochertaigh et al., 2018; Tetzlaff and Soulsby, 2008	Variable (good in summer)	Moderate	High; Acreman and Holden, 2013; Bullock and Acreman, 2003; Davis, 2004; Ameli and Creed, 2019; SNIFFER, 2014
Base rich fens	Variable	Low	Low	Low;	Low	High	Low; Duval and Waddington, 2018
Transition mires/ Quaking bogs	PHWT	Low	Low	Low;	Low	High	Low

Wetland habitat	Water holding capacity	Low flows buffering rating	HOST Baseflow index rating[1]	Confidence level / Refs	High flows buffering rating	HOST Standard % runoff rating[2]	Confidence level / Refs
Open water transition fens	PHWT	Low	-	Low	Low	-	Low
Swamps	Variable	Good	-	Low	Variable (good in summer)	-	Low; Ameli and Creed, 2019
Reedbeds	Variable	Good	-	Low	Variable (good in summer)	-	Low; Ameli and Creed, 2019
Basin fens	PHWT	Low	-	Low; Ameli and Creed, 2019	Variable (good in summer)	-	Low; Lane et al., 2018; Ameli and Creed, 2019
Raised bogs	PHWT	Low	Low;	Medium; Evans 1999; Soulsby et al., 2006; Tetzlaff et al., 2007	Low (potentially good in the short-term following dry periods in summer)	High	Medium; Bullock and Acreman, 2003; Acreman and Holden, 2013; Bragg, 2002;Tetzlaff et al., 2007
Wet woodlands							
Fen Woodland	Variable	Low	Moderate	Low	Variable (good in summer)	Moderate	Medium; Thomas and Nisbet, 2007
Alder Woodland	Variable	Low	Moderate	Low	Variable (good in summer)	Moderate	Medium; Thomas and Nisbet, 2007
Bog Woodland	PHWT	Low	Low;	Low; Evans 1999; Soulsby et al., 2006; Tetzlaff et al., 2007	Low (potentially good in the short-term following dry periods in summer)	High	Low; Bragg, 2002; Acreman and Holden, 2013; Bullock and Acreman, 2003; Tetzlaff et al., 2007
Wet grasslands							
Transition grasslands	Variable	Low	Low	Low	Variable (good, in summer)	High	Low
Wet meadow	Variable	Low	Low	Low	Variable (good in summer)	High	Medium; SNIFFER, 2014; Rothero et al., 2016; Bradley et al. 2010
Fen meadow	Variable	Low	Low	Low	Variable (good in summer)	Moderate	Medium; SNIFFER, 2014; Rothero et al., 2016; Bradley et al. 2010
Transition Saltmarsh	Unknown	Low	-	Low	Low	-	Low

[1] BFI = Baseflow Index. A measure of the proportion of annual flow (0-1) that is contributed towards sustaining baseflows as based on the Hydrology of Soil Types (HOST) classification (Boorman et al. 1995). Where 'High' = BFI > 0.8, 'Moderate' = BFI: 0.8-0.5 and 'Low' = BFI < 0.4. BFI categories based on expert judgement. BFI ratings in table are based on a lumped value averaged across multiple soil types for a given wetland. Where BFI is low, then low flow buffering capacity might be low.

[2] SPR = Standard Percentage Runoff. The % of rainfall expected to occur as surface runoff in a rainfall event as based on the Hydrology of Soil Types (HOST) classification (Boorman et al. 1995). Where 'High' = SPR > 40% (slowly permeable with primarily organic topsoil's that inhibit infiltration), 'Moderate' = SPR: 20-40% (soils with mineral topsoil that allow some infiltration) and 'Low' = SPR < 20% (soils with high infiltration rates). SPR categories based on Lilly and Baggaley (2014). SPR ratings in table are based on a lumped value averaged across multiple soil types for a given wetland. Where SPR is high, then high flow buffering might be low.

[3] Confidence level reflects combination of HOST evidence and number/quality of references lending support. Black text references indicate sources from which the inference of the buffering capacity of a specific wetland type was made. Red text references indicate sources that directly support the nature of the buffering capacity of a specific wetland type.

The following are key messages from Table 3.1 that have reasonable supporting evidence:

High flow buffering:

- The majority of wetlands offer low capacity to mitigate high flows on account of slowly permeable soils and a lack of available free storage due to persistent saturation that limits available water holding capacity. However, such wetlands in a healthy state are likely to offer greater buffering capacity than degraded examples or many land cover types that replace them.
- Floodplain fens, transition grasslands, wet meadows and fen meadows have good, but more variable, capacity to buffer high flows that varies seasonally; the maximum high flow buffering would be expected during the summer months when there is more likely to be free storage in soils and surface hollows. Moreover, vegetation growth during summer improves hydraulic roughness that can slow surface runoff.
- Alder and fen wet woodlands similarly provide good, but variable, seasonally controlled capacity to buffer high flows.
- Swamps and reedbeds often occur close to watercourses on floodplains and on the margins of lochs. When they have available free storage during drier summer spells, they have capacity to hold large quantities of surface water in hollows to buffer high flows.
- Basin fens have variable capacity to store water with the greatest available storage also available in summer. The often poor outflow surface water connectivity of basin fens can help to reduce and delay flooding downstream.

Low flow buffering:

- The majority of wetlands have low capacity to buffer low flows compared to other habitats as the temporary storage of water makes it more prone to loss through evapotranspiration and/or the outflow connectivity is poor.
- Floodplain fens have good low flow buffering capacity due to their hydrological connection to groundwater, helping to sustain baseflows in watercourses.
- Swamps and reedbeds, co-existing in riparian or floodplain settings, may also provide low flow buffering if hydrologically connected to a nearby watercourse, but there is a lack of knowledge on this.

3.2.1 The buffering capacity of blanket bogs

The flood attenuation goal of restoring degraded blanket bogs is often highlighted in policy (see Section 1). Field studies show both planting of *Sphagnum* on bare peat to improve surface roughness (Shuttleworth et al., 2019) and drain blocking to improve storage (Wilson et al. 2011) can reduce peak flows. Drain blocking can also improve maintenance of baseflows during droughts (Wilson et al., 2011). These observations suggest that restored blanket bog can, at small headwater catchment scales, buffer high and low flows more effectively than degraded peat bogs. However, at present the restoration effects at greater spatial scales (i.e. catchment scale) are unknown and difficult to measure (Acreman and Holden, 2013). There also can be a significantly long lag period between intervention and complete recovery; one study showed that 6-7 years following drain blocking, the effects of 40 years of drainage had not been completely reversed (Holden et al. 2011). At the point of complete recovery with re-saturation of the peat, free storage capacity is mostly lost.

Therefore, compared to other wetlands with more variable water holding capacities, for example those that occur downstream in floodplain settings, storage capacity in recovered, healthy blanket bogs is more frequently limited (Acreman and Holden, 2013). Furthermore, in this state, healthy blanket bogs tend to generate rapid runoff that can cause floods in response to precipitation events although the speed of runoff may be influenced by the condition of the peat (e.g. hydraulic conductivity, porosity and peat compressibility) and overlying *Sphagnum* cover (Shuttleworth et al., 2019).

3.2.2 The importance of wetland extent

The overall assessment in Section 3.2 suggests individual wetland types offer varying and often limited capacity to buffer hydrological extremes as supported by Bullock and Acreman (2003) with a subset of wetland types offering relatively high buffering capacity. However, this masks the importance of the natural extent and hydrological connections (i.e., whether the wetland is hydrologically isolated or riparian and the nature of outflows: continuous, ephemeral or intermittent) of wetlands on the hydrological cycle of a catchment (Acreman and Holden, 2013). The role of wetlands in influencing catchment hydrology has been greatly affected by their degradation or shrinkage due to land management and replacement with land cover types that may have even poorer buffering capacity (e.g. urban and intensely managed farmland). Model-based studies (Fossey and Rousseau, 2016; Ameli and Creed, 2019) support the need for sympathetic management of wetlands at the catchment scale within and outwith the extent of any individual wetland body to safeguard against further wetland loss and to preserve or enhance hydrological buffering. It has been predicted that loss of wetlands regardless of type and location within a catchment leads to a loss of buffering capacity under climate change (Fossey and Rousseau, 2016; Ameli and Creed, 2019). Moreover, these same studies showed that restoring the extent of wetlands *at the catchment scale* enhances buffering capacities regardless of whether the wetlands are riparian or isolated. However, the nature of these effects is dependent on the catchment and site-specific nature of wetlands.

