# A review of interacting natural hazards and cascading impacts in Scotland

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# Glossary

- **Natural hazard**: refers in this report to climate and/or weather-related physical event(s) that may affect human or environment systems. Note that this report does not cover geophysical phenomena.
- **Interacting**: where two or more drivers/hazards have a combined effect.
- **Multi-hazard and compound hazard/event**: combinations of multiple, interacting weather-driven hazards across temporal and spatial scales that can contribute to societal or environmental risk, of which there are different types:
  - **Multivariate hazard**: combination of drivers leading to or enhancing an impact (Zscheischler *et al.,* 2021). Synonymous terms: concurrent, compound and coinciding hazards (Tilloy et al., 2019).
  - **Spatially compounding hazard**: hazards affecting multiple locations in a short timeframe resulting in a conglomerative impact (Zscheischler *et al.,* 2021).
  - **Preconditioned hazard**: antecedent conditions triggering or enhancing an impact (Zscheischler *et al.,* 2021).
  - **Temporally compounding hazard**: succession of hazards that result in, or enhance, an impact (Zscheischler *et al.,* 2021). Also referred to as cascading or triggering hazards, chain of events and the domino effect (Tilloy et al., 2019).
- **Impact**: results of climate/weather-related hazards/events.
- **Cascading impacts**: subsequent impacts that extend across built and natural systems and exhibit further interactions (e.g., landslide that blocks an essential transport link to a remote region, disrupting goods and vital services for inhabitants potentially resulting in risks to human health and mortality).
- **Multi-hazard and compound hazard/event risk**: risks comprised of **multiple hazards**, **exposure** of populations/environment in an area to potential multi-hazards, and **vulnerabilities** (susceptibility, deficiencies, lack of capacity) of exposed elements to multi-hazards (adapted from Cardona et al., 2012). Note that the focus of this report is the interaction amongst hazards and their cascading impacts; the report does not *assess* risk.
- **Resilience**: the ability of systems to recover and return to original state after undergoing stress from multi-hazards (adapted from Klein et al., 2003).
- **Anthropogenic**: relates to influences from human activities (e.g., deforestation contributing to heightened landslide risk).
- **Bottom-up approach**: the investigation of hazards with attention to the combination of multiple, interacting drivers/hazards that can cause system failure (Zscheischler et al., 2018).
- **Storytelling**: creating portfolios of multi-hazard events, drivers and impacts to provide tangible, relevant evidence (Zscheischler et al., 2018) using case studies and narratives.
- **Storylines**: descriptive approach with emphasis on understanding the driving factors and plausibility of factors of a multi-hazard, rather than probability quantification, looking at how past events unfolded and how these could conceivably play out in future scenarios with climate change projections (e.g., Shepherd et al., 2018).

## Executive summary

Weather-driven interacting natural hazards (referred to as ‘multi-hazards’ or ‘compound events’) cause significant disruption and damage to environmental and human systems in Scotland every year. Commonly, natural hazards are considered individually; however, natural hazards often arise from a combination of contributing, interacting physical processes. Failure to consider the multiple causes and drivers behind an event and the associated cascading impacts can lead to an underestimation of risk. Due to our changing climate, it is expected that many weather-related hazards will increase in intensity, occur more widely and more often than before, thereby increasing exposure to emerging hazards.

This report provides an overview for Scotland of the nascent research field of compound events and cascading impacts. It provides conclusions concerning how these events and impacts have and may affect Scotland with climate change in the coming decades. The literature review identified publications relating to compound events and cascading impacts, but highlighted a significant lack of Scottish multi-hazard studies. This gap in knowledge is despite strong evidence that interpreting Scottish natural hazards using the framework of compound events and cascading impacts would significantly improve our understanding of these hazards, and potentially lead to improved resilience.

Natural hazards in Scotland were reassessed here using a recently proposed typology for compound events based on their characteristics. Events and publications were re-evaluated and re-categorised as one or more of the types: multivariate (combination of drivers); spatially compounding (hazards affecting multiple locations); preconditioned (enhancement/triggering from antecedent conditions); and temporally compounding (succession of hazards). From this, a portfolio of case studies was created, providing initial evidence on each type and their significant impacts in Scotland. The events include: the concurrence of hot and dry conditions in North European spring/summer 2018; UK flooding from rain on saturated soil in 2019/2020; debris flows from rain on saturated soils in 2015/2016; and successive UK droughts to floods in 2012. This storytelling approach helps elucidate the complexities of compound events.

Finally, a narrative of compound hazard events in Scotland was presented based on literature, the case studies, climate projections and an initial analysis of near future (2031-2060) multi-hazard pairings. This highlighted potential cascading risks and impacts across sectors and the environment in a changing climate.

The literature review exposed a significant gap in Scotland-focused multi-hazard research, even for those more commonly expected pairings of hazards like compound flooding. By revisiting notable, recent weather events in Scotland with a multi-hazard focus, evidence of vulnerability to types of compound hazards was elucidated. This showed how interactions between hazards cause impacts that cascade across human and natural environments in a complex, interconnected network. Many of our identified compound hazard risks correspond to the CCRA3 priority climate risks for UK adaptation. Climate change is projected to intensify and increase the occurrence of compound hazards across spatial and temporal scales. Combining climate projections, CCRA3 priority future risks and our initial multivariate pairing analysis with the information from our re-categorised multi-hazard case studies reinforces the need for a greater understanding of compound hazards and their cascading impacts to ensure resilience.

To better understand multi-hazards in Scotland, we propose the following eight (non-prioritised) high-level recommendations:

1. Re-categorise and reconsider notable single hazards as compound events;
2. Conduct Scotland-focused studies into the compound impacts of: hot and dry conditions, intense rainfall on saturated soil resulting in flooding and landslides, snowfall patterns resulting in changes to streamflows, winter windstorms, and wildfires;
3. Assess temporal sequencing across multiple compound event types;
4. Undertake research to better understand the drivers of compound events;
5. Improve the understanding of multi-sectoral cascading impacts and risks;
6. Assess indicative thresholds and feedback loops for critical infrastructure;
7. Apply storyline approaches to different adaptation and resilience scenarios; and
8. Develop a holistic, multi-sectoral impact-based multi-hazard approach.

# 1. Introduction

Weather-driven natural hazards such as storms, extreme winds, heavy rainfall and floods can cause unanticipated and overwhelming impacts on environmental and human systems (e.g., Bokwa, 2013). Although natural hazards are often considered individually, most are caused by a combination of contributing and interacting weather-related and physical processes, such as flooding or landslides initiated by successive rainfall episodes (e.g., Bokwa, 2013; Zscheischler et al., 2020). Our knowledge of individual hazards has improved greatly in recent decades; however, our understanding of the processes and mechanisms of multiple, interacting hazards, especially those spanning many temporal and spatial scales, is still in its infancy. This lack of understanding makes it difficult to develop a complete interpretation of a region's vulnerability to natural hazards, which can result in an underestimation of risk (Zhuo & Dawei, 2016).

Combinations of multiple weather events (also called 'compound' hazards or events) have triggered or influenced many events, yet because research in this field is still relatively new, accurate recording, quantification and prediction of these events is still emerging (Zscheischler et al., 2020). Obtaining a better understanding of compound events, by disentangling their complex causes, should allow potential risks and impacts that are overlooked in individual hazard analysis to be assessed and prepared for. This would also connect the science, engineering and policy disciplines (Zscheischler et al., 2018).

Within the UK, studies such as Wilby (2019) have called for research and innovation to understand the drivers of interacting hazards and the mechanisms of their cascading impacts. This will increase our resilience to such hazards. The need to understand compounding risks is increasing because of the potentially devastating impacts that such events could cause in the near future (Quiggin et al., 2021). Ciurean et al. (2018) identified gaps in understanding of UK multi-hazard processes, methods for their assessment, interdisciplinary sharing of information, legislative frameworks and in-depth case studies. More recently, the Third Climate Change Risk Assessment (CCRA3) (HM Government, 2022) identified the priority risks for the next UK National Adaptation Programme (and those of the devolved administrations). This includes a summary of the current and future climate risks/opportunities for Scotland (Sniffer, 2021). CCRA3 identified that research is urgently needed on how natural hazards in different regions will alter due to climate change and what cascading impacts these changing hazards will have on populations and different sectors of society (WSP, 2020).

Eight priority UK-wide risks for further adaptation in the next two years were identified by CCRA3 (see https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/). A full list of 61 risks and opportunities were also produced, of which 34 were listed as 'more action needed' risks – many of which relate to climate hazards in general, but with two relating explicitly to interacting hazards and cascading risks: *I1 Risks to infrastructure networks from cascading failures*; and *ID10 Risk multiplication from the interactions and cascades of named risks across systems and geographies*. These are particularly important as it is likely that low-likelihood-high-impact events will become more frequent and grow in intensity due to climate change, thereby challenging the resilience and preparedness of communities (IPCC, 2021).

## 1.1 Aim and objectives of this report

This report explores interacting weather-related hazards and cascading impacts, based on evidence from Scotland and comparable regions. This can help prioritise research and innovation for climate resilience in Scotland. Although natural hazards are influenced by human activities that are warming our climate, the scope of this report is to provide an initial diagnosis into the *natural* processes underpinning compound events and cascading impacts. It does not seek to be an *assessment* of multi-hazard risk, which would require accounting for social and physical vulnerability and not just natural processes.

To achieve the report's aim, we have three objectives:

1. Perform a literature review to collate and synthesise existing international and national projects, initiatives and peer-reviewed publications to provide information relating to multiple, interacting hazards for a Scottish context;
2. Build upon this review to develop, using a bottom-up approach, case studies exemplifying interacting multi-hazards, which focusses attention on the driver and/or hazard combinations that underpin compound events and to create a portfolio of relevant events and impacts (Zscheischler et al., 2018); and
3. In conjunction with climate projections and an initial analysis of multi-hazard pairings for a near future time period (2031-2060), present a narrative of compound hazard events in Scotland and identify areas of potential vulnerabilities and research gaps.

## 1.2 Report structure

The next section of this report (Section 2) discusses the various definitions used in the literature concerning multiple, interacting hazards and their cascading impacts and risk (the definitions used in the report are summarised in the Glossary above). Section 3 describes the methods we use (literature review, case studies and multivariate pairing analysis). Section 4 summarises the literature on weather-related compound events, particularly for Scotland, and presents four case studies. Section 5 describes the potential cascading risks and impacts of such compound events, again for the Scottish context. We then discuss the work undertaken and summarise the potential impacts arising from multi-hazards in Scotland, particularly in the context of climate change (Section 6), which leads to our recommendations (Section 7). The report ends with some conclusions (Section 8). Appendix 1 provides more detail about the literature review methodology, Appendix 2 presents future multivariate climate projections for three key compound events, and Appendix 3 summarises the UK-wide CCRA3 2022 priority risks referenced in this report.

## 2. Definitions

This section details the various terms used to describe interacting weather-related hazards and cascading impacts, and identifies those adopted throughout this report. Refer to the Glossary above for a full list of terms used and their definitions.

### 2.1 Multi-hazards and compound events

Weather-driven natural hazards are rarely individual events; they often arise from the combination of interacting drivers and processes that can influence each other and/or the cascading or cumulative impacts. A plurality of definitions and terms pertaining to interacting hazards are used in the published literature. This applies to both the terminology used to describe the overarching hazard field *and* the characterisation of the interrelationships between the hazards.

Historically, the various climatic and geophysical factors leading to effects that surpass their expected, individual potency was first described as a 'compound hazard' (Hewit & Burton, 1971). In contrast, the term 'multiple hazard' (or 'multi-hazard') encompassed non-related concurrent hazards and successions of events that lead to an impact. Definitions have, however, evolved over time. Currently, there is a dichotomy between the use of 'multi-hazard' (Zhuo & Dawei, 2016; Ciurean et al., 2018; Docherty et al., 2020) and 'compound hazard' (or 'compound event') (AghaKouchak et al., 2020; Bevacqua et al., 2021; Hao et al., 2018). Tilloy et al. (2019) noted a tendency for the term 'multi-hazard' to be used in studies for geomorphological hazards, whereas 'compound hazard/event' is more common for hydrometeorological hazards and is used less often.

There are, therefore, several terms used to describe and quantify the various hazard relationships and interdependencies in both 'compound hazard/event' and 'multi-hazard' literature, such as: 'cascade', 'multivariate', 'interaction' and 'trigger'. Some terms tend to be used mainly by one of the two overarching themes. "Multivariate" is predominately used in compound hazard literature, contrasting with "trigger" and "cascade" which are more common in multi-hazard studies (Tilloy et al., 2019). Various frameworks categorising interacting hazards have been developed across disciplines in recent years (e.g., Gill & Malamud, 2014; Zhuo & Dawei, 2016; Zscheischler et al., 2020). Generally, however – and as adopted for this report – 'compound hazard/event' and 'multi-hazard' are near synonymous and are collectively taken to refer to simultaneous, cascading, and cumulative hazards. A full list of terms and definitions is provided in the Glossary above. To explore these definitions further, this report adopts the multi-hazard typology proposed by Zscheischler et al. (2020) to identify and categorise these events:

1. **Multivariate**: combination of drivers leading to or enhancing an impact
2. **Spatially compounding**: hazards affecting multiple locations in a short timeframe resulting in a conglomerative impact
3. **Preconditioned**: antecedent conditions triggering or enhancing an impact
4. **Temporally compounding**: succession of hazards that result in, or enhance, an impact (Zscheischler *et al.,* 2021)

There is, however, a fluidity within this typology as an event will often be in two or three categories, such as a concurrent event that affects multiple locations, which is simultaneously a ‘multivariate’ and ‘spatially compounding’ event. Where possible, we try to highlight these overlaps in this report.

## 2.2 Cascading impacts

Hazards can cascade across space and time, interacting with primary event(s) to produce unanticipated feedbacks and impacts. An example of interacting hazards which resulted in significant, cascading human health and economic impacts is in California, which experienced prolonged, extreme dry periods between 2012-2016 followed by extreme precipitation winter 2016 to spring 2017. This enhanced vegetation growth, which provided fuel when dried from subsequent hot, dry weather that contributed to wildfire outbreaks. When rain fell on this burnt land, deadly debris flows were triggered in Montecito, California in 2018 (AghaKouchak et al., 2020). The ability for hazards to cascade and interact makes modelling challenging, and despite increased projections of these cascading hazards with climate change, the scales of the associated risks are unknown.

In addition, these multi-hazard events, exacerbated by climate change, will also extend across both environmental and human systems. This can lead to further interactions and cause cascading impacts that can lead to impacts intensified by infrastructure failure and their dependent social functions (Cutter, 2018). Cascading impacts can occur within and outside a directly-affected region, such as debris flows blocking infrastructure routes to disparate settlements (Lawrence et al., 2020). Similarly, the increased frequency of drought conditions from global warming could cause a shift in agricultural practises that could lead to social cascading impacts of job loss and out-migration (Lawrence et al., 2020; Cutter, 2018). ‘Natech events’ are examples of cascading impacts where a natural hazard triggers a technological emergency, such as the Akema chemical plant explosion and fire in Houston, stimulated by flooding from Hurricane Harvey in 2017 (Cutter, 2018). Cascading impacts of multi-hazards can be complex, interrelated and challenging to disentangle as systems function as part of a connected, integrated network (Zehra Zaidi, 2018).

# 3. Methods

To help define Scotland's climate resilience priorities for research and innovation on interacting hazards and cascading impacts, evidence was collated and synthesised through a literature review, which was supported by compilations of case studies. This baseline evidence combined with an initial analysis of select multivariate pairings and future climate projections allowed for exploration of Scotland's vulnerability to multi-hazards. The methods used are described further in the following sections.

## 3.1 Review of existing literature

A cross-disciplinary literature review was conducted. The literature reviewed included a wide variety of sources to minimise publication bias (Collins et al., 2015): peer-reviewed articles (e.g., Natural Hazards and Earth System Sciences, Climatic Change and Weather), grey literature, online news articles (e.g., BBC and The Guardian) and websites of projects and initiatives. Multiple search engines were used: Web of Science, Google Scholar and the University of Strathclyde's SuPrimo library database, to obtain as wide a set of results as possible. This review was performed to explore published and ongoing multi-hazard studies on natural hazards, with a particular focus on Scotland, and to collate information on historical events to form case studies.

As discussed in the definitions section, different disciplines use numerous definitions and labels to describe multiple, interacting hazards. Previous studies have focused on terms used by the respective discipline (e.g., Ciurean et al., 2018), although a multitude of terms are used when dealing with multi-hazards; with monikers used across disciplines but also terms specific to a particular sector (e.g., Tilloy et al., 2019). As this report aims to present a comprehensive overview to create a baseline for Scotland, the interdisciplinary terms 'compound hazard/event' and 'multi-hazard' were used alongside a wide range of relevant key search terms (Tilloy et al., 2019; Zscheischler et al., 2020) to identify as many studies as possible and to extract relevant information pertaining to compound events. The key search terms used are listed in Box 1. The search terms were then combined with *AND* Scotland *OR* UK *OR* United Kingdom *OR* Great Britain *OR* GB, as well as without geographical regions to return global (i.e., non-UK/GB) studies. Appendix 1: Literature search methods and results contains further details of the literature search methods used and numbers of results per search term.