3.3 How do a broad range of wetlands in Scotland buffer extremes of water availability and with what mechanisms?

- **Buffering capacity is wetland type-, health- and location-specific.** The main mechanisms that buffer high and low flows are through [Literature review – Section 3.1.1, Appendices II and III]:
    - o Storage of water, for which controls include:
        - » Topography. This is a key control on the storage capacity with hollows, ridges and channels permitting the accumulation of surface and groundwater inputs;
        - » Vegetation cover. This controls evapotranspiration, canopy interception and soil water infiltration (either as soil moisture or groundwater).
        - » Soil type and condition. This controls the water table level (depth of saturation), soil moisture and infiltration capacity.
    - o Delayed movement of water out of the wetland, for which controls include:
        - » Surface roughness as determined by their topography and vegetation. This controls the speed of runoff from a wetland.
    - o Seasonal variability in used and free water storage capacity is key to buffering extremes.
    - o The degree of hydrological connectivity to sources of water supply and outflows are also important factors on the temporal variability of storage capacity and in turn buffering. For example, outflows from a wetland to a river network can be continuous, ephemeral or intermittent thus determining the contribution of wetlands to streamflow generation.
    - o Buffering capacity may be reduced where a wetland has been degraded through drainage, loss of soil health or removal of vegetation.
- **Knowledge on the buffering capacity of specific wetland types is often limited** [Literature review - Table 3.1; Appendix III]. The complexity of the mechanisms and controls on those mechanisms make it difficult to provide a robust and confident assessment across the whole range of types. A wetland of a certain type can function differently in different locations; site-specific monitoring is required.
- **Our assessment of the 18 wetland types' buffering capacities is mixed, but we have more options available than restoring blanket bog for enhancing buffering capacity** [Assessment based on literature review – Appendices II and III – and indicator-based analysis and own judgement Table 3.1]. Table 3.2 shows the wetland types we have assessed to be most likely to buffer high flows, or both high and low flows, when in a healthy state:

Table 3.2 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	Floodplain fens
Alder and Fen wet woodlands	Swamps
Basin fens	Reedbeds
Transition grasslands	
High and low flow buffering	
Floodplain fens	
Swamps	
Reedbeds	

- o The other wetland types were assessed as having low buffering capacities for low and high flows when fully recovered and healthy.
- o Many wetlands have persistently high water tables meaning that their capacity to hold additional water and buffer high flows is often limited [Literature Review - Table 3.1; Appendix II]. This is because once they are full, they tend to remain so if in a healthy condition (see Section 4).
- o Nevertheless, given the loss and poor health status of many wetlands (over two-thirds were assessed as not being in good health – see Appendix IV), restoration and expansion of wetlands is expected to improve buffering capacity. For example, restored or healthy blanket bogs and raised bogs can offer greater high flow buffering capacity after dry periods in the short term until they become re-saturated compared to degraded ones.

- **Buffering capacity is catchment- and wetland type-specific but improving the extent of a particular wetland can improve buffering capacity** [Literature review - Section 3.2; Appendix III]. Riparian wetlands that are connected to watercourses potentially have a greater capacity to buffer high flows compared to isolated wetlands that are not closely connected to watercourses. However, depending on the 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.

4. RQ 2: How is this buffering capability compromised when wetlands are degraded due to land use conversion or climate change?

In this section, we consider question RQ2 from the point of view of both land use conversion and land use management, as well as climate change. The knowledge to answer this question is dispersed and incomplete due to uncertainties in how vegetation communities and soils will respond to individual changes and combinations thereof. We have, however brought together the building blocks to do so by synthesising results from the technical outputs in Appendices I, III, IV, VI and VIII.

We begin by defining wetland health in Section 4.1. In Section 4.2, we present possible types of land use conversion and management and climate change impacts that might affect wetland health and buffering capacities. The discussion on impacts sheds light on what might be considered as the consequences for the different wetland habitats when they are in poor health. We then explore the results of climate projections developed as part of the project. This provides projections of the possible spatial and temporal nature of climate change impacts, up to 2059. We then present examples of how these projections can be used to look at different buffering capacity impact scenarios. In Section 4.3 we conclude with an overview assessment of the current and future possible health of wetland habitats.

4.1 Wetland Health: What does it mean?

A comprehensive review of the literature on wetlands, described in Appendix IV, provides several notable guides and indicators of health and degradation, including the state of the water balance, that could be used for assessing wetland health. However, due to the wide diversity of wetland types, there is no one clear definition that describes a healthy wetland (see Section 7, Knowledge Gaps).

For the purposes of this study, we make a distinction between wetland health and condition, defining:

- **wetland condition** as the assessment 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** as a characteristic that includes all condition indicators but goes further to include the hydrological functionality, water quality of the wetland and ability of that wetland feature to perpetuate, maintain resilience and sustain itself over time. The hydrological health underpins all the other condition aspects that are measured, and without hydrological health the wetland will not fully function.

Understanding wetland health requires site-based monitoring over long time periods, the use of modelling and expert assessment. In Scotland, key information is normally only gathered on wetland condition through Site Condition Monitoring (SCM). SCM was not set up to measure wetland health in its entirety, but to collect simple and robust condition information that could be used to report designated site condition. Despite this, SCM provides an indication of condition on sites which are deemed to provide the best examples of their type and on sites where management effort is focused.

The data suggests that of the 571 wetland features monitored in SCM (assessed condition NatureScot SCM Data 2021), 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, *leaving a large proportion of the wetland sites in poor or declining health*. Therefore over 40% of Scotland best wetland sites are in unfavourable condition and the situation is not improving.

4.1.1 The healthy wetland

The healthy wetland is one where a series of processes occur within the wetland that enable the wetland system to perpetuate and regenerate. These processes are chemical, biological and physical, and can include a buffering mechanism such as water storage, as well as transformation of nutrients, growth and diversity of living matter. In broad terms these processes can be grouped under water quality, hydrology and habitat. The importance and dominance of each process is determined by the location and size of the wetland. Wetlands are highly dynamic and at any given time all processes may be in balance or alternatively, certain aspects may dominate. This dynamic becomes further complicated when land management and climate change influence those wetland processes and can ultimately reduce wetland health.

The functional wetland is a concept that relates to a human purpose that may become attached to a wetland type, for example flood attenuation (floodplains) or from specific wetland creation as in the case of nutrient reduction (constructed wetlands). In the case of this study, that purpose is the buffering of the climate extremes of flood and drought. Within this context, overall wetland health could be poor but function could be good. Constructed wetlands for nutrient attenuation are a good example where function (nutrient attenuation/water quality) is good but other aspects may be poor (biodiversity). To create resilience and buffering to the extremes of climate change we may have to accept reductions in wetland health or transitions to other types of wetland community.

4.2 Effects of land use conversion and management

Land conversion of wetlands for other uses, through drainage has historically been widespread. This is less prevalent in Scotland today but the impacts of these past conversions and attempted improvements still affect wetland health and capacity to buffer climate impacts. Land use management changes due to changes in agricultural production systems is now more prevalent and effects more subtle. Changes in land use management 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 conversion and management changes both within wetlands and in the catchment of wetlands that can have hydrological impacts have been identified through a literature review.

4.2.1 Land use conversion impacts

Afforestation of blanket bogs and raised bogs associated with drainage ditching can lead to changes in vegetation, increased evapotranspiration and accelerated runoff, especially following clear felling (Robinson et al., 1998; Joosten, 2009; Bathurst et al., 2018). As described in Section 3 (and Appendices I, II and III), this type of drainage could lower water tables leading to conversion to bog woodland or dry scrub/woodland (SNIFFER, 2014). This would be expected to reduce low flow buffering capacity further through increased evapotranspiration losses but may improve high flow buffering capacity by creating more variable water holding capacity if soils aren't heavily degraded.

Drainage and cultivation for agricultural productivity leads to a complete transformation of a wetland to a different type of land use, to loss of soils and vegetation (Cook et al., 2009). Drainage of wetlands to improve agricultural land can also accelerate runoff downstream and exacerbate flood peaks (O'Connell et al., 2007; Čížková et al., 2013). Drainage can lead to changes in species composition in raised bog habitats including a reduction in the abundance of *Sphagnum* (Bellamy et al., 2012) and a transition to degraded bog habitat that is no longer actively growing or accumulating peat (Section 5.4). Owing to their low economic value (compared to other woodland types) alder wet woodlands have been extensively drained and cleared for agriculture (Lake et al., 2015).

4.2.2 Land use management impacts

Alterations of floodplain hydrology through the construction of flood embankments, channel dredging and straightening of channels disconnects the natural exchange of water, sediment and nutrients (Ward and Stanford, 1995; Kondolf et al. 2006; Addy and Wilkinson, 2021). In the case of floodplain fens, this could lead to lowering of the water table and conversion to marshy grassland or wet woodland (SNIFFER, 2014). Under such a scenario, the high and low flow buffering capacity would be expected to reduce through reduced frequency of hydrological connection with the adjacent watercourse that reduces the frequency of temporary floodplain water storage and groundwater recharge. In some cases, floodplains can be actively managed to increase water storage through control structures (sluices, embankments) primarily for reducing flood risk downstream (Acreman and Holden, 2013).

Grazing and moorland burning can reduce water infiltration of soils leading to accelerated runoff (Holden et al., 2014; Murphy et al., 2021). In addition, it can cause peat oxidation, erosion and loss of key controls on buffering mechanisms provided by vegetation cover like *Sphagnum* moss, for example, in the case of blanket bog (Hampton, 2008; Ramchunder et al., 2009; Bruneau and Johnson, 2014). In contrast, wet meadows / marshy grassland habitat may be negatively affected by a lack of management through under-grazing. This can result in changes in species composition towards rank species. SNIFFER (2014) observes that management for livestock and game (including burning) prevents wetland heath from dynamically reverting to blanket bog or wet woodland.

Water abstraction specifically localised over-abstraction of surface- and ground-water for drinking, agriculture, industry, or large-scale tree planting for carbon sequestration purposes at the site of a wetland or within the catchment area. This can lead to a lowering of the water table and wider effects leading to reduced river baseflow (McCartney and Acreman, 2009) and depletion of groundwater reserves. In fen habitats, lowered water tables can result in either a) drying out and desiccation of the habitat or b) a change in the relative proportions of groundwater and surface water inflows, exacerbating eutrophication and fluctuating water levels (Šefferová, Šeffer and Janák, 2008; McBride et al., 2011).

Increased use of agricultural fertilizers because floodplain fens are at risk of enrichment from floodwaters and groundwater, particularly in intensively farmed landscapes (Wheeler, 1984; McBride et al., 2011). The loss of a healthy base-rich fen habitat can be observed in a change in species composition to scrub and woodland, as a result of eutrophication from runoff of agricultural fertilisers and herbicides. Nutrient enrichment from agriculture has caused eutrophication of many Scottish lowland swamps (SNIFFER, 2014).

Appendix I, Section 2, provides more details on the types of land use management found on each type of wetland and their potential habitat conversion trajectories (SNIFFER, 2014).

Resilience of wetlands to land use conversion/ management

Interpretation of the previous overview suggests that certain land use management interventions, such as drainage, can impact severely on both water storage and the capacity to delay the movement of water (see Section 3). Moreover, drainage can affect a wide range of controls on those mechanisms, for example vegetation, soil moisture and topography. Drastic changes to topography can have a long term influence on the surface drainage by accelerating runoff. Accelerated drainage can potentially increase erosion rates resulting in loss of soils and vegetation and the water holding capacity these components offer.

4.3 Climate change – hydrological impacts

It is clear that the occurrence of hydrological extremes of flooding and drought are expected to increase through climate change (Guerreiro et al., 2018; UKCP18, 2018; NatureScot, 2020). However, the hydrological effects of climate change will vary depending on the nature of the catchment and land use practices within it. For example, the combinations of land use and the various controls on water buffering mechanisms (e.g. topography, geology, soil moisture and vegetation) are catchment specific and can result in differences in catchment response to projected changes in climate (Capell et al., 2013; Rivington et al., 2020). The response of catchments under spatially and temporally variable climate change has implications for our understanding and management of wetlands in terms of both how the hydrological processes within wetlands are affected and their ability to buffer hydrological extremes.

Although climate projections are inherently varied and uncertain, there are some aspects we can be certain about: i) future water availability in respect of amount and timing will change, due to alterations in the balance between precipitation input and evapotranspiration output; ii) droughts are likely to occur more frequently, potentially last longer and be more severe (reaching greater soil moisture deficits; UKCP18, 2018; NatureScot, 2020; Soulsby et al., 2021) and iii) flooding events are likely to occur more frequently along with higher intensity precipitation events. The following specific hydrological impacts are likely in Scotland:

- Milder and wetter winters with more extreme precipitation events leading to higher flood frequency (Werritty, 2002; Hiller et al., 2019);
- The estimated probabilistic temperature increases 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, 2018)[2];
- Decreased annual snow cover (area), depth and duration (number of days) from the 2030s in upland areas, leading to increased winter flows and decline of spring flows as snowmelt reduces (Capell et al., 2013; Rivington et al., 2019);
- Average summer precipitation is expected to decrease but extreme rainfall events are expected to become more intense (Chan et al., 2018; UKCP18, 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).

A number of climate change related impacts on wetlands have been predicted that could in turn affect buffering capacity. It has been predicted that more intense droughts will have the greatest impact on wetlands in general by causing wider water level fluctuations (Čížková et al., 2013) and potentially the loss of wetlands through desiccation. The type and degree of change in the wetland habitat will depend on the level of resilience of the wetland to changes in water levels and periodicity. 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). The size of wetlands also determines their vulnerability to future changes and wider hydrological effects; small, isolated wetlands are less resilient to human or natural change compared to larger wetlands (Acreman and Macartney, 2009).

2 For the emissions scenario used in this study (RCP8.5)

Higher rates of evapotranspiration could significantly alter the hydrology of wetlands (e.g., Thompson et al., 2017). Coupled with reduced rainfall and prolonged dry spells, this will reduce the amount of water available to wetlands. Reduced surface wetness and leaf stomatal closure in dry conditions will reduce evaporative cooling hence increasing vegetation canopy temperatures. Evaporation from wetlands where the water table is below surface however would be expected to be less than cases where surface and/or open water dominates and may be correlated with the water table depth (Acreman et al., 2003).

A further consideration in relation to the issue of water availability for wetlands, specifically for vegetation within it, is the role of occult precipitation (dew formation due to plant surface and air temperature differences and condensation of mist on foliage). Occult precipitation may contribute significant amounts of water to the wetland, particularly in respect of providing enough water for plants to survive during dry periods. In Newfoundland blanket bogs, it has been observed to contribute to 20% of the total annual inputs (IUCN, 2014). This implies occult precipitation is particularly significant for *Sphagnum* species as they can take up water directly as they do not have a waterproof cuticle. The contribution of occult precipitation is complicated by the probability that dry conditions are likely to occur at a time during the year when dew formation may be less likely and when evaporation rates are higher. Hence whilst warmer air can hold more moisture, the net effect may be negligible due to evaporation during the day. The contribution of occult precipitation as a source of water is an area that requires further investigation.

Conversely, considering excess water, changes in seasonal weather patterns could also have implications for high flow buffering capacity. With anticipated increases in river flooding frequency during the winter months, the availability of spare capacity is likely to become even more limited compared to the summer months. Thus, the capacity of floodplain wetlands to buffer flooding is likely to become more limited in winter than in summer (Appendix III). In addition, blanket bogs and raised bogs may become more vulnerable to erosion and catastrophic "bog-burst" events due to increased intense rainfall events (Appendix I), further reducing the capacity to buffer high and low flows by reducing water storage capacity within the soil.

4.3.1 The possible spatial and temporal nature of climate change impacts on Scotland's wetland buffering capacity

In this project, we were able to further explore the spatial and temporal nature of climate change impacts on Scotland's wetlands (Appendix VI). This research used the UK Climate Projections 2018 (UKCP18) daily weather data (bias corrected and downscaled to 1 km), the UK Meteorological Office 1 km interpolated gridded observed precipitation and temperature data, and the Digital Soil Map – Hydrological Soil Type (HOST-DSM) Map of Hydrological Wetland Types we developed showing the areas in Scotland most likely to be wetlands at a 50 m grid cell resolution [Appendix VIII; Box 4.1].

The climate projections were produced by an ensemble of 12 different model members run from the HadRM3 Regional Climate Model. These 12 climate projections represent a range of possible futures, with a range of spatial and temporal differences between each ensemble member, based on a single emissions scenario (RCP.8.5) agreed by the PSG. The scenario corresponds to current high emissions rates continuing towards the 2080s. This pathway is likely to lead to a global average temperature increase above pre-industrial levels of 3-4°C. It should be noted that the high and low emissions (RCP2.6) scenarios (and those in between used by the IPCC) are similar up until the 2040s and hence the climate changes to 2060 are likely to be similar between emissions scenarios to 2060. The baseline and future periods considered in this study were 1994-2014 and 2030-2059, respectively.

Key findings from the probabilistic projections used in this study (see Section 3, Appendix VI) were:

- 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.
- May has generally been the driest month in Scotland, but this is estimated to shift later to June in the east. In the west, the driest month is likely to be either similar to the present or later (varied agreement between climate projections).
- 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 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.
- Soils are likely to become drier. The amount of maximum soil moisture deficit (how much water is needed to return them to field capacity) is likely to increase.
- Plant growing conditions will change. The length of the growing season will likely increase; last spring frosts will occur earlier and first autumn frosts occur later. Plant heat stress is likely to increase.

The underlying key message is that the climate in the future will be increasingly variable, meaning greater fluctuations between, and extremes of, wet and dry conditions, over short time periods and between years. There is an increased probability of successive drought months (within years), and back-to-back dry years. For example, dry summers such as 2018 are estimated to be 50% more likely by 2040.

The impact of droughts on wetlands will depend on their nature; there is a distinction between meteorological drought (reduced precipitation input and increased evapotranspiration output) determining the amount of water available to a wetland, and hydrological drought, which is determined by groundwater and changes in water table levels. Meteorological droughts occur over relatively short time periods (days, weeks) whereas hydrological drought is determined by preceding longer-term conditions (months, years). The work presented here (based on the research outputs of Appendix VI) uses meteorological drought as an indicator of low-flow risk, where drought is defined as a deficit between precipitation input and evapotranspiration output from wetlands.

4.3.2 Overview of climate changes and wetland buffering capacity

There are likely to be large spatial and temporal variations in climate change impacts across Scotland (Appendix VI), generally being drier in the east and south, but potentially wetter in the north-west, which will have a range of consequences on different wetland types. There are

Box 4.1 The HOST-DSM map of hydrological wetland types (at 50 m grid resolution was produced by combining soil and land use maps with information on landform types and provides national coverage of areas likely to be wetlands).