***Box 1.*** *List of initial key search terms used in this study.*

Compound event
Multi-hazards
Interacting hazards
Interrelating hazards
Cascading hazards
Cascading impacts
Cascading risks
Cascading disasters
Impact chain
Triggering hazards
Multivariate event
Concurrent hazards
Coinciding hazards
Preconditioned events
Preconditioned compound event
Antecedent conditions AND natural hazards
Temporally compounding
Successive hazard
Sequencing of hazards
Cycling of hazards
Spatially compounding

Initial searches generated few Scotland-specific studies, indicating a potential gap in current research. To gain additional information that may have been missed by these search terms, however, a 'snowballing' technique (Wohlin, 2014) was employed to capture cited literature from within the initial search results. From the references found by these searches, weather and climate drivers of multi-hazards were elucidated and common multi-hazard types were identified. The search terms were then expanded to include combinations of known multi-hazard drivers and typical multi-hazard events to reveal more specific results. These additional search terms used are shown in Box 2.

***Box 2.*** *List of expanded search terms used in this study to obtain more specific results.*

- Hot and dry conditions
- Concurrent hot and dry
- Concurrent drought and heatwave
- Concurrent low precipitation and high temperature
- Compound flooding
- Coastal flooding
- Compound precipitation and wind extremes
- Storm surge and flooding
- Storm surge and precipitation
- Snow drought and stream flow
- Warmer winters and reduced snow cover
- Rain on saturated soil
- Rain on snow
- Successive rainfall events/episodes
- Hydrometeorological compound events
- Hot to wet
- Dry to wet
- Weather whiplash
- Pluvial see-saw
- Drought termination
- Drought to flood

This bottom-up approach focussed on the combinations of drivers that underpin multi-hazards (Zscheischler et al., 2018). This technique was applied to searches for historical case studies, looking at the impact created (e.g., drought conditions in northern Europe in 2018) and working backwards to identify the event drivers. Previous single hazard focused publications were then re-evaluated in a multi-hazard context and re-categorised as compound events using the four types from Zscheischler et al. (2020). These definitions are not rigid: an event is often categorised as a combination of two or three types. Re-examining past events and formulating a multi-hazard understanding of them can create a baseline from which future evolution of these events can be projected (Clarke et al., 2021).

## 3.2 Climate change and analysis of multivariate pairings

Climate change is projected to alter the distribution and intensity of climate variables thereby increasing the likelihood of compound events in the future (Zscheischler et al., 2020). To enhance and support the literature review, the outputs from a climate model were analysed for Scotland. This analysis provides an initial diagnosis of areas that are potentially vulnerable to the considered multivariate pairings. Multivariate refers to two or more variables (e.g., high temperature and low rainfall for the case of hot and dry conditions) leading to a compound event, which contrasts with univariate variables that relate to non-compound events, the traditional way of considering natural hazards. A high emissions scenario (RCP8.5) was selected. Although this corresponds to a future with potentially unrealistic increases in emissions and a global warming of 2 to 4 degrees Celsius, RCP8.5 becomes more plausible for near future projections with regards to cumulative current emissions and policy options (Schwalm et al., 2020), and is recommended by the Committee for Climate Change (2019) for adaptation planning (Garry et al., 2021).

Multivariate hot and dry conditions in Scotland were analysed using UKCP18 data (Lowe et al., 2018) at 12km resolution under RCP8.5 for one ensemble member. Future changes, with respect to the reference period of 1981-2010, in concurrent hot and dry days are shown for a near future period of 2031-2060. Hot days were defined as a day with mean temperature above the daily 90th percentile during the reference period. Since droughts occur on longer timescales than temperature extremes, a dry day was defined as any day during a dry month (months with precipitation below 10th percentile during the reference period). The difference in the number of days which were both hot and dry between the reference period and the future period was calculated to give the projected change in hot and dry days.

Multivariate extreme wind and precipitation extremes in Scotland were also computed using UKCP18 data at 12km resolution under RCP8.5 for one ensemble member with the same future and reference periods of 2031-2060 and 1981-2010. An extreme windy day is a day with an average windspeed above the 90th percentile during the reference period. Extreme precipitation is defined as a day with rainfall above the 90th percentile of all days with at least 0.1mm/day of precipitation. Extreme wind and precipitation days are comprised of days that meet both the extreme wind and precipitation criteria.

A univariate analysis on projected surface snow amounts in Scotland was conducted using UKCP18 data at 12km resolution for one ensemble member under RCP8.5 with the same future and reference periods of 2031-2060 and 1981-2010. To estimate changes in snow cover, the average yearly number of days when the snow cover on the ground exceeded 1mm was calculated. Then the difference in days with snow cover between the future and the reference period was computed for all points on the map.

This analysis is intended to serve as a preliminary estimate of how compound events in Scotland may change in the future, and which areas might be particularly affected. Nevertheless, more research would be needed to study these potential changes in more detail and to increase the certainty in the conclusions reached.

# 4. Compound events in the Scottish context

## 4.1 Multivariate and spatially compounding events

Multivariate compound events are comprised of many concurrent drivers whose effects interact to create an impact larger than the individual element would produce. These events are often closely related to spatially compounding events where hazards in multiple connected locations, often with multiple drivers, cause an aggregated impact. For example, heat and humidity can combine to cause heat stress on populations and affect energy demand (e.g., through air-conditioning). Similarly, the concurrence of hot and dry conditions can generate and exacerbate drought and heatwave conditions, the impacts of which can affect environmental and human systems and can trigger further hazards such as wildfires. Another example is storms, where compound precipitation and wind extremes can damage infrastructure through the erosive effects of wind and rain, but also combine to induce compound flooding through coastal storm surge and inland flooding. Coastal compound flooding can also arise from high tidal conditions and wave overtopping.

This section explores some of the primary processes and impacts of multivariate and spatially compounding events of relevance to the Scottish context, including hot and dry conditions (leading to drought), compound flooding, and wildfires.

### 4.1.1 Hot and dry compound events

**Global overview and context**

Coupled high temperatures and low precipitation, whose combined effects on natural and human systems surpass the severity of that of the individual component, are one of the most studied multi-hazard occurrences in the global context (e.g., Mazdiyasni & AghaKouchak, 2015; Wu et al. 2020; Zscheischler et al., 2021; Ridder et al., 2020). Higher temperatures are often linked with lower precipitation. This joint occurrence will be further exacerbated by increasing feedbacks due to anthropogenic climate change, resulting in more extreme hot-dry seasons (Zscheischler & Seneviratne, 2017).

Increases in hot and dry events have been witnessed globally in recent years and are projected to continue along this trajectory in line with climate projections (Wu et al., 2020; IPCC, 2021). More than 70% of global land areas are estimated to be susceptible to this co-occurrence of weather variables (Wang et al., 2021). A study conducted on concurrent hot and dry periods in the USA, for example, demonstrated a considerable increase and distribution change in this type of multivariate hazard, with week-long heatwaves becoming more common in recent years (Masdiyasni & AghaKouchak, 2015). Northern and mid-latitude land masses are those at risk of being affected more frequently by the occurrence of hot and dry climate events in the future, which will complicate human adaptation responses and environmental resilience (Zscheischler & Seneviratne, 2017; Ridder et al., 2020). A rise in the occurrence of concurrent hot and dry events in Europe is reported to be primarily governed by increasing temperatures attributed to global warming, rather than a lack of precipitation (Vogel et al., 2021; Manning et al., 2019).

Hot and dry compound events, which can lead to meteorological drought conditions over wide areas, are connected to high pressure systems modulated by atmosphere-land feedbacks (Zhang et al., 2021). There is positive feedback between high temperatures and low rainfall due to enhanced evapotranspiration that can deplete soil moisture (Perkins et al., 2015; Sharma & Mujumdar, 2017; Markonis et al., 2021), leading to agricultural drought. This can be further affected by regional forcings and feedbacks (IPCC, 2021). In higher latitudes, such as Scotland, greener land surfaces combined with longer growing seasons can lead to higher evapotranspiration in spring, thereby reducing soil moisture and further increasing the temperature and sensible heat (Zscheischler & Seneviratne, 2017). These effects have been recorded in observations. For example, Afzal et al. (2018) show that potential evapotranspiration in the summer months (June-July-August) of the Eden catchment in Fife, Scotland, increased by 14-18% in the two most recent decades compared with the previous two decades. They also noted that in 2001-2010 water losses due to actual evapotranspiration increased by up to 26% compared with the 1970s and 1980s. Such trends are set to continue, with evapotranspiration projected to increase by up to 25% in the second half of this century. This would lead to a decrease in river runoff and groundwater recharge thereby leading to a soil moisture deficit of 5% to 7% in the 2080s for the medium and high emission scenarios (Afzal et al., 2018).

### UK and Scotland

Studies on compound hot and dry events in the UK and Scotland are scarce, with more focus on the individual high temperature or low precipitation phenomena and their associated impacts, rather than their interconnections (Arnell et al., 2021a). Scotland had previously been sufficiently equipped to endure the impacts of heatwaves which typically occur infrequently, such as that experienced in summer 2018 (Undorf et al., 2020). There is no human health-heatwave plan for Scotland unlike that in England. This is despite higher summer temperatures and less summer precipitation being projected to lead to more frequent heatwaves by mid-century (Arnell et al., 2021a).

There is, however, an increasing recognition of Scotland's vulnerability to water scarcity, despite the perceived water abundance (Gosling, 2014; Visser-Quinn et al., 2021). Nevertheless, dry periods and reductions in daily river flow are primarily used to determine low rainfall and potential drought events (Visser-Quinn et al., 2021) rather than the combined effects of high temperatures and dry conditions. Aghakouchak et al. (2014) highlighted (based on a study for California) that the commonly adopted precipitation-based analyses that disregard temperatures underestimate the likelihood of the droughts, whereas accounting for compound hot and dry events would provide a more representative account.

The lack of studies evidencing compound hot and dry events in Scotland does not equate to an immunity to multi-hazards. Climate projections indicate increased probabilities of higher temperatures and drier periods in Scotland in the near future (Lowe et al., 2018), which could impact water resources, freshwater ecosystems and agriculture. Our initial analysis demonstrates a nationwide increase in the joint occurrence of hot and dry events (Appendix 2: Future multivariate climate projections). Revisiting a notable drought period affecting various locations in Scotland through a multi-hazard lens, such as the 2018 Northern European drought and high temperatures for example

(Case study 1), may elucidate the compound nature of the underpinning factors of these types of events. Studies from the UK and Europe, when used in conjunction with weather and climate data for Scotland, may also allow for a multi-hazard understanding of hot and dry compound events to be developed. Compound hot and dry events lead to significant impacts (Table 1) and hence it is vital that the likelihood of such impacts is not being underestimated, especially as hot and dry events are likely to become more frequent in Scotland due to climate change.

## Case study 1 – 2018 Northern European (including Scotland) spring and summer hot and dry conditions

During the spring-summer months of 2018, combined hot and dry extremes conditions affected many areas across northern Europe including Scotland, due to the prolonged presence of high-pressure conditions (EDO, 2018; McCarthy et al., 2019), resulting in widespread cascading impacts and other hazards such as wildfires (Table 1). The event was attributed to increased temperatures from anthropogenic climate change (Vogel et al., 2019). The UK experienced its warmest and driest summer in over a decade, the 15th driest since 1862 and fourth sunniest since 1929, with the highest daily maximum temperature of 31.9°C recorded at Glasgow, Scotland, and a combined hottest summer season spanning June to August since 1884 (Met Office, 2018; McCarthy *et al.,* 2019). This combination of low precipitation and high evaporation from elevated temperatures is known to facilitate the onset of summer drought conditions (Markonis et al., 2021), and under high temperatures drought propagates from lack of rainfall to soil moisture deficits more rapidly and acutely (Manning et al., 2019). This was the case for the UK during the 2018 summer as prolonged periods of exceptionally high temperatures allowed drought conditions to persist. For the UK, exceptionally dry soil levels were registered in June and July, which were found to have contributed to increasing temperatures through a land-atmosphere feedback loop, particularly in southeast England (Petch et al., 2020; Turner et al., 2021).

The 2018 drought across Europe occurred due to the multivariate pairing of hot and dry conditions, with antecedent conditions influencing factors. In the months immediately prior to the summer season, precipitation was consistently lower than average in Scotland and it was recorded as one of the top three warmest and sunniest May months (EDO, 2018; McCarthy et al., 2019). For the northeast of Scotland in particular, the April to June period was notably the driest since 1984, with rivers such as the Oykel further north showing the lowest recorded flow since 1977; conditions which affected the main drought event in the following months (Turner et al., 2021). Prior to this, the two years preceding the 2018 drought entailed consistently dry conditions across the UK, the succession of which allows for the culmination in 2018 to be considered as a compound drought event preconditioned by antecedent dry conditions (Turner et al., 2021), demonstrating the complexity surrounding compound event identification.

While there are no known studies of the drivers and impacts of the 2018 event in Scotland, parallels can be drawn from Zscheischler & Fischer (2020) on the hot and dry conditions in Germany, which explicitly addresses the multivariate nature of dry and hot weather components intrinsic to the 2018 event rather than the individual hazards. Like Scotland, Germany encountered record breaking high temperatures and low precipitation from March and November of 2018. It was found that exceptional concurrent hot and dry events are extremely likely to become more commonplace in Germany's future. These return period estimates are, however, tentative and dependent upon the method employed (Zscheischler & Fischer, 2020), highlighting the emergent and complex field of multi-hazard analysis. Nevertheless, Zscheischler and Fischer (2020) provide a consistent study of increased likelihood for hot and dry conditions in the summer months through both observation-based scaling and climate model projections, which is highly relevant to Scotland.

***Table 1.*** *Impacts from the 2018 northern European (including Scotland) spring and summer high temperatures and low precipitation.*

| **Driver** | **Hazard** | **Observed impacts** |
|---|---|---|
| High temperatures and low precipitation | Low soil moisture; drought; heat stress | Dry soils across the UK; limited water resources in some catchments (NFU, 2018 as cited in Holman et al., 2021)<br>Effected rain-fed agriculture in Scotland (EDO, 2018)<br>Irrigating farms needed to operate at full capacity; higher labour and energy expenditure (Holman et al., 2021)<br>Agricultural losses from crop failure for grains in particular; reduced yields and livestock feed availability (Vogel et al., 2019; Holman *et al.,* 2021)<br>Economic agricultural losses in Scotland (including heavy winter snow in 2017) evaluated at £161m (Ecosulis, 2019 as cited in Visser-Quinn et al., 2019) |
| | Vegetation dieback | Lower livestock feed supplies due to earlier consumption to compensate vegetation dieback (Holman et al., 2021)<br>Higher livestock feed costs diverted finances from animal wellbeing and infrastructure (The Guardian, 2018) |
| High temperatures, low precipitation and high vapour pressure deficit experienced across Europe in preceding summer growing season (May-June) | Widespread agricultural drought preconditioning before further compounding effects of hot and dry summer | Stressed vegetation when most vulnerable leading to winter wheat losses and low crop yield in France and Germany (Bevacqua et al., 2021)<br>Increased collective agricultural costs due to enhanced widespread need for animal feed; from reduced crop yield; agricultural irrigation equipment demand (Holman et al., 2021)<br>Stress effects on farmer well-being (Holman et al., 2021)<br>A net reduction in carbon uptake of ecosystems was observed across Europe (HM Government, 2022) |
| Hot and dry conditions, preceded by low precipitation in January | Wildfire risk from dead vegetation and moisture loss in new vegetation growth | Wildfires across UK and Scotland (Turner et al., 2020) |

|  |  |  |
|---|---|---|
|  |  | Wildfires near Inverness in June; Golspie, Sutherland in early July; some fires persisted undergrown due to peat presence (Sibley, 2019)<br>Wildfires also swept across Sweden (The Guardian, 2018) |
| High temperatures and low precipitation | Drought propagated to hydrological drought | Drying of rivers and fragmented pools spurred disease, distress, fish kills and reduced water quality (SEPA, 2020) |
| Concurrent and successive episodes of high temperatures and low precipitation | Low river flow and groundwater levels; delay to recovery and recharge | SEPA water scarcity warnings for east and northeast Scotland private water supplies (rivers, wells and boreholes) (Beier, 2020)<br>Financial implications for assistance to over 165 Aberdeenshire private water supplies reported to be £500,000 (Holdsworth, 2019 as cited in Visser-Quinn et al., 2021)<br>Drying of ephemeral streams and reduced water quality from low groundwater in upland rural catchment in Glenlivet area (northeast Scotland) used for distillery purposes (Fennel et al., 2020)<br>Groundwater levels did not recharge until end of 2019 after successive rainfall in the year (Fennel et al., 2020) |

### 4.1.2 Compound coastal and fluvial flooding events

**Global overview and context**

Compound flooding is an area of study where the notion of interacting hazards is well established (Wilby, 2019). In coastal and estuarine regions, flooding is a multivariate event, comprised of a multitude of factors including surface runoff, riverine high flows and oceanographic drivers such as storm surge and high tides and waves (Camus et al., 2021). Storm surge is the piling up of seawater towards the coast, which is principally caused by low pressure and driven by strong winds (Met Office, 2021a). Compound flooding encompasses various combinations of these factors: storm surge and high precipitation; storm surge and peak river flows; storm surge and sea level rise; and general coastal flooding in tandem with peak river flows (Zhang et al., 2021).

The drivers behind compound flooding events, commonly extreme wind and intense, prolonged precipitation, are intrinsically linked to storms. Intense rainfall drives riverine and inland flooding, whilst extreme coastal water levels and storm surges are influenced by extreme winds and compounded by precipitation (Ganguli & Merz, 2019). The combination of these factors prevents river discharge into the sea, causing flooding from both fluvial and extreme coastal sources, in addition to the individual threat of coastal flooding. Large waves generated by stormy conditions on top of storm surge further enhance flood risk (Met Office, 2021a). When united with high tidal conditions, the impacts are intensified, affecting both low elevation coastal zones and further inland populations due to the reach of tidal signals (Kreibich et al., 2014; Ganguli & Merz, 2019). This type of multivariate flooding event is, and increasingly will be, exacerbated by sea level rise and increased precipitation (Camus et al., 2021) (Figure 1). Furthermore, changes to land-use and cover are also likely to result in increased exposure to flooding risk (Zhang et al., 2021). Compound flood events therefore pose amplified multi-sectoral risks, including to infrastructure, transport networks, coastal erosion and environmental degradation.

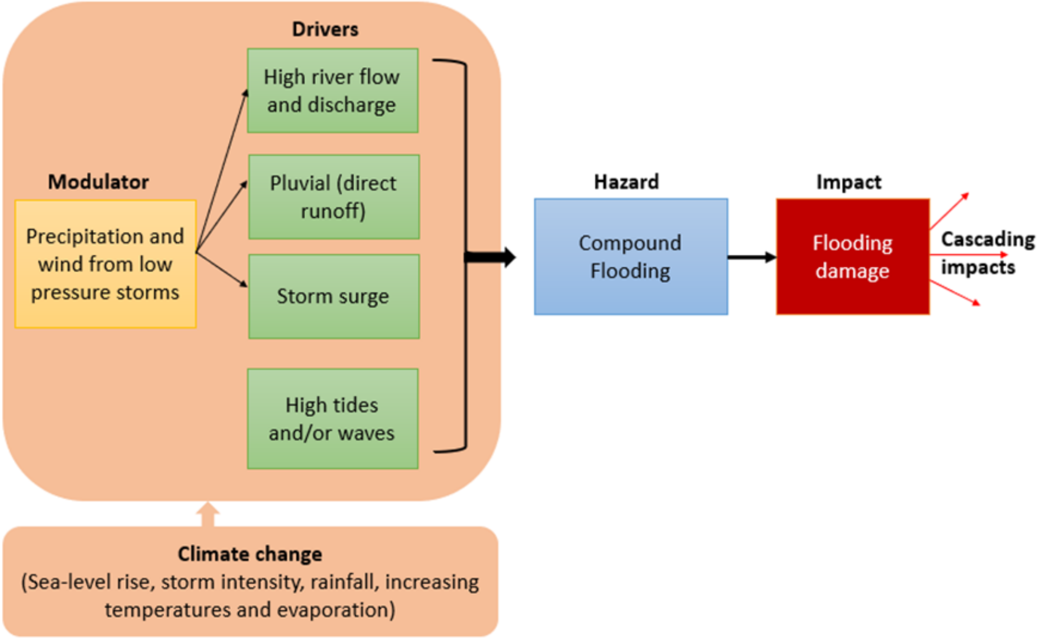

***Figure 1.*** *Physical elements of multivariate coastal and fluvial flooding [adapted from Bevacqua et al. (2021)].*

There have been many instances of compound flooding globally, including Hurricanes Harvey (2017), Sandy (2012) Katrina (2005) in the USA, which arose from storm surge and intense rainfall (Wilby, 2019; Met Office, 2021a; Sadegh et al., 2018). Driver combinations indicative of storm surge are prevalent in coastal regions of western Europe (Ridder et al., 2020). Martius et al., (2016) show that concurrent wind and precipitation extremes are often found in the same region, notably during the winter months of December to February. There are, however, few documented examples of historical compound flood events in the UK and/or Scotland as flood records typically do not take multivariate coastal and fluvial flooding into account.

Compound flooding is intrinsically linked to tropical and extratropical cyclones and atmospheric rivers due to the high winds and precipitation associated with those weather patterns (Zhang et al., 2021). The projected increasing intensity of tropical cyclones and rainfall with climate change (IPCC, 2021) infer a higher future risk of compound flooding in tropical and coastal regions (Zhang et al., 2021). Bevacqua et al. (2020) show that compound flooding in a high emission future is likely to increase globally, particularly in mid-latitudes, driven by increasing extreme precipitation and atmospherically influenced tides such as storm surge. Furthermore, it is virtually certain that relative sea level rise is to continue in most regions. This will increase risks from erosion, coastal flooding (IPCC, 2021) and compound flooding from seawater interactions with riverine processes (AghaKouchak et al., 2020).

Coinciding high river discharge and storm surge levels are linked in western European coastal regions (Couasnon et al., 2020). Western regions such as the North and Baltic Seas, Norway, Spain and north-western and central Europe, are primarily identified as being vulnerable to compound flooding hazards (Martius et al., 2016). Areas near the North and Baltic Seas are susceptible to compound flooding during winter months due to the connection with cold weather storms (Kreibich et al., 2014). Concurrent wind and waves are found to be extremely common for mid-latitude areas, so much so that in some regions the frequency of joint occurrence outweighs a univariate extreme (Catto & Dowdy, 2021). An example of compound flooding is an event in 2012 in Groningen, The Netherlands, where heavy rain caused high river flow and runoff. In addition, discharge was inhibited for five consecutive tidal periods by a storm surge caused by the same low-pressure system, which prompted coastal flooding evacuation calls (Van den Hurk et al., 2015; BBC, 2012a).

With increasing intensity and frequency of extreme precipitation, sea levels and storms throughout Europe (IPCC, 2021), coastal erosion and storm surges have simultaneously intensified (Kumar et al., 2020). Projections of intense rainfall increases the moisture capacity of storms, which suggests a rise in compound flooding probabilities across Europe, particularly along the west coast of the UK (Bevacqua et al., 2019). Quasi-stationary storms also mean rainfall potentially has a longer time to accumulate on an area and for that area to be exposed to a storm surge, therefore amplifying an underestimated compound flooding risk from only studies considering total precipitation (Kahraman et al., 2021). Storms which exhibit both wind and precipitation are also typically found to be longer lived than an event characterised by only one variable (Messmer & Simmonds, 2021; Zscheischler et al., 2021). As storm surges are driven primarily by wind, slower storms may translate to reduced compound flooding from storm surges. Rather than wind-driven storm surge and the dependence of precipitation on compound flooding, Ganguli et al. (2020) find, however, that sea level rise will be the main governing driver for future compound flooding in Europe.

### UK and Scotland

The west coast of the UK is identified as a hotspot for multivariate flooding, combining precipitation runoff and river discharge, storm surge and significant wave heights (Camus et al., 2021). Compound flooding predominately affecting the west of the UK corresponds to a positive North Atlantic Oscillation (NAO) phase which typically brings wet, stormy conditions (Ball et al., 2010). These storms typically generate a storm surge and high river discharge, which occur more frequently in smaller, steeper gradient catchments (Hendry et al., 2019). During the 2013/14 winter, for example, the UK experienced successive storms resulting in compound flooding from storm surge and high tidal conditions across the country (Met Office, 2021a). Whilst the impacts on England are better reported, the west and south of Scotland were also affected by high tides and strong winds, with compound flooding in Dumfries and Galloway (Thorne, 2014) and in numerous other coastal settlements (BBC, 2014).

Earlier studies highlight the vulnerability of the south-western Solway Firth coastal area in Scotland to storm surge and river flow coincidence (e.g., Svensson & Jones, 2004). A more recent investigation reveals that flooding and wind hazards are most strongly interlinked in the north and west of Scotland where the topography enhances precipitation (Hillier & Dixon, 2020). Ganguli & Merz (2019) also show a strong dependence between storm surge and peak river flows along the north-eastern coast from Aberdeen to Wick from similar topographical mechanisms. Furthermore, storms may become more intense and longer in duration in future, therefore, increasing exposure to flood conditions (Fowler et al., 2021). The cumulative effects of multiple, successive storms causing flooding and erosion are also important future considerations (Thorne, 2014).

Because of the complex relationships between drivers and processes, future projections of compound flooding from storm surge and river discharge in the UK are mixed, with decreasing wind speeds potentially reducing risks (Ganguli & Merz, 2019). Our initial analysis indicated a potential decrease to compound storm surge and inland flooding from projected decreasing windspeeds (Appendix 2: Future multivariate climate projections); however, this exploration does not account for changes in storm intensity and duration, topography or sea level rise. As for other areas in Europe, sea level rise will play an increasingly important role in compound flooding in Scotland (Ganguli et al., 2020). Sea level rises caused by anthropogenic climate change are not uniform across Scotland (Ball et al., 2010). Low elevation coastal zones, such as lowland island areas on the Outer Hebrides, will be exposed to compound flooding from elevated sea levels preventing freshwater discharge, in addition to increased winter precipitation (Angus & Hansom, 2021). Extreme wave height in the north is expected to increase in severity (Wolf et al., 2020). Compound flooding from storm surge and river discharge may be underestimated for the northern, mountainous coast of Scotland as it requires specialist climate model simulation (Gudmundsson et al., 2012; Ganguli et al., 2020), demonstrating a need for tailored research and improved models. Discrepancies between results determining drivers for compound flooding (e.g., Bevacqua et al., 2019; Ganguli et al., 2020) further illustrates the need for targeted compound flooding studies in Scotland. Some recognition of multivariate compound flooding is already happening, however, as shown by the MYRIAD EU project (2021), which is developing a multi-hazard and multi-sectoral pathway for disaster risk management in the North Sea region.

### 4.1.3 Multivariate wildfire risk

**Global overview and context**

Wildfires, by definition, are multivariate compound events, i.e., they are triggered by an extreme of more than one variable. High temperatures combined with low soil moisture and humidity and high winds are conditions conducive to wildfire propensity. Significant, record-breaking wildfire outbreaks and extreme high temperatures have been observed in the USA, Canada and Australia (White, 2021; BBC, 2022a) and increasingly extending into parts of the Arctic (White, 2020) in recent years. Climate simulations focus on predicting the right weather combinations of conditions for events like wildfires, such as high temperatures and strong winds. Globally, there is increasing evidence to support a future increase in frequency and duration of fire weather conditions driven by increasing temperatures (IPCC, 2021). Ridder et al. (2020) found that pairings of strong wind and low precipitation hazards are prevalent in mid-latitude regions, and often occur simultaneously alongside low soil moisture levels and increased fuel abundance, wind and low precipitation, and low precipitation and high temperature pairings.

A predisposition for hot and dry events to occur during summer and autumn months indicates the seasonality of the climate drivers in mid to high latitudes. This is influenced by higher levels of inbound solar radiation and decreased precipitation resulting in an increased surface temperature (Wu et al., 2020). The association of these hazards with warmer, drier summers and autumns therefore intensifies wildfire risk and their associated agricultural and forestry economic losses across Europe (Ridder et al., 2020). However, these conditions are not unique to the summer/autumn, with the concurrence of hot and dry events increasing during spring and early summer, extending traditional wildfire seasons (Vogel et al., 2021).

**UK and Scotland**

Arnell et al. (2021) found that wildfire risk is rising rapidly throughout the UK, although there is some disagreement around the timings of future changes due to the various indices used. The Met Office's Fire Severity Index (FSI), an evaluation of the severity of a wildfire based on the Canadian Fire Danger Rating System (Met Office, 2021b), indicates an increase in the number of days with exceptional fire weather over parts of Scotland after 2050 (Arnell et al., 2021b). The Fine Fuel Moisture Code (FFMC) index, which is representative of moisture content in fuels such as shaded forest litter (NWCG, 2021), shows an accelerating increase in fire conditions from the present day onwards (Arnell et al., 2021b). An increase in wildfire frequency is, however, almost certain, with it being more probable to experience more wildfires in the north of Scotland (Arnell et al., 2021b). Furthermore, the projected increase in winter temperatures and rainfall (Lowe et al., 2018) can translate to a profusion of vegetation due to longer growing seasons, which provides more dry fire fuel when followed by hot and dry periods (Belcher et al., 2021; Kopp et al., 2017). Fires on Scottish moorland are often limited due to the high moisture content of the saturated soils and moss and litter layer, reducing ignition of heather and grasses. Nevertheless, both the moss and canopy plants provide readily ignitable fuel sources from even small fires if sufficiently dry (Davies et al., 2008 as cited in Davies & Legg, 2016), which could occur with the projected and current hot and dry periods.

Wildfires in the UK are predominately ignited by recreation activities, which poses another risk level as hotter and drier springs and summers could attract more outdoor activities, necessitating fire risk management for more potential warm season fires (Belcher et al., 2021; Albertson et al., 2010). Gazzard et al. (2016) approximates a total of £55m goes towards fire suppression efforts in the UK per year. However, wildfires are not confined to warm conditions as some large occurrences have been recorded near the end of February when the fine fuel moisture content is intensifying, and services are less prepared (Davies & Legg, 2016). It is believed that the high temperature indicators used in determining fire danger could mask the risk for colder UK regions (de Jong et al., 2016 as cited in Arnell et al., 2021b). For example, a succession of wildfires spread across Scotland in April 2019, including West Dunbartonshire and remote regions in the Highlands and Morayshire (BBC, 2019). The wildfires in the Highlands were due to the extremely dry conditions combined with wind fanning the blaze despite cool temperatures (BBC, 2019). Wildfires in the UK have predominately impacted the environment through habitat damage, increasing carbon emissions and affecting soil stabilisation. Threats to human health and infrastructure are therefore possible (Arnell et al., 2021b).

## 4.2 Preconditioned compound events

Preconditioned compound events are characterised by a precedent climate-driven condition that leads to or amplifies an impact, such as rain falling on saturated soil which can result in increased flooding or landslide risks, or rain falling on snow which catalyses snowmelt flooding. A lack of winter snow from milder, wetter winters can precondition soil moisture levels and stream flow in spring/summer due to the lack of snowmelt.

In this section, preconditioned events of rainfall on saturated soil and warm season snow drought are explored, looking at national and international studies and presenting information for the Scottish context.

### 4.2.1 Snow drought and streamflow preconditioning

**Global overview and context**

Although hot and dry extremes are generally associated with our changing climate, an increase in winter temperatures and rainfall projected for the UK can also have detrimental impacts through the preconditioning of reduced snow cover on spring stream flow. Milder winters bring an increase in precipitation falling as rain saturates the ground and is then lost to runoff (which could influence winter flooding) rather than being stored as snow that usually holds water until the onset of warmer spring temperatures (Huning & AghaKouchak, 2020) (Figure 2).

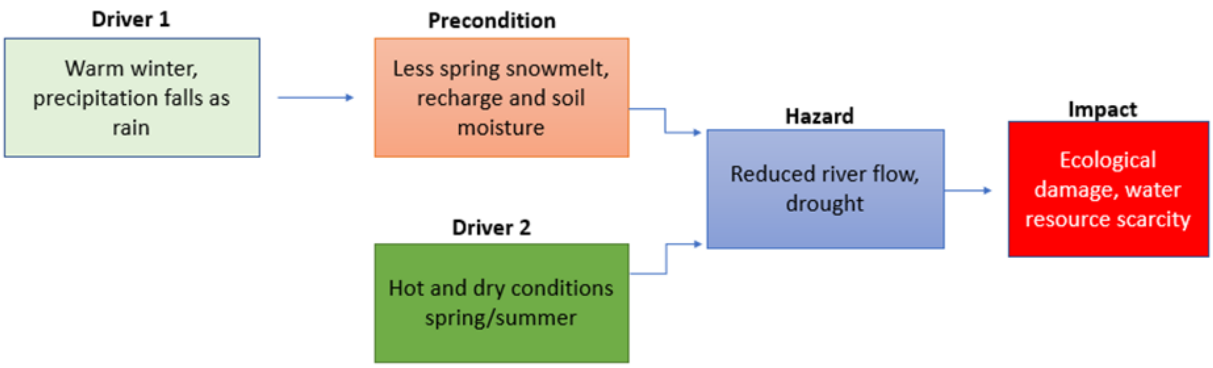

***Figure 2.*** *Flow diagram depicting preconditioning effects of warmer winters on precipitation and snow cover and example impacts [adapted from Bevacqua et al. (2021)].*

This preconditioning is called snow drought. Different types of snow drought exist, classified by dependence on precipitation and temperature. The impacts of warm snow season drought, whereby warmer temperatures in conventional snow seasons either trigger early snowmelt of existing cover or snow precipitation is replaced by rainfall and therefore leads to no snowmelt recharge, can be significant (Rivington et al., 2018). Reduced spring river and groundwater recharge from the lack of snowmelt can contribute to hydrological (streamflow) drought, yet also has implications for agricultural drought as snow cover is intrinsically linked to soil moisture storage (Niu & Yang, 2006; Markonis et al., 2021).