We first identified areas where soils are permanently or seasonally wet using the Hydrological Soil Type - Digital Soil Map (HOST-DSM) and where they also have land uses that can be directly associated with wetland types. Because the hydrological wetland typology is based on broad, landscape-scale hydrological features, we then classified landform type information available for these areas into hydrological wetland types, using descriptions of characteristics such as slope, relative landscape position and topography. See Appendix VIII. We hope that this mapping work can be able to support mapping required by Article 19 of the Flood Risk Management (Scotland) Act 2009.

considerable caveats that need to be considered in what determines the response of wetlands and how this relates to buffering capacity. Such changes will have impacts on the biological, physical and chemical processes in wetlands that change the control factors (i.e., topography, vegetation). This may then alter the health of wetlands through differentiated alterations of one or more of its functions. This in turn may lead to a change in a wetlands' buffering capacity. In Appendix IV on Wetland Health, our assessment[3] of the potential future health of different wetlands given climate change and no action taken to help them, suggests that 10/18 wetland types will become poor in health.

The extent of the climatic impact on wetlands is likely to vary depending on geographical location and the context specific nature of a wetland. These include location-specific differences in the particular controls on buffering mechanisms (Section 3.1.1). It will also depend on the type of wetland, and its current condition and health in that location. These site and context specific variations make it difficult to generalise about the impacts of climate change on wetlands and their buffering capacity. Hence care needs to be taken when indicating impacts on particular wetlands.

Nevertheless, the following examples can provide an insight into how changes to buffering capacity might be qualitatively assessed as a result of the analysis of climate projections, based on our own expert judgement. The increased variability in weather producing extremes of low and high flows is key to better understanding climate change projections and their interaction with land use activities. The interesting scenarios occur when such extremes of low and high flows combine within the same year and how the different levels of wetland health may affect their response. For example, if much of the increase in water comes later in the year in the form of extreme rainfall after a dry summer spell, then the resilience of a healthy bog will mean that it will more likely recover from being dried out, yet now have free storage capacity in order to better function as a buffer for that extreme rainfall event. If the bog is a degraded one in poor health, for example because it has been drained, then the consequences of drying followed by extreme rainfall will probably lead to extreme runoff and flooding, accompanied by further peat erosion (e.g. "bog-bursts" – see Section 4.3, above) and hence a further reduction in health and consequently buffering capacity.

The ability of vegetation and wetlands to recover from droughts will depend on the type of wetland, the drought duration and how re-wetting occurs (i.e. slowly or rapidly from heavy rainfall). A gap in our understanding of how wetlands may respond to future variations in reduced water availability and nature of re-wetting appears to be in how the impacts affect vegetation, or if vegetation cover has been lost, what the consequences are for the soils. If wetlands dry out and vegetation dies, then re-establishment may be by a different species, depending on the nature of re-wetting. Regarding the duration of reduced water availability, for low-flows in rivers, APEM (2017) considered 30 days to be short-term, but the effect on wetlands will vary depending on wetland type and location specific factors (connectivity, health and groundwater hydrology). A further factor is that the return period for droughts is likely to decrease, hence dry periods becoming more frequent (UKCP18, 2018). Climate projections also indicate that severe autumn storms are more likely, risking rapid re-wetting from heavy rainfall. The consequences will vary depending on wetland type, health and water content at the time of re-wetting. Dry soils can become hydrophobic and combined with intense rainfall could generate significant runoff leading to increased soil erosion. In contrast, prolonged low intensity rain may be more effective at rewetting soils (Doerr and Ritsema, 2006) with reduced risks of negative consequences. If wetlands are already saturated, then buffering capacity is limited and heavy rain is likely to result in flooding (Section 3).

Table 4.1, below, provides an overview of other plausible changes in climatic conditions and what their impacts may be on buffering capacity. These interpretations are based on our current knowledge and judgement, with the above caveats. We also provide indications of our levels of certainty (High / Medium / Low) about the probabilities of changes occurring and what the consequences may be.

3 This assessment was based on grey literature, engagement with external experts (details provided in Appendix IV) and Appendix IV lead author's own expert opinion.

Table 4.1 An overview of plausible projected changes in climatic conditions and what their impacts may be on the buffering capacities of wetlands.

Climatic change (Level of Certainty H/M/L [a])	Scenario	Impacts on wetlands (Level of Certainty H/M/L)	Combined effects on buffering (Level of Certainty H/M/L)	Wetland vulnerabilities (Level of Certainty H/M/L)
Longer summer drought periods (H)	Increased drying of wetlands in a summer followed by flooding in autumn	Drying soils (H), reduced vegetation growth (M) and health (M), changes in species composition (L), increased fire risk (H)	Reduced low flow buffering but increased short term high flow buffering if the peat soil maintains resilience and does not become hydrophobic or eroded	Bogs – high due to fire risk and drying (H) Fens – low as they tend to have large stores of water (H) Springs and flushes (M) These wetlands can return and expand quickly if water supply resumes
More intense precipitation events (H)		Rapid re-wetting of soils (H), erosion risk (H) on exposed soils (L on stable floodplain soils)		
Successive drought years (H)	Back-to-back years with spring or summer droughts, occasional high intensity summer rainfall and winters with above average precipitation	Reduction in area of wetlands (H) Succession to grassland and trees (M) Reduced vegetation growth and changes to species composition (M)	Buffering temporarily lower due to reduced vegetation growth and decreased extent or volume of available storage (L)	Fens subject to vegetational changes (M) Reduction in area of bogs (H) due to increased fire risk and loss of vegetation
High precipitation winters (H)		Erosion risk (H) Catastrophic peat failure (H) Structural change to wetlands caused by water movement within wetland. (M)	Buffering (M) due to reduced surface roughness (flattened vegetation) and depth of water no longer effected by surface roughness	Expansion of areas influenced by springs and flushes (H) Fens and bogs would generally benefit from this scenario. Increased flushing of nutrients on one hand but also increased atmospheric nitrogen input (M)
Reduced winter snow cover (M to 2040, H afterward) higher minimum temperatures (H) and reduced freezing periods (M)	Milder winters with less snow cover (area), reduced depth and duration (fewer days), less intense cold and fewer frosts (first autumn frost later, last spring frost earlier)	Reduced snow cover will alter the surface albedo and hence higher energy input to vegetation, soils and water leading to microclimate warming (H). Reduced late spring and summer flows from melting snow will potentially reduce area of high altitude flushed wetlands (M)	Buffering (M) *Sphagnum* communities sustained by steady snow melt will reduce in size	Whilst there may be reduced snow cover, there may be similar or increased amounts of rainfall. The consequences may be that water input to wetlands is more than from snow, but the time of input is changed, with reduced slow release from snow melt in the spring (L)

[a] **Note on certainty levels:** The level indicated is our assessment of how certain we are that a type of climatic change will occur, what the impact on wetlands will be and what the combined effects will be on their buffering capacity. There are further areas of uncertainty, for example how occult precipitation may change in the future. High = we are certain there is a high probability of this occurring. Medium = there is a medium level of certainty, with a range of probabilities of this occurring. Low = we have a low level of certainty about this occurring, as there are still large uncertainties about the probabilities. Low levels of certainty also reflect where there are large knowledge gaps.

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

- **Land use conversion, land management and climate change have impacts across the full range of buffering mechanism controls** [Literature review – Section 4.2]
    - o These impacts alter the healthy functioning of wetlands by affecting the physical, hydrological, chemical and biological processes that determine the controls on buffering mechanisms (Section 3.1.1), i.e., topography, degree of connectivity to the hydrological system, soil, vegetation and surface roughness.
    - o In most cases, buffering capacity is weakened by such impacts, although at times it can improve. The exact impacts of these impacts on wetland buffering capacities are however dependent on site- and catchment-specific controls and wetland health for which there is often insufficient data and knowledge
    - o There is more literature on land use management impacts on buffering capacity than on climate change ones and this difference represents the fact that climate change represents a yet untravelled pathway. [Literature review – Section 4.2, 4.3]
- **Due to climate change, there is likely to be greater inter- and intra-annual variability in weather conditions, with altered seasonality and more frequent extremes of weather affecting wetlands** [Analysis of climate change projections, Section 4.3.1]
- **Climate-change related drought and flooding episodes will pose risks to wetlands and their buffering capacity** [Own assessment of available evidence – Section 4.3.2, Table 4.1]
    - o Wetlands are dynamic, adaptive systems when provided space and time to adapt, yet we do not fully understand how climate extremes will affect them.
    - o Consequences on buffering will depend on the health of the wetland, and the timing and frequency of the climate events.
    - o Impacts could be beneficial or detrimental. For example, blanket bogs may have greater capacity in the short term to store water and buffer high flows following droughts as the water table level falls thus providing spare capacity. However, if the bog is in an unhealthy state, the peat may become hydrophobic and exacerbate runoff leading to downstream flooding.
    - o Rain-fed wetlands (e.g. raised bogs, bog woodland and blanket bog) are more vulnerable to meteorological droughts.
    - o Groundwater-fed wetlands (e.g. basin fens, base-rich fens and fen meadows) are more vulnerable to hydrological drought.
- **There remain large uncertainties as to whether wetlands are more resilient to climate change than land management** [Own assessment of available evidence - Section 4.3.1]
    - o The natural resilience of wetlands' buffering capacities to impacts from climate change, for example those that impact vegetation cover or soil moisture, might be greater than from land use conversion or management activities that create changes directly affecting the topographical infrastructure of the habitat (e.g. through drainage and landscaping).
- **The future health of most types of wetlands is likely to decrease as a result of climate change if no action is taken** [External expert/own assessment – Appendix IV]
    - o Land management and its impacts are within our control, whereas the climate is not. This research has indicated that it is possible to estimate future climatic conditions to guide which land management can be conducted to protect wetland health.