Areas such as eastern Russia and Europe, alongside the western US, have been identified as snow drought hotspots. Europe in the years preceding 2018 saw an increase of 16% in the duration of snow droughts (Huning & AghaKouchak, 2020). However, although the effects of climate change on snow cover is commonly documented, the relationship between reduced snowfall (a snow drought) on streamflow is less studied (Dierauer et al., 2021). Snowpacks, which are more transient or reduced due to milder winters, will affect groundwater and streamflow processes. This assertion, however, is often difficult to demonstrate due to competition from other elements intrinsic to a warming climate such as higher evapotranspiration rates, changes to vegetation structure and the increase in wildfire frequency (Siirila-Woodburn et al., 2021).

An increase in global temperatures with global warming will likely result in an increase in snow drought (IPCC, 2021). The increase in frequency and severity of snow droughts expands into the mid-century and 2080 time periods (Dierauer et al., 2021). With reduced snowfall in the future comes the potential for more hydrological drought conditions and the associated cascading impacts, such as the effect of changed water resources on vegetation, water resource management and agricultural practises (Siirila-Woodburn et al., 2021). Furthermore, snow drought periods can affect water quality through water retention times and subsurface interactions (Segura, 2021).

### UK and Scotland

In the last 50 years, snowfall and cover have both reduced in Scotland in line with increasing global temperatures through wetter, warmer winters. Diminishing snow cover duration in the UK is estimated at 20-30 fewer days of snow cover between the periods of 1960-1980 and 1990-2010 (Brown, 2020). This is corroborated by our analysis which indicates a projected decrease in snow cover throughout Scotland, with the snowiest areas showing the largest decrease in cover (Appendix 2: Future multivariate climate projections).

Extreme snow events have still occurred in the last decade, such as in the winter of 2017/2018 when freezing temperatures were brought by easterly and northerly continental cold air flows (Ballantyne et al., 2021), referred to as the ‘Beast from the East’. Milder winters, intermixed with periods of low temperatures, may also become more problematic as witnessed in Alaska in December 2021. In this event, warmer temperatures and heavy rainfall, uncharacteristic to the normally cold and dry conditions, allowed for ice to form as the rain rapidly froze and bound to roads, thereby prompting closures and causing wide-ranging power failures – conditions set to occur more frequently with future climate projections (BBC, 2021a). Nevertheless, future overall reductions in snow cover are likely to be variable, particularly where colder temperatures can persist, such as in higher elevations or upper latitudes in the north and north-west that could allow precipitation to fall as snow and permit extended durations of snow (Brown, 2020). Snow in the UK is intrinsically linked to the NAO, with positive NAO phases bringing dominant warm westerly winds and associated mild, wet conditions (Met Office, 2021c). These conditions more strongly affect snowfall and cover at lower elevations whereas in higher elevations, colder temperatures allow for more snow accumulation and persistence (Spencer & Essery, 2016), although projections show reductions of snow cover and even persistent snow patches at all altitudes (Trivedi et al., 2007).

## 4.2.2 Rain on saturated soil

### Global overview and context

The role of rain falling on saturated soil is increasingly recognised as a cause of landslides and flood responses for many catchments, which can be overlooked when solely considering rainfall characteristics (Berghuijis et al., 2016). This is found for Europe where excess soil moisture is considered a major flood proponent across the Mediterranean region, Germany, The Netherlands and the UK – the latter being affected predominately in winter months (Berghuijis et al., 2019). Flooding is a significant hazard in Europe as it brings high risks to human health and mortality and economic losses, whose frequency is projected to increase in the region (Kumar et al., 2020). In July 2021, severe flooding in Belgium, the Netherlands and Germany caused hundreds of fatalities and caused significant damage to infrastructure and transport, and affected industry and agriculture. The floods were recognised to be driven by antecedent soil moisture content in addition to slow moving intense rainfall weather systems (World Weather Attribution, 2021). In a study on flooding and landslide drivers in southern Norway, Poschlod et al. (2020) project a 38% increase in heavy rainfall on saturated soil events in the summer period (June-September) of the years 2070-2099 under a high emissions scenario. This entails increasing landslide and flooding implications; whilst rain-on-snow events decrease with diminishing snow levels in a warming climate.

### UK and Scotland

The preconditioning effects of intense or successive periods of rainfall on antecedent soil moisture levels (Figure 3) are known precursors to flooding and landslides in the UK (BGS, 2021). This type of phenomena is not confined to the autumn/winter period, yet during these months the effects can be acute due to low evaporation and high precipitation levels (BGS, 2021). Flooding and landslides are commonly classified as concurrent hazards; however, their interactions and mechanisms require further investigation (Docherty et al., 2020). Landslide impacts can also cascade from rainfall induced flooding events that cause erosion of the slope foot and subsequent landslides (BSG, 2021). Antecedent soil moisture levels are particularly important for flooding in Scotland, especially in winter and spring months, as higher proportions of rainfall are lost to runoff and peak flows are higher with subsequent events (Ballantyne et al., 2021) (see Case study 2).

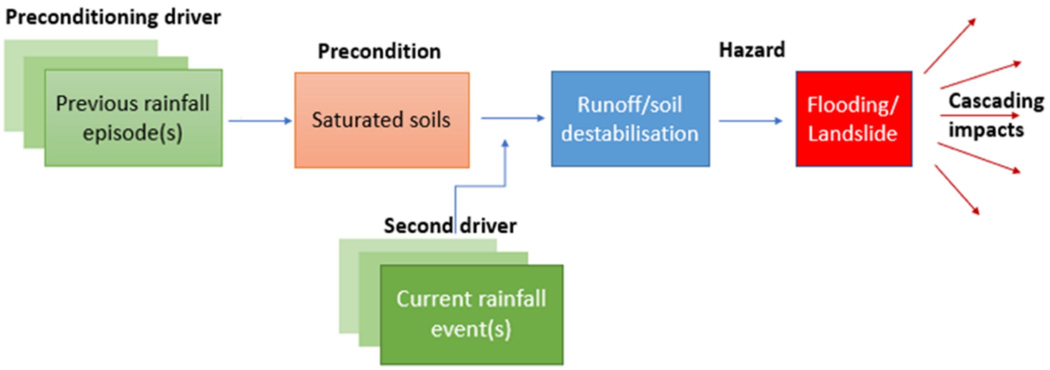

***Figure 3**. Preconditioning effects of rainfall on soil moisture levels that, due to more rain on saturated soils, leads to flooding and landslide impacts and cascading risks [adapted from Bevacqua et al. (2021)].*

## Case study 2 – 2019/2020 UK flooding from rain on saturated soil

During the 2019/2020 winter, the UK experienced widespread and prolonged flooding events in November 2019 and again in early 2020, which impacted transport, agriculture, and property damage (Sefton et al., 2021). These floods were the result of preconditioned saturated soils due to rainfall events throughout the preceding year, and the further compounding arrival of a succession of storms (Dennis, Ciara and Jorge) that broke precipitation records (Sefton et al., 2021; Davies et al., 2021). This series of storms produced a rapid succession of intense rainfall events onto saturated catchments, which may have been further preconditioned by persistent high precipitation and low soil moisture deficits in the previous months (Parker et al., 2020).

Flooding in February 2020 affected catchments in southern Scotland and extended south to areas in northern England and southern Wales (Parker et al., 2020). This highlights the spatially compounding potential of multi-basin flooding events from successions of weather fronts and antecedent soil conditions typical of winter. These could be underestimated if, as is often the case, they are considered at the single catchment scale (De Luca et al., 2017). In addition to flooding impacts, 42 landslides linked to precipitation from these storms were recorded across the UK (Sefton et al., 2021).

Further widespread impacts from rainfall were observed later in 2020, when intense precipitation events connected to a cluster of convective-driven thunderstorms occurred over central and eastern Scotland in August (Sharpe & Cranston, 2021). It is accepted that, in addition to the intense rainfall delivered in this short window, antecedent high precipitation and saturated soils throughout August (Haines, 2020) were contributory factors to flash flooding (Sharpe & Cranston, 2021) and therefore potentially influenced other impacts (Table 2).

***Table 2.*** *Hazards and impacts arising from the 2019/2020 rainfall events.*

| **Driver** | **Hazard** | **Observed impacts** |
|---|---|---|
| Extreme rainfall on saturated soils | Surface water and river flooding | Flooding in Stonehaven<br>Over 190 properties flooded across Perth & Kinross<br>Extensive flooding in Grangemouth and Falkirk<br>Surface water flooding in Fife, Kirkcaldy hospital (Sharpe & Cranston, 2021) |
| | Flooding | A68 carriageway in Midlothian washed away (Sharpe & Cranston, 2021) |
| | Heavy rain and blocked culvert | Union Canal (Polmont) breach and closure of Edinburgh-Glasgow rail line (Sharpe & Cranston, 2021) |
| | Landslides | Train derailment at Carmont (near Stonehaven) causing 3 fatalities and line closure for ~3 months (Haines, 2020)<br>Evacuation of caravan park (Fife) (SEPA, 2020a) |
| | Flooding of Black Devon River | Erosion exposed major gas pipe |

Debris flows, water-laden fast-moving landslides, are reported to occur in Scotland when triggered by intensive and protracted rainfall episodes; usually following wet weather periods that precondition soil saturation levels (Ballantyne et al., 2021). Antecedent soil moisture enhances shorter and weaker rainfall effects on debris flow occurrence (Sparkes et al., 2017). The intrinsic link between rainfall and debris flows explains the frequency of these hazards in areas of Scotland such as at the A83 'Rest and be Thankful' pass (Sparkes et al., 2017) (Case study 3). Overall precipitation and the intensity of events have increased in Scotland in recent decades, particularly for winter rainfall across the north and west (Sniffer, 2021). Projections demonstrate a continuing wet trend for winter and, despite a general move towards drier conditions in summer, intense rainfall events in summer months are likely to increase (Lowe et al., 2018). This increase in wetness and intensity translates to soil saturation preconditioning and the propensity for runoff flooding, which could be further exacerbated by urbanisation (Ballantyne et al., 2021). The intensification of wetter conditions similarly increases the probability of slope failures. There are gaps in understanding of the effects of repeat rainfall and flooding (Johnston et al., 2021). The sequencing of dry to wet conditions, which are discussed in Section 4.3, may also influence the likelihood of landslides due to soil and infrastructure damage caused by dry periods. Preconditioned events of rain on saturated soil therefore have the potential to affect both urban and rural areas with increasing frequency.

Crucially, although uncertainty remains in climate projections of extreme rainfall, this type of event is set to become more frequent and intense as the climate continues to warm (WSP, 2020). Fowler et al. (2021) found that rainfall extremes, both long-duration (>1 day) and short-duration (sub-daily 1-3hr), are intensifying with climate change; the latter, in particular, being linked to increases in localised flash flooding.

### Case study 3 – 2015/16 debris flows from rain on saturated soils (including Storm Desmond)

The 2015/2016 winter, characterised by Storm Desmond, delivered consistent, heavy rainfall leading to widespread flooding and associated impacts on infrastructure, property and agriculture in Scotland and England (McCarthy et al., 2016; Zurich & JBA, 2015). Storm Desmond had a significant impact on slope stability at the A83 'Rest and be Thankful', triggering a debris flow (Sparkes et al., 2017). Antecedent soil conditions from previous storms exacerbated impacts from precipitation (McCarthy et al., 2016). Although intense rainfall was recorded, it did not correspond to the time of the slope failure and a retrospective inspection of conditions revealed high precipitation the week prior to the slip that preconditioned the debris flow setting (Sparkes et al., 2017). Nevertheless, as demonstrated by a large event at the same location in October 2014, lower antecedent precipitation levels followed by a more intense period of rain can also cause debris flows – rainfall characteristics which are projected to increase with climate change (Sparkes et al., 2017).

Similarly, a debris flow event at Lochailort in August 2016 blocked the single railway line and road to Mallaig. These were also driven by intense precipitation delivered on antecedent saturated soils (Palamakumbura et al., 2021). Landslips have continued to occur along the 'Rest and be Thankful' mountain pass in recent years. The A83 and the Old Military Road were closed in 2021 due to prolonged rainfall on melting snow in February. These roads had only just reopened after a new safety barrier installation in 2020 (BBC, 2021b). Debris flows damage infrastructure, disrupts transport and rural communities, and causes economic losses; however, no recent fatalities have been recorded in the Scottish Highlands due to such events (Sparkes et al., 2017).

## 4.3 Temporally compounding events

Temporally compounding events encompass a succession of hazards that result in or amplify impacts in an area, such as temporal clustering of precipitation episodes or storms and sequences of heatwaves or droughts (Zsheischler et al., 2020). This can also extend to sequential episodes of different climate conditions, such as the transition from hot or dry periods to wet.

In this section, temporally compounding events of successive hot or dry to wet conditions are explored in the Scottish context.

### 4.3.1 Successive hot or dry to wet conditions

**Global overview and context**

A type of temporally compounding multi-hazards is the succession of hot and/or dry to wet conditions, and vice versa, in a specific area. This is less commonly studied when considering the prevalence of literature on hot and dry compound hazards (Zhang et al., 2021). For example, this type of multi-hazard can be characterised by a heatwave preceding intense precipitation and flooding events (Zhang et al., 2021) (Figure 4). The transition between hot and wet conditions is generally understudied (You & Wang, 2021).

Similarly, there are temporally compounding hydro-hazards, defined by the succession of contrasting drought conditions (often intrinsically linked to hot conditions) and extreme precipitation (Visser-Quinn et al., 2019). The rapid and sudden change from dry to wet conditions is encompassed by the phrase 'weather whiplash' (Loecke et al., 2017; Parry et al., 2021) and also referred to as the 'drought-pluvial seesaw' (He & Sheffield, 2020). The wet conditions associated with drought terminations often culminate in high flow and flooding events. This makes it an important multi-hazard to consider, especially for a warming climate (Parry et al., 2016; Visser-Quinn et al., 2019). Hydro-hazards of drought and flood, however, are usually considered in isolation (Visser-Quinn et al., 2019). Hillier et al. (2020) found that multi-hazard risk of dry and wet events could be overestimated as it is unlikely for concurrent drought and cyclone related hazards, and their aggregated impacts, to occur. However, this does not account for the hazards posed by the abrupt transition between these conditions.

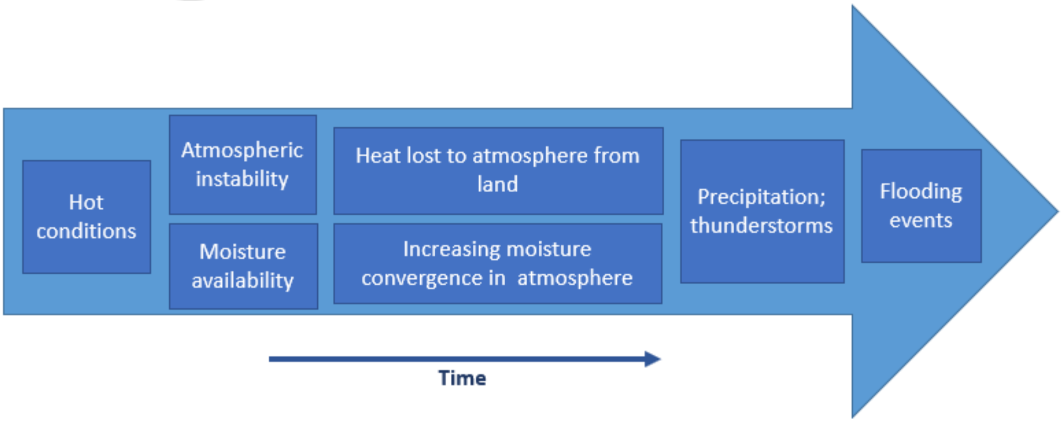

***Figure 4.*** *Progression of temporally compounding multi-hazard of hot and wet extremes [adapted from Zhang et al. (2021)].*

Climate projections indicate an increase in frequency and intensity of precipitation events, with fewer light precipitation episodes (IPCC, 2021); a future climate which, therefore, lends itself to an increase in both drought and flooding occurrences (Fowler et al., 2021) and successive hot and/or dry to wet conditions. Wu et al. (2021) found that temporally compounding hot to wet hazards show an overall global increase. Dry to wet events are also experienced globally. Such events have increased in occurrence and in land area affected over the last 30 years (De Luca et al., 2020), with around an 11% average for droughts succeeded by flooding in the following season, particularly during spring-summer months and especially in sub-tropical and mid-latitude areas (He & Sheffield, 2020).

In central USA, the sequencing of heat waves and flooding has been recognised, and with an increased chance of heatwaves, an enhanced risk of this temporally compounding hazard can be speculated (Zhang & Villarini, 2020). This extends to western USA, where increased frequency and severity of rapid changes from dry to wet conditions are observed and projected to increase with climate change (Swain et al., 2018; Parry et al., 2021). Studies on hot to wet temporally compounding events in China are more prevalent in the literature (e.g., Wu et al., 2021; Chen et al., 2021; You & Wang, 2021). You & Wang (2021) show one in four heatwaves were followed by intense precipitation between 1981-2005 in China. Urbanisation contributes to this multi-hazard event due to urban heat island effects and their role in extreme precipitation. Hence, urban areas will be predominately affected by increases in this compound event type (Wu et al., 2021). Sequencing of hot and wet extremes are observed over Europe, including Spain (Zhang et al., 2021) and Switzerland (Wu et al., 2021). Globally, Europe was found to have the highest frequency of dry to wet conditions (He & Sheffield, 2020).

### UK and Scotland

Visser-Quinn et al. (2019) identified hotspot regions exposed to dry and wet sequencing in the UK of which half were found to experience temporally compounding dry and wet conditions. The southwest of the UK and the northeast of Scotland are areas requiring particular focus as they exhibit both successive cycling from dry to wet (and vice versa), as well as concurrent drought and flood events between catchments (Visser-Quinn et al., 2019). Stonehaven was identified for its vulnerability to flooding from the River Carron, including compound coastal flooding, and to drought and water scarcity (BBC, 2021c) that could occur simultaneously or consecutively. It is postulated that northeast

Scotland will experience drought during summers more frequently during which, despite a small population, economic repercussions may still be high due to the prevalence of private water supplies in the region (Visser-Quinn et al., 2019). Furthermore, collective periods of spatially compounding drought, affecting multiple locations in the same time window, indicates a widespread stress on water resources. The abrupt change in dry to wet conditions from the enhancement of changes in timing and seasonality of hydro-hazards weakens resilience planning and, therefore, a holistic interpretation of the hydrologic dynamic is required (Visser-Quinn et al., 2019).

Successive dry to wet extremes of drought and flooding were experienced in the UK in 2012 (Case study 4). More recently, an abrupt transition from dry to wet conditions was experienced in April-May 2021, where rainfall increased from 20.1mm in April (29% of the 1981-2010 monthly average) to 119.5mm in May (177% of the monthly average) (Parry et al., 2021). This is the largest difference in rainfall between April to May in from the same year since 1910. This is in line with climate projections, so it is probable for temporally compounding dry to wet events to continue (Parry et al., 2021). Visser-Quinn et al. (2019) also suggest that temporally compounding hydro-hazards will increasingly affect more hotspot regions towards the end of the century.

## Case study 4 – 2012 Successive UK drought to flood events

Successive dry to wet extremes of drought and flooding were experienced in the UK (including Scotland) between April and July 2012, resulting in widespread and frequent flooding throughout the rest of the year from increasingly saturated soils (Parry et al., 2013) (Table 3). The preceding drought conditions from January through March particularly affected areas in England, prompting hosepipe bans and affecting agriculture, with wildfires threatening areas of the Scottish Borders (Kendon et al., 2012). More than twice the monthly average of rain was recorded in England, Wales and eastern and southern areas of Scotland in April, June and July with intense precipitation events and thunderstorms (Parry et al., 2013). This transition from dry to wet helped water resource recovery, but also resulted in flooding that compounded the cumulative impacts from successive hazards (Parry et al., 2013).

***Table 3.** Impacts from the temporally compounding dry to wet period of 2012.*

| Driver | Hazard | Observed impacts |
|---|---|---|
| Dry conditions January-March | Drought | Soil moisture deficits; hose pipe bans; wildfires (Kendon et al., 2012) |
| Heavy, sustained and frequent intense rainfall in spring and summer months | Flooding | Waterlogging of land; reduced crop and livestock fodder yields and crop rot; marooned livestock; runoff contamination; heavy metal pollutant mobilisation from mines; economic losses (Parry et al., 2013)<br>Evacuations in Wales, Yorkshire, eastern Scotland; tourism and |

| | | |
|---|---|---|
| | | recreation losses (Parry et al., 2013) |
| | Flooding and landslides | Infrastructure damage and delays; freight train derailment at Tulloch people stranded in cars and trains; heat stress (BBC, 2012b) |
| | Flooding and rising water levels | Ground nests of wetland birds eliminated; stranded fish as flood receded (Parry et al., 2013) |

The UK (including Scotland) is, in general, experiencing more frequent record-breaking heavy rainfall and unprecedented high temperatures (Slingo, 2021; Kendon, 2021). Extremely wet days have increased especially for Scotland (Lowe et al., 2018), which translates into more frequent and severe flash flooding risks for which urbanisation is a major intensifier (IPCC, 2021). Although, summers are to become drier overall, rainfall periods are projected to be more intense (Sniffer, 2021). The narrow window of recovery between the succession of extremes challenges resilience and preparedness for a range of stakeholders (Parry et al., 2021). Therefore, there is a need to investigate the drivers, mechanisms and impacts of temporally compounding dry and wet conditions on Scotland's hydrological situation.

# 5. Cascading risks and impacts

## 5.1 Context

Interacting hazards pose one of the most significant challenges when assessing climate risks for both the natural and built environments. As well as the direct impacts from the various interactions and sequencing between hazards (see Section 4 above), risks are often systemic and can cascade across and between sectors, amplifying the scale and range of impacts, leading to system failures. For example, disruption on one infrastructure network can quickly cascade onto other infrastructure networks (Jaroszweski et al., 2021). WSP (2020) demonstrated that the consequences of impacts due to interacting hazards and risks may have wide multi-sectoral repercussions. These interlinked impacts are likely to be exacerbated by climate change.

Across the UK, there are many examples of cascading impacts, such as (adapted from Jaroszweski et al., 2021):

- interruption to power supplies, which is frequently highlighted as a key example of a cascade failure caused by extreme weather such as storms;
- impacts from single or from more complex, compound hazards on infrastructure and networks (water, transport, energy), which can prevent the operation of critical infrastructure;
- societal reliance on IT and communications infrastructure is an increasing risk, with knock-on (downstream) at particular risk from further cascading impacts; and
- a high number of impact chains with other sectors causing, for example, delays to travel and freight.

Jaroszweski et al. (2021) conclude the interruption of power supplies is the single risk with the highest cascading impact across the UK, with disruption of IT and communication services the second highest impact risk with significant downstream impacts. As an example, Figure 5 shows how a multivariate compound hazard – in this case, high temperatures and reduced summer rainfall (i.e., hot and dry conditions) – can produce multi-sectoral cascading and interlinked impacts.

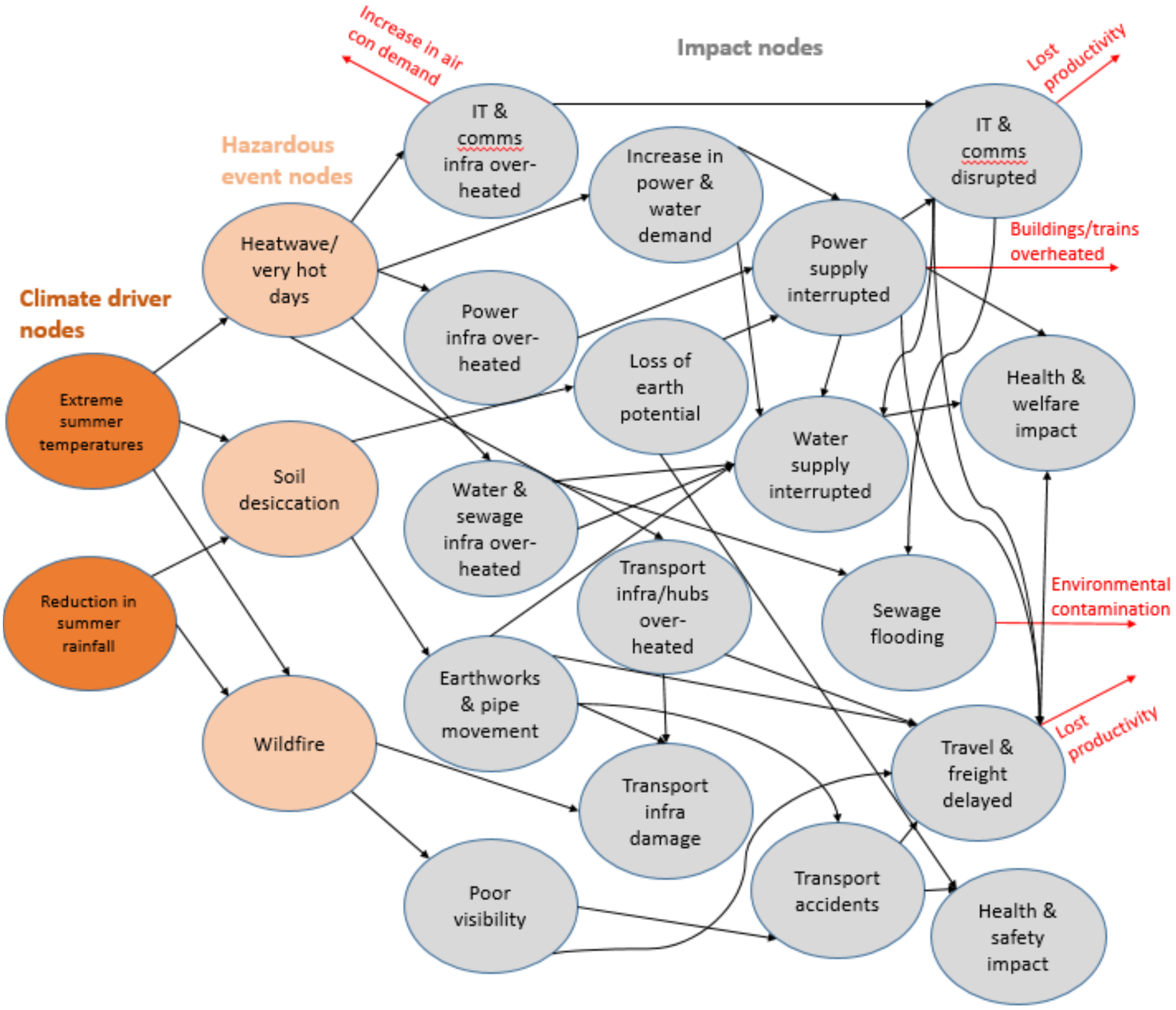

***Figure 5**. An example of multi-sectoral cascading impacts. In this example, the risks from high temperatures and reduced summer rainfall (i.e., hot and dry conditions) on infrastructure are assessed. Here, the three outcomes of heatwaves, wildfire and soil desiccation can result in a series of impacts to critical infrastructure which, in turn, can lead to other impacts across the sector and beyond (red arrows/text) [adapted from Jaroszweski et al. (2021); modified from WSP (2020)].*

## 5.2 UK priority risks from the Third UK Climate Change Risk Assessment (CCRA3)

Aside from the recent technical reports produced for the Climate Change Committee (Jaroszweski et al., 2021 on critical infrastructure; WSP, 2020 on interacting risks on the built and natural environments), which was independent advice and evidence for the Third UK Climate Change Risk Assessment (HM Government, 2022), there is a paucity of studies and information relating to cascading impacts and/or the impacts of climate change on complex natural hazards interactions across Scotland.

Jaroszweski et al. (2021) detail ‘urgency scores’ for risks specific to Scotland to infrastructure, with the following identified as priority ‘more action needed’ (risks are shown along with confidence assessments for reference), with additional ‘further investigation’, ‘sustain current action’ and ‘watching brief’ risks also identified (not shown) (refer to Jaroszweski et al. (2021) pp. 5-6 for more details):

- **Risks to infrastructure networks** (water, energy, transport, ICT) from *cascading failures* (medium confidence)
- **Risks to infrastructure services** from *river and surface water flooding* (medium confidence)
- **Risks to transport networks** from *slope and embankment failure* (low confidence)
- **Risks to transport** from *high and low temperatures, high winds and lightning* (medium confidence)

More broadly, the following is an abbreviated summary of the most significant for the UK (note: this summary has been abbreviated and is not specific to Scotland) multi-sectoral risk pathways (from interlinked climatic driver to impact) stemming from cascades. The effects for infrastructure and the built and the natural environment were considered. The information comes from WSP (2020), and relates to selected impacts now (2020s) and in the medium to long-term future (2080s) with associated ‘ratings’ of confidence (only high and medium ratings shown) (see WSP (2020) pp. 20-21 for more details):

- **Increase in summer temperatures and reduction in summer rainfall** (including heatwaves, low summer river flows and soil desiccation): leading to cascades including productivity losses (medium 2020 and high 2080), travel and freight delays (medium 2080), transport infrastructure damage and IT/communications disruption (medium 2020 and 2080), habitat and biodiversity degradation, environmental water shortages and algal blooms (all medium 2020 and high 2080), and reduced water quality and soil condition (both medium 2080)
- **Extreme winter rainfall events and increases in winter rainfall** (riverine, surface and groundwater flooding): leading to cascades including water supply disruption and sewer flooding (medium 2080), travel and freight delays, transport and building damage and productivity losses (all medium 2020 and high 2080)
- **Sea level rise and storms** (coastal flooding and erosion): leading to cascades including loss of flood defences (medium 2080), saline intrusion, coastal squeeze and other environmental impacts, and coastal infrastructure damages (all high 2080)

These urgency scores and priority risks were then taken forward to the Climate Change Committee’s Technical Report for CCRA3 (Climate Change Committee, 2021). Eight highest priority UK-wide risks for further adaptation in the next two years were then adopted by CCRA3 (HM Government, 2022); see Table A.2 in Appendix 3: CCRA3 2022 priority risks (UK-wide) for the eight UK-wide priority risks. The full list of 61 UK-wide risks and opportunities is available: https://www.theccc.org.uk/wp-content/uploads/2021/07/Independent-Assessment-of-UK-Climate-Risk-Advice-to-Govt-for-CCRA3-CCC.pdf. Of these 61 risks and opportunities, 34 are listed as ‘more action needed’ risks – many of which relate to climate hazards in general as well as complex interacting hazards and cascading risks, with two relating explicitly to interacting hazards and cascading risks: *I1 Risks to infrastructure networks from cascading failures*; and *ID10 Risk multiplication from the interactions and cascades of* *named risks across systems and geographies*. These urgency scores and priority risks are explored in the Scottish context in Section 5.3 below.

Alongside Jaroszweski et al. (2021), CCRA3 has created a series of interlinked systems maps (similar to Figure 5 above) showing principal interactions within and between key sectors in the UK, as well as an interactive online tool (available at https://kumu.io/wspdigital/asc-interacting-risks-map) that visualises a single combined map where users can select different climate inputs to identify multi-sectoral risk pathways that are of interest. While risks were assessed separately for England, Northern Ireland, Scotland and Wales in CCRA3, political boundaries are not a usual unit of analysis for the natural environment, thus CCRA3 did not report on the current and future impacts by country (Berry & Brown, 2021). Nonetheless, while not specific to Scotland, these interactive system maps provide a useful and relevant resource.

## 5.3 Multi-sectoral cascading impacts in Scotland

In this section, we explore, where possible, some of the priority risks identified in Jaroszweski et al. (2021) and WSP (2020) for the Scottish context, relating them to some of the primary compound event pairings identified through the review in Section 4 above. This exercise, however, is not exhaustive, and many of the categories below overlap with others. Nevertheless, it serves to identify some of the multi-sectoral priority risks Scotland faces from cascading impacts in a changing climate. These are summarised and discussed in Section 6.

### Dry and hot summers and drought

Despite the notion of Scotland being a ‘water rich nation’, recent studies have projected an increase in the frequency (a two or threefold increase) and duration of water scarcity events (Gosling, 2014; Visser-Quinn et al., 2021; Arnell et al., 2021) caused by increased summer dry and hot conditions. This is in line with UKCP18 climate change projections that show a spatially varied reductions in total annual precipitation, but with higher summer temperatures resulting in greater evaporative demand and reduced winter snow cover replenishment of streams and groundwater storage in the future (Rivington et al., 2018). The combined effects of dry and hot conditions can produce drier soils, particularly if there are long periods of reduced precipitation and hot temperatures to increase evapotranspiration rates. This may affect the succession from agricultural to hydrological drought (Figure 6). This will also affect the persistence of drought events as more rainfall will be required to balance soil moisture deficits and heat induced increases in evapotranspiration can create a drier overall state and intensify temperature extremes through the reduced evaporative cooling capacity of dry soils (Manning et al., 2019; Mueller & Seneviratne, 2012). More frequent dry and hot events can also precondition the soil and result in multi-year droughts.

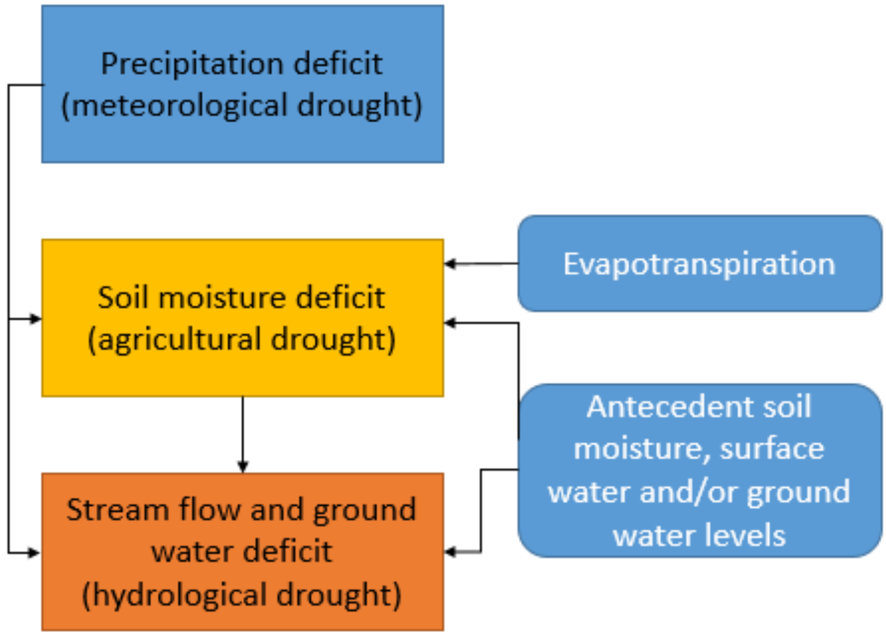

***Figure 6****. Simplified schematic of the processes and drivers relevant for meteorological soil moisture (agricultural) and hydrological droughts [adapted from Seneviratne et al. (2012)].*

CCRA3 (HM Government, 2022) highlights the potential risks in the UK from dry and hot summer conditions, including water supply disruptions from drought and reduced water quality in the natural environment, with environmental water shortages, algal blooms and reduced water quality, which are all rated as medium or high cascading risks in 2080 for the UK (WSP, 2020). The mycelium of connections and feedbacks between hazards and the cascading impacts for water availability is, however, complex; causal-flow diagrams such as Figure 7 (not region-specific) can be used to help elucidate potential risks from multiple hazards such as hot and dry conditions on water security.