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

5.1 Wetlands as a home for species of conservation concern

Ninety-eight out of 700 species on the Scottish Biodiversity List (SBL) in the two highest categories of concern "conservation action needed" and "avoid negative impacts", are associated with wetlands (Appendix V). The distribution of these species groups across wetland types can be seen in Table 5.1, below. Blanket bog appears to have the widest range and number of species groups (24) on the list. Although this is perhaps not surprising given its large extent across

Table 5.1 Summary of the wetland species in the Scottish Biodiversity List (SBL) by their primary wetland habitat and the main taxonomic grouping. Only species listed in the SBL categories "Conservation action needed" and "Avoid negative impacts" are included. Note that "General wetland" refers to species that are found across a wide variety of habitats or where habitat descriptions are imprecise.

Wetland type	Aquatic invertebrates	Birds	Fungi	Mammals	Non-vascular plants	Reptiles & amphibians	Terrestrial invertebrates	Vascular plants	TOTAL
Blanket bog	6	1	4		4		6	3	**24**
Fen meadow		2					1		**3**
Fen woodland, alder woodland, wet woodland		1	5					1	**7**
Fens: Base-rich fens, alkaline fens					4		3	8	**15**
General wetlands	3	2		3	2	2	1	2	**15**
Open water transition fens		1							**1**
Reedbeds and swamps		4	1				1		**6**
Transition mires and quaking bogs					6			2	**8**
Wet heath		1	3					1	**5**
Wet meadows, marshy grassland		5			1	1	4	3	**14**
TOTAL	**9**	**17**	**13**	**3**	**17**	**3**	**16**	**20**	

Scotland (c. 1,795,000 ha - Bruneau and Johnson, 2014). By comparison, transition mire and quaking bogs with only 1420 ha *(ibid.)* are still home to 8 of these species despite their small extent. Note that "General wetland" refers to species that are found across a wide variety of habitats or where habitat descriptions are imprecise.

5.2 Rare plant species at risk due to increases in dryness or wetness of wetlands

Broad potential trajectories of habitat change and causes of change have been made for different wetland types (Appendix I, Section 2). However, it is difficult to predict the impact of hydrological change on species without detailed knowledge of species' niches. This is unavailable in a comprehensive fashion for most species groups, but for plants we have summaries of these niches in the form of Ellenberg Indicator Values (Ellenberg, 1988). Using the Ellenberg Indicator Values for water (EIV-F) for each species compared against the mean for each wetland community highlights the species that might be at moderate or severe risk due to an increase in different wetlands' wetness or dryness (see Box 5.1 for overview of the approach; see Section 1, Appendix VII on "Linking Ellenberg indicator values for water (EIV-F) to risk from low and high flows" for details). Table 5.2 shows the rare plant species identified in the National Vegetation Classification (Rodwell, 1991a; 1991b; 1992; 1995) and plants listed in the SBL at risk from increased wetness and dryness.

Table 5.2 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 by wetland type. Note that the analysis has been carried out on the National Vegetation Community (NVC) that the species belongs to, not to the specific species (see the bottom of the table for the key to the NVC community codes given in brackets after the name of the rare species).

		Increased wetness		Increased dryness	
Wetland type	**Species Name (and main NVC community)**	**Severe**	**Moderate**	**Moderate**	**Severe**
Bog woodland	[*]*Pyrola rotundifolia (W18)*			X	
Fen woodland, alder woodland, wet woodland	[*]*Pyrola rotundifolia (W3)*		X		
	[*]*Corallorhiza trifida (W3)*	X			
Fens: Base-rich fens, alkaline fens	[*]*Minuartia verna (M10)*	X			
	[*]*Schoenus ferrugineus (M10)*			X	
	[*]*Carex capillaris (M10)*		X		
	[*]*Carex vaginata (M11, M12)*	X			
Raised bog/Depressions on peat/Blanket bog	[*]*Sphagnum pulchrum (M2)*			X	
	[*]*Campylopus setifolius (M15, M17)*			X	
	[*]*Rhynchospora fusca (M16)*			X	
	[*]*Campylopus shawii (M17)*			X	
	[*]*Betula nana (M19)*			X	
Transition mires and quaking bogs	[*]*Potamogeton coloratus (M9)*			X	
	[*]*Pyrola rotundifolia (M9)*	X			
Reedbeds and swamps/Open water transition fens	[*]*Wolffia arrhiza (S14)*			X	
Wet meadows, marshy grassland, fen meadow	[†]*Oenanthe fistulosa (MG13)*				X
	[†]*Anagallis arvensis (OV28)*	X			

Key to National Vegetation classification communities: M2 *Sphagnum cuspidatum/recurvum* bog pool community, M9 *Carex rostrata-Calliergon cuspidatum/giganteum* mire, M10 *Carex dioica-Pinguicula vulgaris* mire, M11 *Carex demissa-Saxifraga aizoides* mire, M12 *Carex saxatilis* mire, M15 *Scirpus cespitosus-Erica tetralix* wet heath, M16 *Erica tetralix-Sphagnum compactum* wet heath, M17 *Scirpus cespitosus-Eriophorum vaginatum* blanket mire, M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire, S14 *Sparganium erectum* swamp, W3 *Salix pentandra-Carex rostrata* woodland, W18 *Pinus sylvestris-Hylocomium splendens* woodland, MG13 *Agrostis stolonifera-Alopecurus geniculatus* grassland, OV28 *Agrostis stolonifera-Ranunculus repens* community.

The analysis of rare species, in Table 5.2, above, shows a slight preponderance of species presences in habitats at risk of increased drying (n = 11) compared to increased wetting (n = 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. vaginata* 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 5.2). *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.

Box 5.1 Ellenberg Indicator Values used to qualify risk levels by characterising the species in terms of their environmental preferences.

Ellenberg Indicator Values for Water (EIV-F) 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. E.g., *if species X has a much lower EIV-F than the sample's average it can be assumed that this species would be at risk of an increase in abundance of water should there be increased flooding. Similarly, if species Y has a much higher EIV-F than average it is more at risk from drought than the average species from that sample.*

5.3 A closer focus on climate change impacts on plant biodiversity

In this section, to see what the further impact on plant biodiversity might be, including on rare species, we focus on two of the possible impacts of climate change resulting from the spatial and temporal analyses presented in the technical output on climate change impacts (see Section 3 in Appendix VI).

5.3.1 Shift of the month with the maximum drought – May - June

The implications are that the maximum drought in any year will be more likely to occur in June, rather than May in most of Scotland, with the exception of the north-west Highlands.

Biodiversity Impacts: Species of drier microhabitats in wetlands in southern Scotland 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.

5.3.2 Increase in consecutive drought months

The findings in Section 4 using the UKCP18 projections suggest that all the ensemble projections are in agreement that, in the southern part of Scotland the average number of months with successive droughts would increase.

Biodiversity Impacts: This set of projections suggest increased impacts on biodiversity in southern wetlands, driving species community change towards those more typical of drier areas with the concomitant loss of species from wetter microsites in each habitat. For example, should blanket bogs, raised bogs and depressions on peat dry out in the south of Scotland, Table 5.2 suggests that there would be up to five rare plants at moderate risk of losing out as a result of this type of long-term change, i.e., *Sphagnum pulchrum* (M2), *Campylopus setifolius* (M15, M17), *Rhynchospora fusca* (M16), *Campylopus shawii* (M17), and *Betula nana* (M19).

5.4 A final note: Changes in vegetation communities change the buffering capacity of wetlands

Increased frequency of hydrological extremes projected under climate change - 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 and prevention of any recovery (Acreman et al., 2009). Such changes have the potential to fundamentally affect the hydrological character of a wetland through altering the roughness and soil water infiltration (Marshall et al., 2014). Furthermore, loss of vegetation could reduce canopy water storage capacity through reduced rainfall interception and alter transpiration rates. It is important to consider both rare species and common, especially those that form the dominant species of particular wetland habitats, e.g., the bog building *Sphagnum* species which are not only necessary for and responsible for new peat accumulation and water holding capacity but also have effects on water chemistry. Even for *Sphagnum*, little is known about species dynamics as hydrology changes and there is the potential for replacement of one S*phagnum* species by another with different tolerances as the Ellenberg-F value ranges between 6 and 10 for different species (Hill et al., 2007). These changes could in turn lead to a reduction in the water holding capacity and buffering capacities of certain wetlands.

5.5 Conclusion

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 plant 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 plant species at risk if there is more drying out of these communities. Some of these impacts will likely be buffered since many wetlands are a mosaic of different habitats which share many species.

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. We also lack comprehensive knowledge of species niches for species other than plants, which makes predicting the impacts of hydrological change impossible for most wetland types.