Areas particularly vulnerable to increased frequency and duration of droughts are on the east coast of Scotland, ranging from the south-east, such as the Tweed catchment, up to the north-east of Scotland (Visser-Quinn et al., 2021). These areas also exhibit a high concentration of private water supplies and groundwater resource dependence, enhancing the risk of water scarcity and reduced quality for household, industrial and agricultural use (Rivington et al., 2018; Fennel et al., 2020; MacDonald et al., 2005). In Scotland, 60% of land is comprised of livestock farming and 10% arable (Scottish Government, 2020 as cited in Visser-Quinn et al., 2021), and water abstractors are predominant on the east coast. In a study on compound temperature and humidity levels on UK agriculture, increases in the duration and frequency of potato blight are expected (e.g., risk increasing by 67% on the east coast of Scotland), whilst heat stress on livestock is estimated to mostly affect England (Garry et al., 2021). Although days optimal for growing are set to increase across the UK, this will be of limited benefit to annual crops (Arnell et al., 2021). The intricacies of low summer rainfall and its connection to drought in Scotland, however, requires further research, including drivers, modelling for propagation, severity and recovery, and what constitutes a ‘normal’ baselevel from which to measure the context of climate change (Rivington et al., 2018).

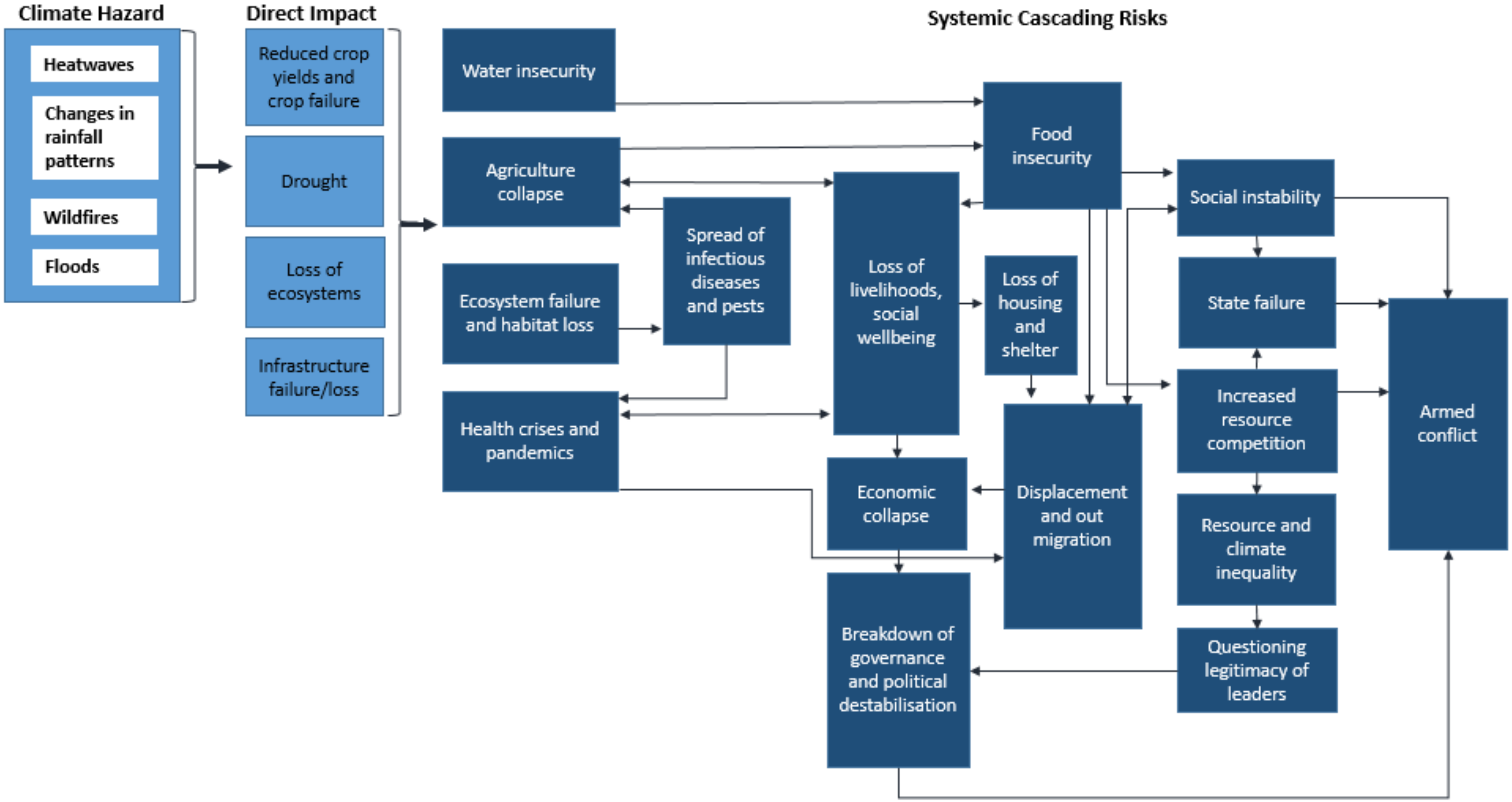

***Figure 7.*** *Cascading water insecurity risks stemming from multi-hazards [adapted from Quiggin et al. (2021)].*

### Extreme rainfall, floods and landslides

Extreme rainfall triggers both flooding and landslide hazards. Rain on preconditioned, saturated soil can increase riverine and runoff flooding. Urban areas, characterised by large swathes of impervious surfaces, are particularly vulnerable to surface water flooding that arise from intense rainfall episodes and can create flash flooding events (Speight et al., 2021). Increases in rainfall and runoff are projected for Scotland (WSP, 2020), with more frequent and intense precipitation events and short duration rainfall to become more common in both summer and winter months (Lowe et al. 2018; Fowler et al. 2021). Furthermore, storms may move more slowly, therefore increasing the rainfall delivered at a certain location (Kahraman et al., 2021). This, in combination with increasing populations and urbanisation, will intensify the risks of surface water (pluvial) flooding in Scotland where over 100,000 properties are currently identified as vulnerable in the SEPA National Flood Risk Assessment (Speight et al., 2019; 2021). Impacts from flooding have the potential to cascade across sectors; disrupting power and water supplies, overflowing sewers with added associated risks to human health (ClimateXChange, 2016a), and causing travel and freight delays (WSP, 2020).

Landslides and debris flows are predominately caused by rainfall on preconditioned saturated soil (Ballantyne et al., 2021) which will likely be impacted by projected increases in rainfall frequency and intensity. Impacts from landslides cascade across power, water, infrastructure and agriculture sectors including risks posed directly to exposed buildings and communities (Huggins et al., 2020). Landslides can block, bury, erode and cause subsidence to roads and railways, and threaten human life (Huggins et al., 2021). Landslides commonly affect rail and road networks in the UK: between 2014-2019, 381 rail earthwork failures were recorded (Network Rail, 2018 as cited in Johnston, et al., 2021). In addition to projected changes to precipitation, expansion of road and rail traffic on ageing assets increases vulnerability to damage and greater exposure of humans to these risks. This is pertinent for the integrity of rail embankments with the introduction of larger, faster trains (Johnston et al., 2021).

Both flooding and landslides, caused by extreme rainfall, correlate to the CCRA3 UK priority risks of extreme winter rainfall events and increases in winter rainfall, leading to additional cascades including water supply disruption and sewer flooding, travel and freight delays, transport and building damage and productivity losses (all medium to high in 2080).

### Snow and streamflow

Snow melt significantly contributes to streamflows in many Scottish catchments (Gosling et al., 2002). Therefore, reduced winter snowfall and cover from milder, wetter conditions could increase water scarcity risks from diminishing streamflow and groundwater recharge (Bell et al., 2016). This is acutely important for upland catchments rather than low elevation areas that are not predominately governed by snowmelt processes; however, low-flow effects can be felt in lowland rivers with the combination of rising temperatures and declining precipitation in warmer months (Capell et al., 2012). Winter flows may increase due to more precipitation falling as rain, increasing the risk from flooding as soils become saturated and rivers burst banks, especially if rain falls on existing snow, such as the 1993 flooding event in Perth (Capell et al., 2012; Gosling et al., 2002). This correlates to the CCRA3 UK priority risks of habitat and biodiversity degradation, environmental water shortages and water supply distribution issues (all either medium or high risks). Uncertainties remain over the likely future changes to the amount and timing of snow cover in Scotland; snow is, therefore, an important factor to consider in future studies and resilience planning in Scotland due to its significance on water resources (Bell et al., 2016).

### Winter storms

Winter storms – typically compounding combinations of high winds, snow and freezing conditions – are often linked with major multi-sectoral cascading impacts. There have been several recent examples of winter storms causing significant cascading impacts in Scotland. These include Storm Frank in 2015/2016, which affected transport links and cut power to ~6,000 homes (Barker et al., 2015), and the 'Beast from the East' snowstorm in the winter of 2017/2018, which saw freezing temperatures brought by easterly and northerly continental cold air flows (Ballantyne et al., 2021) and hit during lambing season which led to increased losses of newborn lambs through hypothermia and exposure to the elements. Storm Arwen in November 2021 saw extreme winds and heavy snow hit Scotland, causing large scale damage, several fatalities, and cascading impacts to utilities, services and across many of Scotland's forests. It is understood that 4,000 hectares of woodland (an estimated 8 million trees) were blown down during Storm Arwen, which increased to 7,000 with the arrival of Storms Malik and Corrie (BBC, 2022b). Agricultural yield decreases (cereal and oilseed rape) and production rates were also observed in Scotland due to the unfavourable weather conditions experienced in winter 2017/2018, spreading into spring and early summer of 2018 (WSP, 2020).

Despite recent notable storms in recent decades, evidence of trends of increased storminess are weak and this topic urgently needs further research (Slingo, 2021). While risks to infrastructure and transport network cascading failures from low temperatures are, however, highlighted in Jaroszweski et al. (2021), these cascading impacts are generalised in WSP (2020) and winter storms are not explicitly listed as a priority risk for the UK, highlighting a notable gap in knowledge.

### Rising temperatures and changing weather regimes

Soil erosion is an impact from the combination of water and wind. It is a natural process, although increased rainfall caused by climate change can result in habitat degradation from soil erosion (Brown et al, 2016; WSP, 2020). In Scotland, around 35% of peatlands show signs of erosion, which has largely occurred as a result of land use change, but also increased rainfall in the west of Scotland (Lilly et al., 2010). However, evidence that erosion rates are increasing as a result of more rainfall falling in heavy precipitation events remains inconclusive (Brown et al, 2016). This cascading impact is rated as medium in 2080 in the UK (WSP, 2020). There is also evidence that rising temperatures have contributed to changes in the composition of vegetation in the Scottish Highlands with around half of the Scottish uplands affected, including a demonstrated shift towards less distinctive vegetation communities, combined with an increase in species such as highland rush and a decrease in specialist snow-bed liverworts (NERC, 2015; WSP, 2020). These cascading impacts are all rated as medium in 2020 and high in 2080 for the UK (WSP, 2020).

**High temperatures and wildfires**

Risks can cascade beyond the primary hazard produced by multivariate or preconditioning drivers that can proliferate spatially and temporally with unanticipated effects (Lawrence et al., 2020), including heatwaves and droughts “setting the scene” for wildfires (White, 2021). Although there is some ambiguity surrounding the timing of increased future wildfire frequency in the UK, the potential impact of wildfires is identified as likely to affect multiple sectors (WSP, 2020). Changes to the patterns of snow melt can influence the distribution, occurrence and extent of wildfires, although the mechanisms and feedbacks of cascading impacts require further investigation through a multi-hazard lens (AghaKouchak et al., 2018). Warmer temperatures in winter can also cascade to cause extreme heatwave impacts in summer months due to premature snow melt and the associated vegetation growth that can further reduce soil moisture levels and amplify heatwaves through land-atmosphere feedback processes (The Guardian, 2020).

Scottish peatlands are, and will increasingly be, susceptible to wildfires. In May 2019 for example, a six-day wildfire on blanket peatland in the internationally-important Flow Country (a vast expanse of blanket bog in the North of Scotland) is calculated to have released the same amount of carbon as six days of Scotland’s total greenhouse gas emissions in 2017. Higher carbon losses with more severe blanket bog fires are possible (Ricardo Energy & Environment, 2019). This is further impacted by the condition of the peatland: healthy peatlands retain five times more carbon during wildfires than drained peats and peatland impaired by significant wildfires exhibit inhibited carbon sequestration properties (WWF, 2019). Financial costs therefore extend from the initial hot and dry event, down the impact chain to peatland restoration, with the costly nature of firefighting in remote locations and other impacts such as reparations to affected water supplies additional cascading risks (Albertson et al., 2010). Risks to sequestration and stores of carbon from multiple hazards are identified in CCRA3 as one of the eight priority areas that necessitates urgent attention due to their potential for increased emissions (HM Government, 2022).

Scottish forests are also likely to be increasingly vulnerable to wildfire, with the rise of the duration and frequency of hot and dry conditions that could impact the understorey and weaken surviving trees to subsequent pathogen attacks and stresses (ClimateXChange, 2016). Synergistic interplay between wildfire and insect attack are documented as an important multiple-stressor risk that requires development of analytical techniques in forestry (Hanewinkel et al., 2011), fire damaged trees are less resilient to insect attack and additionally those remaining survivor trees can be prone to additional insect infestation (McCullough et al., 1998 as cited in Kerns & Ager, 2007). Wildfires can also facilitate the spread or introduction of invasive species into the ecologically disrupted areas, some of which could include plant species, such as cheatgrass in the USA, that could increase future fire risk through their growth patterns and composition (Kerns et al., 2006; Zouhar et al., 2003 as cited in Kerns & Ager, 2007). The MYRIAD EU (20022) project in Scandinavia highlights that the increase in hot temperatures could allow for habitats to be extended, such as those of pine beetles. Invasive non-native species, pests and diseases one of eight priority climate change risk assessment areas for attention in CCRA3 (HM Government, 2022). Like peatlands, wildfires in forests could simultaneously undermine the potential for carbon capture and bioeconomy (MYRIAD EU, 2022).

Hazardous conditions caused by wildfire smoke can extend to other areas where it can impact respiratory, cardiovascular, perinatal and mental health and increase mortality, alongside the attributable financial implications (Reid et al., 2016; AghaKouchak et al., 2020). The solar radiation absorptive qualities of the black carbon smoke and soot elements can, through its accumulation on snow covered land, affect hydrological processes of melt rates which can lead to changes in runoff and associated flooding (Flanner et al., 2007; AghaKouchak et al., 2020). Furthermore, the emissions produced by wildfires drastically increase greenhouse gas emissions (Kopp et al., 2017), which are significantly higher in peat rich locations like parts of the UK (Albertson et al., 2010).

### Other notable climate driver-cascading impact relationships

The ‘see-saw’ or ‘weather whiplash’ temporal succession between compound hazards, such as dry to wet conditions or multiple years of low rainfall, can result in significant socio-economic losses (e.g., energy, water, agriculture) through the exhaustion of recovery resources dealing with the immediate and cascading impacts (De Luca et al., 2020). The cumulative impacts of the dry and wet conditions can surpass those of the individual hazards by the potential increased vulnerability and exposure to human and environmental systems (He & Sheffield, 2020), thereby challenging long-term resilience. Furthermore, multiple, yet spatially remote (including international) compound hydro-hazard occurrences may destabilise global supply chains (De Luca et al., 2020) that may impact the UK and Scotland, which is identified as a priority adaptation area for the UK in CCRA3 (HM Government, 2022). To date, however, there are limited studies in the UK context in this area, highlighting a notable gap in knowledge.

# 6. Discussion

This study sought to highlight Scotland's vulnerability to multi-hazards and cascading impacts for resilience planning, especially in the context of a changing climate. A literature review showed that very few Scotland-specific studies on multi-hazards exist. This lack of studies is despite there being a pressing need for such studies due to vulnerability from multiple and interacting hazards as well as to properly account for Scotland's topography, processes and land uses, and its changing climate. Table 4 serves as a summary of the wide-ranging and interconnected nature of natural hazards and their cascading impacts in the Scottish context, explored in this report and in relation to the CCRA3 (HM Government, 2022) priority risks discussed in Section 5 (shown in full in Table A.2 in Appendix 3).

There is a gap in knowledge relating to several interacting hazards in Scotland, including hot and dry events, preconditioning effects from warm season snow drought, and sequencing from one hazard to another (e.g., hot/dry to wet conditions) for which there is little baseline data. Scotland is often perceived as a water abundant nation (Gosling, 2014), however, compounding impacts of hot and dry conditions exacerbate soil moisture levels which can in turn further increase the severity of multivariate events (Zscheischler et al., 2015; Zscheischler et al., 2020). This reaffirms that multivariate and antecedent conditions are fundamental to the occurrence of natural hazards, highlighting the need for more Scotland focused, interacting hazard studies to inform resilience and preparedness.

There are corroborating climate projections of increasingly hot and dry conditions in Scotland's future (Lowe et al., 2018). Initial diagnosis of this multivariate pairing indicated a likely increase in the frequency of these conditions across Scotland – not just in the drier northeast. The results showed marked increases in the number of hot and dry days in the northwest. This indicates the need for specific research and optimisation of planning and resources to prepare for hazards uncharacteristic of regions that could be especially vulnerable to water scarcity, such as Scottish islands. The implications of these events can cascade across sectors, affecting agriculture and global food supplies (IPCC, 2021), water resources, energy demand, ecological and human health. The impact on agriculture was evident during the 2018 drought, which saw aggregated crop losses. CCRA3 (HM Government, 2022) identified supply risks to UK food, goods and vital services from disruption and the collapse of global supply chains, in addition to the priority risk area of national crops, livestock and commercial trees from multiple hazards. CCRA3 highlights risks from increases in hot and dry days, which affect soil and water quality, habitat degradation, transport disruption and freight delays, and building overheating. IPCC (2021) predicted an increase in the frequency of concurrent extreme events, which impact similar sectors (e.g., food supplies), occurring in different locations due to global warming.

Furthermore, wildfire risk from hot and dry conditions is preconditioned by increasing fuel loads from greater vegetative growth due to milder, wetter winters (Lowe et al., 2018) and increased evapotranspiration processes (Afzal et al., 2018). This could undermine efforts to achieve net zero carbon emissions, as well as increasing the risk from subsequent flooding and landslide events due to the increased frequency of dry to wet sequencing.

Despite overall summer drying trends in the future, data from UKCP Local (2.2km) suggests future increases in the intensity of heavy summer rainfall events (Lowe et al., 2018). These events also contribute to the risks identified by CCRA3 (2021) concerning threats to soil and water quality, habitat degradation, transport and infrastructure disruption and further marginalisation of rural communities. The Evidence Report for the CCRA3 noted that it is not possible to model sequences of events, such as many dry years. Such sequences could cause severer effects for certain sectors than a single extremely dry year (WSP, 2020).

This study has also highlighted the need for more targeted studies on typical hazards in Scotland, such as preconditioned rain on saturated soil and multivariate compound flooding events. These are needed to have a holistic consideration of the cumulative and cascading impacts of such events. Although the antecedent conditions of soil saturation are understood as precursors to flooding and landslides, more focus is needed on understanding how this influences risks and impacts. This is especially the case when considering the projected changes to precipitation intensity and patterns demonstrated by our analysis, and the acknowledgment of the cycling between dry and wet conditions that further influences infrastructure integrity.

Although a number studies on compound flooding were identified for the UK, in general, and Scotland, in particular, there is uncertainty around the dominant drivers that are specific to Scotland. This uncertainty is demonstrated by conflicting European studies, with some studies suggesting a dominance of precipitation, whereas others indicate sea-level rise as being dominant. There is also uncertainty about the influence of climate factors for Scotland, e.g., wind speed and interactions with storm speed and duration of precipitation. This uncertainty necessitates specific research on compound flooding in Scotland. Notably, Kendon et al. (2021) found, based on maximum gust speeds measured by the UK wind network, that there are no compelling trends in storminess over the last five decades. Nevertheless, Slingo (2021) argued that the evidence for changes in storminess is weak and how this characteristic is changing needs to be addressed with some urgency. Our initial analysis indicates a declining trend of compound flooding from storm surge and precipitation extremes due to projected reductions in windspeeds. This does not account for the potential of slower moving storms and longer precipitation events at a given location. This is compounded further by steep orographic catchments in Scotland that increase flash flooding, and does not take into account the potential of increased extreme wind speeds, extreme wave height (Wolf et al., 2020) or rising sea levels (IPCC, 2021) that could put low coastal elevation zones and islands at particular risk.

The warming of the Arctic regions has led to a substantive change in future sea-level projections, especially at the 95th percentile. An additional 5 - 10cm rise in sea level by 2100 is now predicted over earlier estimates also based on CMIP5 climate projections. However, the processes behind ice sheet collapse, particularly for Antarctica, remain very uncertain and continued monitoring and process studies are vital (Slingo, 2021). UK coastal flood risk is expected to increase over the 21st century and beyond under all emission scenarios considered. This means that we can expect to see both an increase in the frequency and magnitude of extreme water levels around the UK coastline. This increased future flood risk will be dominated by the effects of sea-level rise, rather than changes in atmospheric storminess associated with extreme coastal sea-level events (Lowe et al., 2018). CCRA3 indicated a significant risk from sea level rise and storms with an increase chance of coastal flooding and erosion, which can cascade to water supply, habitat and carbon sequestration loss as well as risk to settlements. These predictions demonstrate the importance of Scotland-focused studies on this topic.

Cascading impacts from these event types are often intangible, and it is difficult to quantify risk with precision. The storytelling approach used through the case studies of historical events in this report can help elucidate and communicate the complexities of multi-hazard events and their impacts. The case studies allowed for an initial, high-level compound analysis to be conducted, in addition to applying knowledge gained from international studies to the Scottish context. The case studies on past events demonstrated how multi-hazards have affected Scotland and provide a basis for forecasting how these events may evolve in a changing climate. The impact-centric perspectives, which looked at multi-hazard drivers and attributed them to past events, could be expanded to explore alternative potential impacts, such as envisioning how the outcomes could have been worse if the drivers had been slightly, but plausibly, different (Zscheischler et al., 2021).

More multi-hazard focussed initiatives are in development for the UK as a whole, including through the Natural Hazards Partnership (NHP), which is a consortium of public bodies that provides a forum to exchange knowledge and best practice on natural hazards. NHP provides advice to government and emergency responders on these topics and encourages the development of new services. As a key member of the NHP, the British Geological Survey (BGS, 2021) is conducting preliminary research into the impacts of interacting hazards in Great Britain using GIS tools, statistical analysis and qualitative and semi-quantitative approaches. They are identifying where multiple hazards co-exist, how they interact and what their potential interrelated effects. In a next step, they plan to create a multi-hazard map for Great Britain by using a ‘compound hazard index’ approach and finally they seek to publish the map through the MImAS tool. The MYRIAD EU project also is developing multi-hazard interpretation of risk in different sectors across Europe, where Scotland features within the North Sea initiative. However, there is a gap in Scotland-specific multi-hazard progress.

***Table 4.*** *Impacts arising from multi-hazards in Scotland and their relevance to the CCRA3 2022 priority risks, with likely future changes due to climate change. Numbered highest priority risks for further adaptation in the next two years (#1-8) are taken from CCRA3 (HM Government, 2022); see* ***Error! Reference source not found.*** *in Appendix* 3: CCRA3 2022 priority risks (UK-wide) *for the eight UK-wide priority risks. The full list of the 61 UK-wide risks and opportunities are available here:* *https://www.theccc.org.uk/wp-content/uploads/2021/07/Independent-Assessment-of-UK-Climate-Risk-Advice-to-Govt-for-CCRA3-CCC.pdf*.

| **Hazards** | **Impacts** | **CCRA3 priority risks** | **Future changes** |
|---|---|---|---|
| Concurrent hot and dry conditions and land feedback processes (multivariate; spatially compounding) | Lower capacity for dilution in low flow rivers leads to increase in pollutant concentration (ClimateXChange, 2016b) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards | Climate projections of increasingly hot and dry conditions in Scotland's future (Lowe et al., 2018) |
| | Low river flow, increase in water temperature, reduced habitat increasing vulnerability of aquatic life due to reduced dissolved oxygen and water quality (ClimateXChange, 2016b)<br>Upstream migratory fish obstructed (ClimateXChange, 2016b)<br>Freshwater fish survival, invasive species replacement (ClimateXChange, 2016b) | #2 Risks to soil health from increased flooding and drought<br>#3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions<br>#8 Multiple risks to the UK from climate change impacts overseas | IPCC (2021) state an increase in the frequency of concurrent extreme events, and impacting similar sectors (e.g., global food supplies), being experienced in different locations due to global warming.<br>Projected water scarcity vulnerability for NE Scotland and private water supplies (Visser-Quinn et al., 2021) |
| | Increased irrigation, changes in land use and changes in agricultural patterns could change areas and severity of ecological consequences (ClimateXChange, 2016b) | | |
| | Soil desiccation impacting water quality and soil conditions, Plant growth, water quality, carbon sequestration, infrastructure (WSP, 2020)<br>And mobilisation of pollutants to water systems and reduced infiltration and recharge (Fennel et al., 2020)<br>Reduced agricultural productivity across regions and countries (Bevacqua et al., 2021) | | |
| | Heat stress on humans and agriculture (Undorf et al., 2018) | #2 Risks to soil health from increased flooding and drought | |

| Hazards | Impacts | CCRA3 priority risks | Future changes |
|---|---|---|---|
|  |  | #3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions<br>#5 Risks to supply of foods, goods and vital services due to climate related collapse of supply chains and distribution chains |  |
|  | Optimum conditions for wildfire (IPCC, 2021) | #7 Risks to human health, wellbeing and productivity from increased exposure to heat in homes and other buildings<br>#4 Risks to crops, livestock and commercial trees from multiple climate hazards |  |
|  | Water resource scarcity (Visser-Quinn et al., 2021) |  |  |
| Extreme rainfall; fluvial and pluvial flooding; storm surge (multivariate; spatially compounding) | Coastal property damage from flooding and erosion; productivity loss, health and welfare (WSP, 2020; Sniffer, 2021) |  | Conflicting analysis: some state a declining trend in compound flooding from inland flooding and storm surge due to projected reductions in windspeed (Ganguli et al., 2020) – others state increasing trend in compound flooding from storm surge and precipitation due to increasing rainfall projections (Bevacqua et al., 2019).<br>Potential for increased slower moving, longer lived storms – longer duration of precipitation delivery (Kahraman et al., 2021)<br>Increased erosion from exposure to successive storms (Thorne, 2014) |

| Hazards | Impacts | CCRA3 priority risks | Future changes |
|---|---|---|---|
| | | | Rising sea levels with climate change are a major component of compound flooding (Ganguli et al., 2020)<br>Gaps in understanding of how compound flooding will manifest in future how climate change factors will interact with Scotland's orography needs investigation (Ganguli & Merz, 2019) |
| Fluvial and pluvial flooding; and storm surge (multivariate; spatially compounding) | Loss of natural saltmarsh flood defence (NatureScot, 2017) | | Conflicting analysis: some state a declining trend in compound flooding from inland flooding and storm surge due to projected reductions in windspeed (Ganguli et al., 2020) – others state increasing trend in compound flooding from storm surge and precipitation due to increasing rainfall projections (Bevacqua et al., 2019).<br>Potential for increased slower moving, longer lived storms – longer duration of precipitation delivery (Kahraman et al., 2021)<br>Increased erosion from exposure to successive storms (Thorne, 2014)<br>Rising sea levels with climate change are a major component of compound flooding (Ganguli et al., 2020)<br>Gaps in understanding of how compound flooding will manifest in future how climate change factors will |
| | Saline intrusion (WSP, 2020) | | |
| | Loss of important salt marsh habitat from coastal squeeze (WSP, 2020) impacting biodiversity and carbon storage (NatureScot, 2017)<br>Sewerage overspill leading to contamination of private water supplies (ClimateXChange, 2016a) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multiple hazards<br>#3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions | |
| | Chemical and runoff contaminant mobilisation (ClimateXChange, 2016b) | | |
| | Power system failure or interruption and infrastructure damage (Huggins et al., 2020) | #6 Risks to people and the economy from climate-related failure of the power system (CCRA3) | |

| Hazards | Impacts | CCRA3 priority risks | Future changes |
|---|---|---|---|
| | | | interact with Scotland’s orography needs investigation (Ganguli & Merz, 2019) |
| Warm season snow drought; streamflows (preconditioned) | Reduced spring/summer stream flow and groundwater levels from changes in snowmelt; drought propagation (Rivington et al., 2018)<br>Reduced flows affecting energy production; aquatic ecology; seasonal availability of water resources (Harrison et al., 2001) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards<br>#6 Risks to people and the economy from climate-related failure of the power system | Projected milder, wetter winters in Scotland (Lowe et al., 2018)<br>Declining snowfall projected, although snow extremes may still occur in future (Ballantyne et al., 2021)<br>Snowfall may persist at high altitudes in N and NW where it is cold enough to fall as snow (Brown, 2020) |
| | Albedo effect of reduced snow cover (ESOTC, 2020) | #3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions | |
| | Rising snow line could reduce habitat and distribution (Harrison et al., 2001)<br>Reduced protection from frost: losses of over-wintering crops and plants (Harrison et al., 2001)<br>Increasing wetness impacts on sheep and deer health, vulnerability to parasites; warmer temperatures allow insect infestations (Harrison et al., 2001) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards<br>#4 Risks to crops, livestock and commercial trees from multiple climate hazards | |
| | Increased rainfall instead of or onto snowpack leading to flooding of properties; pollution from run-off; soil degradation (Harrison et al., 2021) | #2 Risks to soil health from increased flooding and drought | |

| Hazards | Impacts | CCRA3 priority risks | Future changes |
|---|---|---|---|
| Rain on saturated soil; landslides (preconditioned) | Heavy rain on bare agricultural land leading to nutrient leaching; suspended solids, diminishing soil heath and agricultural productivity; Impacted water quality (Kumar et al., 2020) | #2 Risks to soil health from increased flooding and drought<br>#3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions | Increased quasi-stationary storms allowing longer rainfall delivery on areas (Kahraman et al., 2021)<br>Increased frequency and intensity of precipitation episodes in summer and winter (Lowe et al., 2018) and short duration rainfall (Fowler et al., 2021) |
|  | Saturated soil reduces shear strength drives deep-landslides (Bevacqua et al., 2021) and debris flows (Ballantyne et al., 2021) impacts on transport and infrastructure and delays to travel and freight (WSP, 2020)<br>Saturated soil reduces shear strength and drives shallow soil landslides (Bevacqua et al., 2021)<br>Runoff and rain leading to river, surface and groundwater flooding: disruptions to power and water supplies; sewer flooding; delays to transport; building damage; impaired water quality (WSP, 2020) | High risk rating identified for transport, infrastructure from slope failure in 2080 (WSP, 2020)<br>Risks identified for damage caused by river, runoff and groundwater flooding (WSP, 2020) |  |
| Dry to wet conditions (temporally compounding) | Flooding, increased runoff and pollution impairing water body quality (Whitehead et al., 2009 as cited in Parry et al., 2016) and cascading impacts on freshwater ecology | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards<br>#2 Risks to soil health from increased flooding and drought | Future increases in both hot, dry conditions and rainfall conducive to cycling of dry to wet (Fowler et al., 2021) |
|  | Bog bursts and peat slides from dry condition cracks that allow quick permeation of rain/flood - washed away and damaged peatland habitats; reduced carbon sequestration capacity (Kirkpatrick Baird et al., 2021) | #3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions |  |
|  | Soil cracking and soil deterioration impacting transport sector through slope failure (CCRA3, 2021) and agriculture productivity (Parry et al., 2013) | #2 Risks to soil health from increased flooding and drought |  |

| Hazards | Impacts | CCRA3 priority risks | Future changes |
|---|---|---|---|
| | Increased wildfire propensity from dry/hot conditions leading to soil destabilisation and landslide/debris flow when followed by rain: threat to human life and infrastructure (Moftakhari & AghaKouchak, 2019) | #3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions<br>#4 Risks to crops, livestock and commercial trees from multiple climate hazards<br>#8 Multiple risks to the UK from climate change impacts overseas | |
| | Narrow window between hot/dry and wet extreme events challenges emergency response resources (Parry et al., 2021) | | |
| Wildfire; hot conditions (multivariate) | Impacts of smoke on human health (Reid et al., 2016)<br>Acceleration of snowmelt due to solar radiation absorbing properties of ash accumulating on surface leading to changes in riverflow or flooding (AghaKouchak et al., 2020) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards<br>#2 Risks to soil health from increased flooding and drought | Uncertainty around projections of future wildfire occurrence in Scotland (CCRA3)<br>Increase in 'optimum' fire conditions – hot and dry periods – which also increases outdoor recreational activity and potential for ignition. Combined with increased fuel load from milder, wetter winters extending vegetation growth (Albertson et al., 2010) |
| | Carbon emissions from fires – especially from peat-rich areas (Alberston et al., 2010) | #3 Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions | |
| | Destruction of forest understory and weakening of surviving trees to pathogens, insects and disease (ClimateXChange, 2016c)<br>Spread of invasive and non-native species to burned areas (ClimateXChange, 2016c) | #1 Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards<br>#4 Risks to crops, livestock and commercial trees from multiple climate hazards | |
| | Landslide risk on burned land (Moftakhari & AghaKouchak, 2019) | | |