To make effective predictions of biodiversity change at a site level one needs information of species preferences and hydrological regimes. This has been done for a limited number of sites (e.g., Swetnam et al. 1998; Thompson et al., 2009; Dwyer et al., 2021) and this site-focused approach could be extended to specific ones in Scotland. For a broader ability to predict change it would be necessary to properly monitor the hydrological regime and species distributions at a number of sites in order to develop models of species change in relation to hydrological change.

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

- **Wetlands are home to many species of concern with respect to their conservation.**
    - o Ninety-eight out of 700 species on the Scottish Biodiversity List (SBL) in the two highest categories of concern “conservation action needed” and “avoid negative impacts”, are associated with wetlands. [Literature review - Table 5.1]
- **We have a very limited ability to predict the impacts of hydrological change on wetland biodiversity.**
    - o We lack comprehensive data on most species’ niches as well as site-specific hydrological conditions. [Literature review - Section 5.2]
- **We can identify wetland plant species at risk within each national vegetation community class and whether they are rare species.**
    - o We have information on species' niches with respect to plants. [Literature review - Section 5.2]
- **Most wetland vegetation communities possess some species at risk of increased dryness and some at risk of increased wetness.**
    - o This includes a small number of rare plants and two plants on the Scottish Biodiversity List. [Indicator-based analysis – Table 5.2]
- **Changes in vegetation communities can change the buffering capacity of wetlands.**
    - o For example, the bog building *Sphagnum* species are not only necessary for and responsible for new peat accumulation but also for water holding capacity and have effects on water chemistry. [Literature review – Section 5.4]

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

The answers to this question that we present in this section are based on our overall expert assessment and the knowledge-exchanged with a broad range of project workshop participants as part of our engagement approach.

6.1 Opportunities

The principal opportunities for encouraging positive enhancements to wetlands’ buffering capacities derive from:

- The Scottish policy environment:
    - o The third Land Use Strategy 2021 – 2026 (LUS-3): calling for large scale ecosystem approaches and the development of a “resilient water environment” that can “help Scotland adapt to our already-changing climate” (p31), noting peatlands as a “sponge” to mitigate flood impacts.

- o Scottish Biodiversity Strategy Post-2020 – A Statement of Intent (SBS): highlighting the multiple benefits of wetland-based Nature Based Solutions as a means for increasing not only biodiversity but also to gaining the multiple benefits of tackling climate change, flooding and improving water quality (p3). It also contains a commitment to protect 30% of Scotland's land by 2030 (p4).
- o Flood Risk Management (Scotland) Act 2009 (FRM Act), Article 20: requiring the 6-yearly assessment of natural features, including wetlands, whose alteration or restoration can contribute to flood risk management.
- o The second Scottish Climate Change Action Programme 2019-2024 (SCCAP-2): promoting large scale habitat restoration; promoting peatland restoration as a means of mitigating climate change, supporting biodiversity, and mitigating flood impacts.
- o Fourth National Planning Framework (NPF-4) – improving the natural environment for the wellbeing of communities and supporting the green recovery.
- o River basin management plans (RMBP) – ensuring, among other aspects, the achievement of good baseflows in Scotland's water courses.

- The consequences of Brexit and the need to redesign agri-environmental schemes;
- Organisations in the public and private sector developing net zero emissions targets and investing in natural capital assets to net-off their residual operational carbon emissions (Scottish Water, 2021);
- Operational trends: the frequency of Site Condition Monitoring of sites has reduced in recent years;
- Increasing awareness of the weaknesses in existing traditional approaches to targeting wetland management, monitoring wetlands and incentivising restoration-based management. Our assessment of the pros and cons of these approaches is provided in Table 6.1 below.

6.2 Potential changes in land or water management, which could enhance the buffering capacity of wetlands in Scotland

We have identified 16 approaches, ranging from operational management activities to monitoring, that we believe would increase the buffering capacity of wetlands in Scotland. In Table 6.2, below, we provide a short description of each, and our assessment of their advantages and of their potential barriers to implementation. In the final two columns, we identify i) complementary approaches by way of their ID numbers, which might reduce some of their barriers; and ii) which policies the approach would support if implemented.

Table 6.1 Summary of the key pros and cons of three traditional management approaches.

Traditional Approach	Pros	Cons
Designated sites	Targets wetland management efforts on the 'best' sites	• Restrictive and does not account for dynamic habitats or the effect of the extremes of Climate Change • Based just on biodiversity value • Wetlands considered as isolated sites • Does not take into account the wider catchment zones that might provide water influxes into the wetland to regulate its water balance

Wetland monitoring focussed on Site Condition Monitoring	Focusses on sites with specific aspects which are currently valued e.g., biodiversity
	
	Provides a standardized approach to monitoring
		• Restricted approach
		  • Only condition measured
		  • Does not measure hydrological or hydro-chemical factors of health
		  • Designated sites only
		• Process slow to react to change
		• Many wetlands do not suit a standardised approach

Agri-environmental schemes	Open to all registered land managers
	
	Relatively easy to measure outputs
		• Low uptake of schemes
		  • Unattractive payment rates for farmers to "wet-up" land
		  • Complexity of the scheme puts off many smaller landowners
		  • Prescriptions restrictive, inflexible and not adaptive
		• Do not represent good value for money; administratively costly
		• Often not integrated with other projects
		• Has not delivered large gains for wetlands

Table 6.2 Summary of the key advantages of and barriers to proposed alternative management approaches.

ID	Alternative approaches	Description	Advantages (* indicates examples identified by participants of the Project Results Workshop 27th October 2021)	Barriers (* indicates barrier identified by participants of the Project Results Workshop 27th October 2021)	Complementary approaches (ID)	Support provided by policy
	Operational management					
1	Active management of wetland water balance	Sustained tailoring of a wetland's water levels and fluxes following its initial restoration, e.g., using controllable sluices	Increase in variability of the wetland and therefore buffering capacity An adaptive response to projected increase in climate variability caused by climate change An example of this can be found in The Mound, a designated site in the Dornoch Firth.* https://sitelink.nature.scot/site/1202	Requires human resources on the ground. Could be automated with remote sensing, but needs human back up, or innovation in practical methods not requiring technology Requires regular monitoring of water balance Requires understanding of potential changes to the water balance due to climate change Mistakes can be costly and who would take responsibility?*	12	Green recovery SBS; LUS-3; NPF-4 FRM Act RBMP
2	Selective modification rather than wholesale removal of flood embankments to hold and control release of floods	Modification could be the partial removal of flood embankments (Addy and Wilkinson, 2021) or the installation of sluices to retain water	Increases hydrological connectivity of altered floodplains Reduces the negative impacts of flood embankments on high flow and low flow buffering capacity (see section 4.2.2) Less costly than fully removing embankments Sluices rather than removal allows controlled release of flood waters An example is being provided in the River Nith, Dumfries*	The use of sluices could be automated but requires some human intervention and monitoring Requires landowners' and infrastructure owners' agreement for possible expansion of flooded areas May cause concern for landowners* Without sluices, reduces the possibility of controlling a slow release of flood waters.	12 11	FRM Act
3	Sympathetic management or restoration of wider catchment connected to wetland	Conservation and restoration of water influxes outwith, but connected to, the wetland footprint	Improved hydrological connectivity between wetlands and catchment Increase in health and thus likelihood of offering buffering capacity	Requires identification of the causes of hydrology impact both direct (e.g. drainage ditching) and indirect to inform correct remedial actions Need to extend resources outwith designated sites	15, 5	FRM Act RBMP Private water supplies
4	Wetland-friendly management of connected groundwater	Monitoring and incentivisation of appropriate use of groundwater through variable charging mechanisms, similar to electricity grid	Responds to likelihood of groundwater abstraction increasing due to climate change as surface water reserves become depleted. Helps to preserve health of wetlands which may aid buffering capacity	Groundwater monitoring is difficult Tension between wetland requirements and commercial or private water supply needs	15 11	SCCAP-2 Private Water Supply policy; Commercial abstraction in agriculture/ the whisky industry

ID	Alternative approaches	Description	Advantages (* indicates examples identified by participants of the Project Results Workshop 27th October 2021)	Barriers (* indicates barrier identified by participants of the Project Results Workshop 27th October 2021)	Complementary approaches (ID)	Support provided by policy
5	Adaptive wetland management, experimentation and learning by doing	On selected strategic and well monitored sites experiment with different management regime to optimise buffering but also Natural Capital. For example, reinstatement of irrigated meadows and use of sluice gates to control water storage and release for controlling floods	Fills site-specific knowledge gaps on how to increase buffering capacity for both low flows and high flows	Failure of some projects will have to be accepted and taken into account in overall costs Monitoring and learning systems needed	15	SCCAP FRM Act
6	Giving space and time for dynamic wetlands to adapt	Rather than conserve in current state, acknowledge that wetlands are dynamic and evolve. Provide areas for wetlands to slowly expand or shift location, or to succeed to other wetland types	Mitigates unprecedented and uncertain climate change impacts. Allows the wetland to adapt naturally and resiliently to climate change Resilient buffering capacity for low flows and high flows	Uncertain outcomes Monitoring required to keep a check on the adaptation pathway of the wetland Requires landowner agreement for possible change in wetland areas	5 12, 15 11	
7	Altering grazing regime for targeted improvements to wetland	Reducing grazing to improve the vegetation structure to enhance hydraulic roughness, or to maintain desired wetland types	Increase in buffering capacities for high flows	Can be difficult to enact but could be achieved through outcomes payment system		
8	Expansion and management of large-scale networks of wetlands	As done by Central Scotland Green Network (CSGN), identify existing links between wetlands and identify current gaps and fill those gaps through wetland creation	Increased low and high flow buffering capacity Increased resilience of wetlands Increased biodiversity The full range of wetland types are maintained and restored. Including hitherto under-appreciated, rare or isolated wetland types such bog woodland and transitional salt marshes	High resource costs – the degraded state of individual wetlands and the hydrological links to other wetlands and wider catchments, would mean considerable efforts and funding are required to bolster wetland health and functioning Requires landowner agreement for expansion in wetland areas	13, 12 9, 10 11	Large scale ecosystems approaches and habitats LUS-3; FRM Act RBMP

ID	Alternative approaches	Description	Advantages (* indicates examples identified by participants of the Project Results Workshop 27th October 2021)	Barriers (* indicates barrier identified by participants of the Project Results Workshop 27th October 2021)	Complementary approaches (ID)	Support provided by policy
	Enabling activities					
9	Adopt a Water Framework Directive (WFD) approach to wetland protection	The WFD includes all types of wetlands	The full range of wetland types are maintained and restored. Increases resilience of wetlands and buffering capacity Awareness of wetlands is raised as they are considered part of the health of the whole catchment	Costly to put into action across all wetlands Unless targeted, it might mean potential dilution of funding to wetlands in dire need or in areas of high flood/drought risks	12, 13, 14	WFD
10	Development of a strategic Wetland Climate Change Action Plan	Develop a strategic plan of how the functions of all wetlands can be beneficially harnessed for society and ecosystems	Raise awareness of the importance of all wetlands and the ecosystem services provided and instigate action on the ground Provide a clear action plan to counter the effects of climate change			SCCAP-2, LUS-3
11	Create catchment partnerships of land managers and businesses	Provide the conditions for groups of individuals to come together to create working partnerships	Lots of good examples to follow from river catchment partnerships	Difficult to maintain a diverse group of actors working together under a common goal	14, 15	
12	Investment in local human resources	Invest in local human resources for the maintenance of wetlands	Can be considered part of the green recovery Makes up for the lack of capacity in wetland restoration in Scotland Provides critical support for active management of wetlands	Long-term public investment required to pump prime Market forces would probably not work in this case		NPF-4 LUS-2
13	Integrated habitat challenge funds	Funding sufficiently to flexibly respond to new government and climate challenges	Flexible way to fund, targeted at current need or areas where activity is required quickly Could combine with private funding to increase the incentives Resourced with a simple and well-planned application process	Sometimes hard to measure and quantify the exact output and benefits Will not work without flexibility		Post-Brexit agri-environmental schemes

ID	Alternative approaches	Description	Advantages **(* indicates examples identified by participants of the Project Results Workshop 27th October 2021)**	Barriers **(* indicates barrier identified by participants of the Project Results Workshop 27th October 2021)**	Complementary approaches (ID)	Support provided by policy
14	Alignment of wetland management with commercial output/ income	Trial schemes like the Insh Marshes scheme to produce viable wetland products	Not reliant on Government funding, but would benefit from government seeding, like the Civtech challenges Would optimise the wetland resource fully and provide other benefits Increase the perceptual value of wetlands Provide alternative farm income, Gov/Private	Focus may be on only commercial or paid for output at the expense of biodiversity Creation of perverse incentives creating undesired outcomes Gaming[4] of scheme by private sector		Post-Brexit agri-environmental schemes
	Monitoring					
15	Setting up of a network of monitoring sites	Selected wetland reference sites representing different wetland types across Scotland's biogeographical zones	Will provide the detailed real time information on wetland health, to enable suitable management responses to climate change	Will take time and has resource implications but could optimise remote sensing		FRM Act
16	Completing the national inventory of wetlands		Will provide an accurate overview of the wetlands resource and provide opportunity mapping resource	Poor access to data and limited capacity to analyse it* Cost and scale of task*		FRM Act

[4] Policy gaming is the process of an actor seeking loopholes in policy instruments in order to accrue personal or organisational advantages to the detriment of achieving the goals of that policy. A recent example of policy gaming in Scottish agriculture is the existence of "slipper farms" (STFA CALLS ON GOVERNMENT TO STOP CREATION OF A NEW GENERATION OF SLIPPER FARMERS (tfascotland.org.uk)).

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

- **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.**
- **Of the 16 approaches assessed, potential key changes in land or water management for enhancing wetland buffering capacity in Scotland were identified.**
  - o Many of these approaches can provide direct cross-sectoral support to current government policies and can be combined to mitigate barriers to implementation (own assessment - Table 6.2). Some examples include:
    - » The expansion of wetlands through the creation of large-scale wetland networks could potentially increase buffering capacity and wetland resilience. However, effectiveness depends on the catchment specific hydrology, arrangement of wetlands, wetland health and types of wetlands present; our assessment suggests that prioritising efforts on for example floodplain fens, wet grasslands and deciduous wet woodlands may be more effective (Table 3.2). Expansion would support policies requiring ecosystem approaches, but this requires significant levels of resources and stakeholder agreement from landowners and other actors (Table 6.2; Section 3.2.2).
    - » The active management of wetland water balances to maintain seasonal variability would be an adaptive management response to increasing climate variability (Table 6.2).
    - » If coupled with investment in local community employment in such activities, combined they would have the benefit of directly supporting the Land Use Strategy, National Planning Framework-4, Green recovery, and the Flood Risk Management Act 2009, as well as supporting River Basin Management Plans (Table 6.2).
- **Key barriers to implementing potential changes in land or water management for enhancing wetland buffering capacity in Scotland were also identified, including:**
  - o Significant requirements for funding, human resources, and monitoring.
  - o Reaching agreements with landowners and other actors.
  - o 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).

7. Key knowledge gaps

Wetland hydrological functioning. The following wetland habitats remain particularly understudied in terms of their hydrological functioning (Section 3.2). Water balance studies are required for: *Transition mires and quaking bogs; open water transition fens; basin fens; bog woodland; fen meadow; transition grassland; transition saltmarsh.* However, there is also a general need to research wetland types which, although well studied in the international literature, available knowledge on these types may not be applicable to the distinctive character of Scottish examples. For example, blanket bogs, raised bogs and floodplain fens. How assemblages of different networked wetlands function together over seasons and annually and their relationship to streamflow generation, are also key knowledge gaps. We also need to further develop the evidence base for the low and high flow buffering capacities of the types of wetlands that our findings suggest have good potential (see Table 3.2).

Development of mapping and modelling tools to help prioritise which wetlands to restore and reconnect at the catchment scale. This would build on the HOST-DSM national scale mapping of potential wetland distribution presented in Appendix VIII. This mapping would include where wetlands have been, where they currently are and where they might be able to prosper under different future climate scenarios. Robust, validated hydrological models can be developed to inform the high and low flow buffering effects of different wetland restoration scenarios under different climatic and land use conditions, in different locations. Such tools have not been applied at the catchment scale in Scotland.

Wetland Health. With the climate changing quickly and with drought and flood extremes more common and impactful, real-time knowledge of how wetlands and managers of adjacent land respond is critical to effective decision making to protect wetlands and other catchment land uses. A combination of remote sensing, ground truthing and research can fill this gap. An effective way to measure wetland health and begin to fill the many knowledge gaps is to set up reference wetlands where intensive monitoring could be used to inform management of similar communities on non-monitored sites (see Sections 6 and 8).

Climate change. There is a need to improve the modelling of future evapotranspiration and wetland hydrology. This requires the use of more sophisticated vegetation and soil water balance models using wetland type specific parameters and site monitoring to provide calibration and validation data. Whilst there is improving capabilities to estimate future meteorological drought, there remains large uncertainty in our ability to model hydrological drought. Additionally, the climate model projections used in this study are known to not represent extreme events well (i.e. droughts, high rainfall events, low minimum temperatures). Newer projections based on Convection Permitting Model simulations are required. The future impact on the role of occult precipitation with respect to buffering capacities needs to be researched. Finally, climate impacts on snow cover and consequences on water storage and release are poorly understood.

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 most 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 do not know how this would translate into community change as competitive interactions under changed hydrological conditions have been little studied. Additionally, how such changes (at the plant community level or in site hydrological regimes) then cascade into driving change in other species is also unknown. Finally, the difference in the impacts on biodiversity of the two climate change impacts related to drought (discussed in Sections 5.3.1 and 5.3.2) highlights that we know little about how shifting hydrological conditions may affect biodiversity. For example, is it the intensity, length or timing of drought that results in the biggest impacts?

Downstream impacts due to changes in wetland buffering capacity. Changes in wetlands are likely to have downstream consequences on water use by agriculture, industry and businesses, as well as on aquatic biodiversity. Furthermore, this could result in changes of flood risk downstream and avoided or added flood damage costs depending on the nature of changes to buffering capacity. There is a need to better research these economic and ecological impacts.

Developments in future land use policies and economics. There is increasing interest in the use of land for carbon sequestration. This is leading to acquisition of large areas of land, including wetlands, for tree planting, peatland restoration and 'rewilding'. This is associated with changes in rationales for land ownership and hence changes in land management practices. These changes are likely to have consequences on catchment hydrology and hence wetlands and their buffering capacity.

8. Recommendations on enhancing the buffering capacity of wetlands in Scotland

We have shown in this report the importance and complex nature of wetland buffering capacities in Scotland (Section 3), and the need to better understand these at the site-level across a range of wetlands. The study also shows the importance of enhancing wetland resilience as this is crucial at a time when hydrological extremes are becoming more prevalent due to climate change. As described in Sections 4 and 5, many wetlands are not in good health and, for the majority, that health will likely decline, along with their buffering capacities and biodiversity. To counter this, a shift in land management towards adaptive management (Mysiak et al., 2010) is recommended with the aim of promoting the well-managed expansion of the full diversity of wetlands to better connect wetlands to both water courses as well as to each other, and to provide them the space and connectivity to facilitate their natural dynamic capacities to adapt.

The following key messages and associated recommendations for increasing the buffering capacity of Scotland's wetlands are underpinned by what we consider to be the most wide-ranging, interdisciplinary set of technical outputs currently available about water holding capacity, buffering capacities and health with respect to these 18 categories of wetland habitat found in Scotland:

- **Wetlands are more resilient if hydrologically connected to watercourses and each other.**
    - o **Create, restore and manage networked wetlands.** Although isolated wetlands still offer additional useful storage capacity and possible specific biodiversity interest, and thus should be invested in, resources should be targeted creating larger areas of interconnected wetlands of different types. The different specific characteristics and capacities of the composite wetlands would then plug gaps in overall landscape-scale buffering capacity and improve the resilience of the original

wetlands (See Sections 3 and 4). Together with engineering solutions and other nature-based solutions (such as good soil management, site-sensitive tree establishment (i.e., riparian woodlands) and river restoration), networked wetlands would help to maintain the overall resilience of the catchment system should one part of the system or wetland network weaken due to climate change. This would support the current Land Use Strategy, the Scottish Biodiversity Strategy and SCCAP with their focus on large scale habitat development using ecosystems approaches. NatureScot is setting up a pilot in the Borders for this type of approach.

  - o **Invest in active wetland management to facilitate the sustained tailoring of a water levels and fluxes (Table 6.2, Alternative management approach 1). Link this to:**
    - » **Investment in local human resources for the maintenance of wetlands, as part of a green recovery plan (Table 6.2, Alternative management approach 12).** E.g., supporting the NPF-4 and the third Land Use Strategy's aim of supporting community wellbeing. It would also encourage community involvement in flood risk management (FRM Act 2009).
    - » **Design incentive schemes for large-scale wetland restoration that will cover land ownership (Table 6.2, Alternative management approach 13 & 14). Create catchment partnerships of land managers and business (Table 6.2, Alternative management approach 13 & 14).** E.g., the Alewater catchment group and the Tweed Forum (Scottish Borders) have brought together all interests to create a wider dynamic of communication and management, as well as generate funds.

- **Blanket bogs are the most common wetland in Scotland and should be restored because of their extent and since their buffering capacity has been reduced due to degradation. However, relative to area, the buffering capacities of other wetlands are likely to be comparatively greater than blanket bogs (and other peatlands) when in a healthy state.**
  - o **Target additional resources on managing or restoring wet meadows, fen meadows, floodplain fens, swamps, reedbeds, transition grasslands, basin fens and certain types of wet woodlands that provide relatively higher low and/or high flow buffering opportunities.** E.g., in order to maximise water management benefits (Section 3.3).
  - o **Broaden future policy related to wetlands.** E.g., in future land use, climate change and biodiversity strategies, include this broader set of wetlands and their role in low flow as well as high flow buffering.
  - o **Resolve potential policy conflicts between achieving targets for flood and drought management, net GHG emissions reductions, forestry and biodiversity.** E.g., wetland restoration for buffering may not always be incentivised by the drive towards maximising carbon emissions reductions. The pressure currently placed on tree planting means that wetlands and their function can be lost. Also, take into account that those wetlands that provide the biggest return on net GHG emissions reductions (e.g. blanket bogs) when restored are not necessarily the ones that will provide the best returns for long term buffering capacity for hydrological extremes.
  - o **Adopt the Water Framework Directive approach to wetland protection.** E.g., in which all wetlands are valued. This needs to be engaged as climatic conditions become more extreme.

- **The current focus on designated sites can miss opportunities for increasing buffering capacities across Scotland.**
  - o **Target resources to include wetlands outwith designated areas (Table 6.2, Alternative management approach 3).** E.g., as the full extent of wetlands is greater than the current extent of designated sites. This designation system was set up to protect specific sites from management pressures but not from major climatic change which will not respect site boundaries.
  - o **The current designated site series criteria may require a re-evaluation for some sites.** E.g., to allow a refocus on what is important in terms of wetland health for the future, and not a historical concept of wetland protection. This will allow the expansion of focus on what is important for wetland protection. The individual species become less important, whilst space for the mosaic and succession of wetland habitats becomes more important. A caveat is that for some very demanding specific species, certain sites may require specific protective prescriptions to ensure their survival.
  - o **Develop new funds for wetland restoration that considers areas vulnerable to flooding or droughts.** Wetland restoration and expansion for buffering high and low flows should be targeted within catchments that overlap areas at extreme

risk (e.g. there are about 106 Potential Vulnerable Areas already identified for NFM measures by SEPA; Flood Risk Management Maps (sepa.org.uk)). This should complement, not replace, funding support for peatland restoration for carbon sequestration and storage purposes. The extensive blanket bogs that tend to be the focus of restoration are mostly found in the north and west of the country, whilst most of the large populations at risk are in the south and east. The opportunity is that the south and east have many of the smaller types of wetlands that can provide greater variability of available water storage (those outlined in Table 3.2) and thus greater high and low flow buffering capacity that can ultimately reduce flood and drought risk closer to people and infrastructure at risk.

- **Wetland condition is not the same as wetland health.**
    - **Review the current system of Site Condition Monitoring, in the long term by focussing a new approach on wetland health and functionality.** Information on wetland health that covers both the condition, and the underlying hydrological function of the wetland is lacking. Use remote sensing, coupled with more intensive monitoring and the ground truthing of wetland sites to monitor real time change in wetlands and functionality so that an alternative system of Site Health Monitoring can be implemented.
    - **Modify how Site Condition Monitoring currently works in the medium term.** The inclusion of the WETMECS system, which combines water supply mechanisms, levels and vegetation as a compulsory aspect of SCM would provide a much clearer understanding of the hydrology and provide information relevant to wetland health. In addition, water quality and microbial monitoring should be part of SCM. Repeat a revised wetland SCM at no more than 5 yearly intervals.
- **Without more site-specific data and knowledge, predicting impacts on buffering capacity or biodiversity due to land use and climate change remains difficult.**
    - **Complete the Scottish Wetland Inventory.** Use a combination of remote sensing, existing historical information, and ground truthing**.** The policy and management focus on designated sites over the years has resulted in a gap in knowledge of the health and location of important wetland sites outwith the designated site series.
    - **Develop a network of representative reference wetlands across Scotland (Table 6.2, Alternative management approach 15).** Do long term monitoring to understand the ecohydrology that underpins the characteristic vegetation of different wetland types. Existing projects have not been sustained or extensive enough to provide meaningful results for some wetland habitats.
    - **Experiment with different management regimes.** Any new monitoring programme should include experimentation with different land use management regimes to identify impact on buffering capacity. For example, by altering the topography in different ways e.g., restoring hollows, swales and adding bunds around the wetland to provide additional available storage during high flows (Hewett et al., 2020) or by switching the grazing regime to monitor the improvement in vegetation structure.
    - **Utilise experience of climate extremes from other countries.** Other countries and states are actively measuring wetland health e.g., California and are already experiencing the extremes of drought and flood and ascertaining the response of wetland communities to these extremes.
- **Mainstreamed, cross sectoral planning is required to improve wetland health across Scotland and raise the financial inputs to sustain a 'good' level of health.**
    - **A strategic Wetland Climate Change Plan should be developed (Table 6.2, Alternative management approach 10)** to prioritise wetlands in a changed climate and society looking for different wetland function. This would also align well with Water Framework Directive objectives.
- **More communication and capacity development are needed on the different roles that each wetland habitat can play with respect to buffering low and high flows.**
    - **Develop more wetland specialist capacity and build greater awareness of different wetland roles within the key agencies of the Scottish Government.** This would include not only those people in SG, SEPA, Scottish Water, and NatureScot tasked with improving flood and drought management and biodiversity but also staff from across these organisations, from finance to planning. In the case of SG, we recommend including professionals from the Rural Payments Inspection Division and those involved with NPF-4 responsibilities. Since local knowledge and infrastructure will become increasingly important as the impacts of climate change are felt, local government will need to play a key linking role between policy implementation and local interest groups.

- **Build awareness and high-level alliances with non-water sectors** including forestry (Scottish Forestry, Forestry and Land Scotland, CONFOR), farming (tenants, NFUS), estate management and the newly formed Regional Land Use Partnerships.

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