# 7. Recommendations

Based on the outcomes of this study, and building on the CCRA3 (HM Government, 2022) and the supporting documentation (e.g., WSP, 2020; Jaroszweski et al., 2021; Climate Change Committee, 2021), here we provide eight high-level recommendations that could be undertaken by research organisations and Government to better understand how compound events and cascading risks interact within and between sectors in Scotland:

1. **Historical data and event analysis**: Recategorising observed single hazard events as compound events would help reframe thinking towards multi-hazards. Currently, organisations cataloguing natural hazards may take a siloed approach to data collection as they do not consider events as coming about by a combination of factors. Revisiting notable events affecting various locations in Scotland through a multi-hazard lens, such as the 2018 Northern European drought and high temperatures (see Case study 1), may elucidate the compound nature of the underpinning factors of these types of events. Studies from the rest of the UK and Europe, when used in conjunction with weather and climate data for Scotland, may also allow for a multi-hazard understanding and the building of evidence.
2. **Consider key combinations of compound events across Scotland**: A detailed, Scotland-focused compound events and impacts analysis using the typology from Zscheischler et al. (2020) is required to accurately represent interacting risks identified in this study. Not doing so could underestimate these risks if they are considered using an individual hazard focus. Based on expert advice and judgement, these hazards include the following priority compound events, which are matched to CCRA3 priorities:

    a. Hot and dry conditions – CCRA3 highlights the potential risks in the UK from the combination of dry and hot summer conditions, including water supply disruptions from drought and reduced water quality in the natural environment, however few studies exist in Scotland to support adaptation actions;
    b. Flood and landslides from extreme rainfall – Evidence exists for storm surges and coastal regions, and for likely increases in extreme winter rainfall events and winter rainfall, however their connection to flooding and landslides (caused by extreme rainfall falling on saturated soils) is less understood. The intensification of surface water (pluvial) flooding is also likely in Scotland, but research remains in its infancy;
    c. Snow events (snow drought) and streamflows – Uncertainties remain over the likely future changes to the amount and timing of snow cover and the interplay with spring and summer streamflows in Scotland. Snow is an important factor to consider in future studies and resilience planning due to its significance to water resources and energy in Scotland;
    d. Winter storms – Despite recent notable storms in Scotland in recent decades (combining extreme winds and extreme rain or freezing conditions), evidence of trends of increased storminess are weak and urgently needs further research; and

    e. Wildfires and hot weather conditions – The combination of hot and dry (drought) conditions and their connection to fire weather conditions is likely to increase in a warming climate in Scotland, but there is limited evidence in the literature, highlighting a notable gap in knowledge.

3. **Modelling sequences of compound events**: Current modelling typically assesses linear pathways of singular hazards. There is a significant gap in knowledge about event sequencing in Scotland, including the 'see-saw' or 'weather whiplash' temporal succession between compound hazards. In order to better understand the impact of multiple or sequences of events (such as rapid dry to wet conditions, or multiple years of low rainfall), further modelling is required. We recommend that temporal sequences across multiple compound event types are assessed to calculate how different outcomes might occur within and across different sectors.
4. **Understanding the drivers of multiple compound events across Scotland**: There are few examples in the literature that explore and categorise multi-hazards as compound events, highlighting a need to investigate the drivers and mechanisms that are specific to Scotland's situation, both for present and future conditions.
5. **Better understanding of multi-sectoral Scotland-specific cascading impacts and risks**: The UK-wide level CCRA3 mapping does not recognise the national (Scottish) or location-specificity of risks and impacts. This is a dual issue for both the built and the natural environments, including critical infrastructure. A multi-sectoral analysis would provide a better understanding of cascading impacts and the economic consequences of such risks, which could inform adaptation efforts.
6. **Infrastructure thresholds and feedbacks**: Using inputs from stakeholders, it may be possible to identify some indicative threshold and feedback loops for exposed critical infrastructure. It would be particularly beneficial to formally identify the scope of these thresholds and loops and to find a way to model their effects, such as through indicators. This would enable better representation of their impacts on cascading and interacting risks.
7. **Revised adaptation and resilience approaches**: In order to better understand interacting risks within the contexts of different responses, we recommend that further research could be conducted to develop, apply and test the risks against different adaptation and resilience scenarios using storytelling and storyline approaches. Moving beyond high-level, descriptive, adaptation scenarios to sector/sub-sector specific plans may act as a lens through which the benefits of adaptation (and, inherently, urgency of action) may be better understood.
8. **Multi-hazard impact-based forecasting**: While we acknowledge there are activities underway in Scotland to continually improve the forecasting of single natural hazards, including surface water flood forecasting for example, we recommend a multi-hazard approach be increasingly adopted that is both impact-based (including sectoral cascading hazards) and incorporates all weather-driven hazards (including their interactions). We recommend a study be commissioned that reviews national and international best practise for both single and multi-hazard impact-based forecasting across various forecast lead times and assesses their applicability in the Scottish context.

# 8. Conclusions

This report investigated the relatively new field of interacting, weather-driven multi-hazards. We sought to develop a better understanding of Scotland's vulnerability to these types of hazards and their cascading impacts, particularly for a changing climate. We had the three following objectives:

- To review the available literature to develop a summary of multiple, interacting natural hazards that are particularly relevant for Scotland;
- To develop a series of case studies of recent examples of these hazards in Scotland and their impacts; and
- To identify potential vulnerabilities for Scotland from these hazards, particularly with regards to climate change, and to recommend actions to improve our understanding of compounds hazards and cascading risks.

The main conclusions for each of these objectives are as follows:

1. The extensive literature review revealed a significant gap in Scotland-focused research across all multi-hazard types. These interactions are identified as *potential future risks* – even those triggered by more typical or expected hazard pairings (e.g., compound flooding). Climate change will exacerbate the spatial and temporal distribution and the frequency of occurrence of compound hazards and their cascading risks and impacts. The pairs of key weather variables that contribute to these compound events (e.g., hot and dry weather) are predicted to occur more often and cover a greater area as the climate changes.
2. Four case studies, created by revisiting recent events with a multi-hazard interpretation, demonstrated the applicability of this interpretation to the Scottish context. These case studies are: (1) the concurrence of hot and dry conditions in North European spring/summer 2018; (2) UK flooding from rain on saturated soil in 2019/2020; (3) debris flows from rain on saturated soils in 2015/2016; and (4) successive UK droughts to floods in 2012. The case studies highlighted Scotland's current vulnerability to compound events. All studied events had significant impacts, which were made worse by hazard interactions. Our impact-centric bottom-up approach demonstrated how cascading impacts from multi-hazard events extend across sectors and natural systems in a complex, interconnected network. This approach complicates risk attribution but is vital that this type of event be included.

The expected increase in both the distribution and frequency of hazard events due to climate change clearly shows the need for a significant change from individually assessing hazards to adopting a fully multi-hazard approach. Combining the case studies with UK climate projections and an initial analysis of multi-hazard pairs for Scotland reinforces the pressing requirement for Scotland-focussed research in this field. To help prioritise multi-hazard research in Scotland we have made eight high-level recommendations that we believe would be particularly effective in improving Scotland's adaption actions and climate resilience plans.

# Appendices

## Appendix 1: Literature search methods and results

The search terms used in the literature review are at times broad, and some searches came with a plethora of results (e.g., 59,629) that cannot be reviewed in their entirety for this study. To overcome this, results were sorted based on their relevance to the search terms and manually combed through by reading the abstracts until the results were no longer relevant to the search terms. Where applicable, a minimum of five pages (~50 results) were analysed per search term. To capture as much information as possible, and to understand which multi-hazards are more emergent, the date range of publications was not limited. Similarly, a broad range of research areas were explored as the multi-hazard field encompasses different disciplines (Tilloy et al., 2019). Literature searches were carried out between 07/11/2021 and 22/12/2021.

A summary of the search terms used are presented in Table A.1. The total filtered results in the tables include duplicates since the searches often came with similar results. This table documents the initial search into multi-hazards, demonstrating the lack of Scotland focused studies particular to this area of research. More detailed searches were subsequently conducted using more specific multi-hazard key terms. Furthermore, an investigation into single hazard focused publications (e.g., drought) was performed to reframe and compile multi-hazard evidence for Scotland.

***Table A.1**. Summary of the literature search process using Web of Science for Scotland, UK and global multi-hazard studies.*

| Search term | Research areas permitted in search | Returned results | | | Filtered results | | |
|---|---|---|---|---|---|---|---|
| | | Scotland specific | UK | Unspecified location | Scotland specific | UK | Unspecified location |
| “Compound* hazard*”; “compound* hazard*” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | Meteorology and atmospheric sciences<br>Physical sciences<br>Environmental sciences Ecology<br>Geography<br>Geology<br>Water resources<br>Engineering<br>Oceanography<br>Agriculture<br>Forestry<br>Biodiversity conservation<br>Plant sciences | 2 | 3 | 23 | 1 | 3 | 13 |
| “Compound* event*”; “compound*event*” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 1 | 4 | 208 | 1 | 3 | 120 |
| Multi-hazard*; multihazards*; multi-hazard* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain; multihazard* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 10 | 773 | N/A | 3 | 19 |
| “Concurr* hazard*”; “concurr* hazard” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 8 | N/A | N/A | 3 |
| “Multivariate hazard*”; “multi-variate hazard*”; “multivariate hazard*” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain; “multi-variate hazard*” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 123 | N/A | N/A | 4 |
| Concurr* hot AND dry; concurr* hot AND dry AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 2 | 94 | N/A | 1 | 36 |
| Drought* AND heatwave*; Drought* AND heatwave* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 14 | 321 | N/A | 3 | 41 |
| “Compound flood*”; “compound flood*” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 5 | 123 | 4 | 4 | 56 |
| “Snow drought” AND “stream flow”; “snow drought” AND “stream flow” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 1 | 99 | N/A | 0 | 31 |
| “Saturated soil” AND rain AND landslide*; “saturated soil” AND rain AND landslide* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 29 | N/A | N/A | 6 |
| “Saturated soil” AND flood*; “saturated soil” AND flood* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 109 | N/A | N/A | 6 |
| “Antecedent moisture” AND landslide*; “antecedent moisture” AND landslide* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 19 | N/A | N/A | 16 |

| Search term | Research areas permitted in search | Returned results | | | Filtered results | | |
|---|---|---|---|---|---|---|---|
| | | Scotland specific | UK | Unspecified location | Scotland specific | UK | Unspecified location |
| “Antecedent moisture” AND flood*; “antecedent moisture” AND flood* AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 0 | 99 | N/A | N/A | 20 |
| “Drought to flood”; “drought to flood” AND Scotland OR UK OR United Kingdom OR GB OR Great Britain | | 0 | 1 | 17 | N/A | 0 | 14 |
| **Total number of publications** | | **2,080** | | | **408** | | |

## Appendix 2: Future multivariate climate projections

Due to the limited number of Scottish-focused studies on multi-hazards, a pilot study exploring select multivariate pairings in Scotland was conducted. This builds on results from the literature review, allowing for an initial diagnosis of vulnerable areas to be presented. This section demonstrates the results of multivariate pairing analysis for Scotland assuming the high emissions climate-change scenario (RCP8.5) for the near future (2031-2060). Generated climate projections on snow cover and rainfall in Scotland are also reported. The results are shown in the following subsections for: 1) multivariate hot and dry conditions, 2) multivariate compound wind and precipitation extremes, and 3) snow cover and snow drought.

### Multivariate hot and dry conditions

The multivariate results for concurrent hot and dry conditions are shown in Figure A.1. The map for current conditions shows concentrations of hot and dry days in northeastern Scotland, which was also identified in previous studies. This corresponds to areas that are vulnerable to water scarcity and agricultural drought. Hot and dry days are projected to increase for all areas of Scotland, although these increases are more marked in the west/northwest and the islands (currently the wettest areas of the country), which suggests a need to refocus on adaptation awareness for resilience against such compound events in these areas.

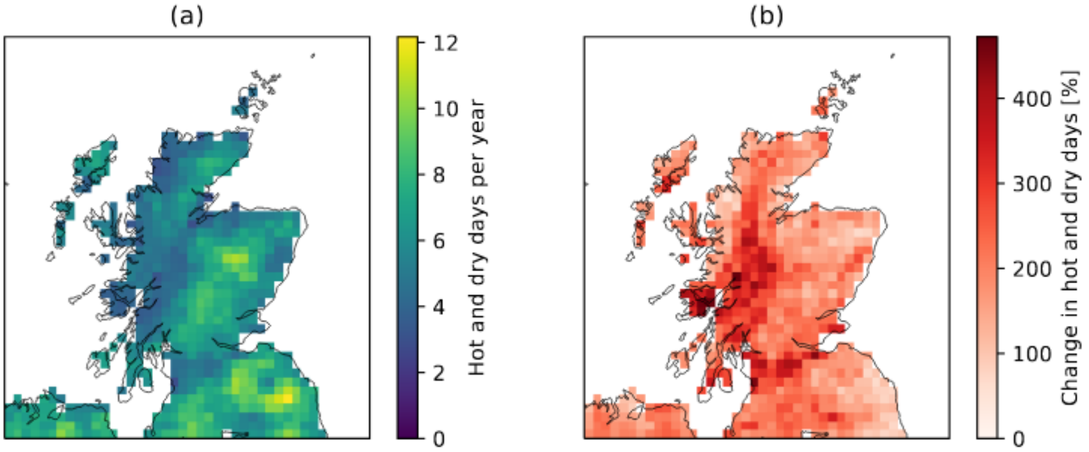

***Figure A.1*** *(a) Hot and dry days per year averaged over the baseline 1981-2010, (b) percentage change in hot and dry days per year projected for the near future (2031-2060)*

### Multivariate compound wind and precipitation extremes

Figure A.2 shows the results of multivariate wind and precipitation extreme pairing in Scotland's near future (2031-2060). The map for current conditions shows greater prevalence of wet and windy days in the west/northwest. The number of wet and windy days are projected to decrease or not change over the whole of Scotland but this is primarily due to reduced wind speeds. Higher resolution, local studies are needed for an accurate evaluation of compound flooding from storm surge and inland flooding especially considering changes of frequency, intensity and duration of precipitation with climate change (as discussed in Section 4.1.2 on compound flooding). Furthermore, the role of sea level rise is significant for compound flooding events but is not accounted for in this analysis.

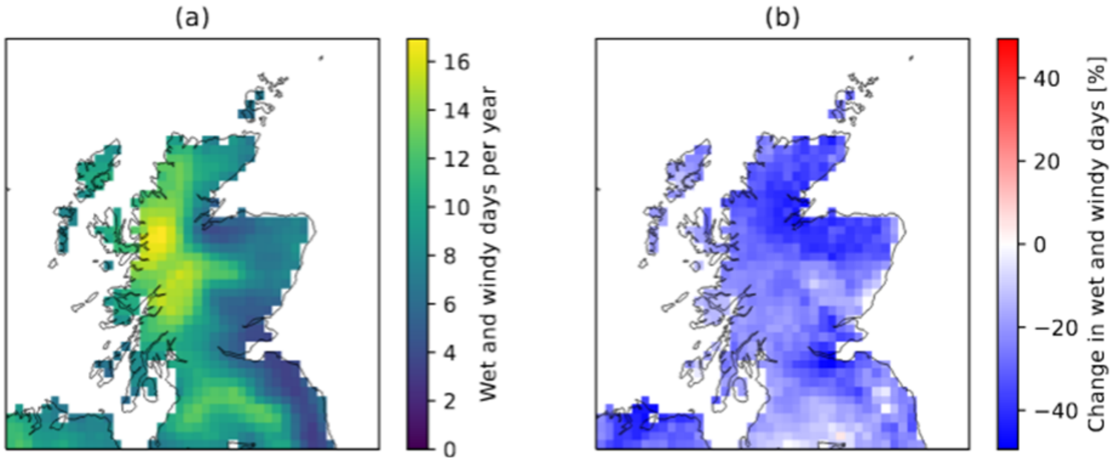

***Figure A.2**. (a) Days per year that have both extreme precipitation and wind conditions averaged over the baseline 1981-2010, (b) Percentage change in wet and windy days projected for future period (2031-2060).*

**Snow cover and snow drought**

The results for snow cover are shown in Figure A.3. The map for current conditions shows greater prevalence of days with snow cover in the Highlands. The number of days of snow cover are projected to decrease in all areas of Scotland but with the largest decreases (of up to 70%) are in the areas with the most days of snow cover currently, which matches previous analyses (Brown, 2020; Ballantyne et al., 2021). Nevertheless, there is a continued expectation for extreme snow events in the future. The effect of the topography of Scotland on snow covers requires more detailed analysis and snow cover is known to be hard to model. As demonstrated in Section 4.2.1, projected reduction in snow cover could have implications for spring/summer stream flow in snowmelt fed water courses in these areas. Few studies exist for the effects of warm season snow drought on streamflow worldwide, let alone for a specific Scotland context, yet those investigating this preconditioned event in western USA have shown water scarcity and cascading impacts on ecology and water management therefore more research is needed to establish a Scottish baseline evidence.

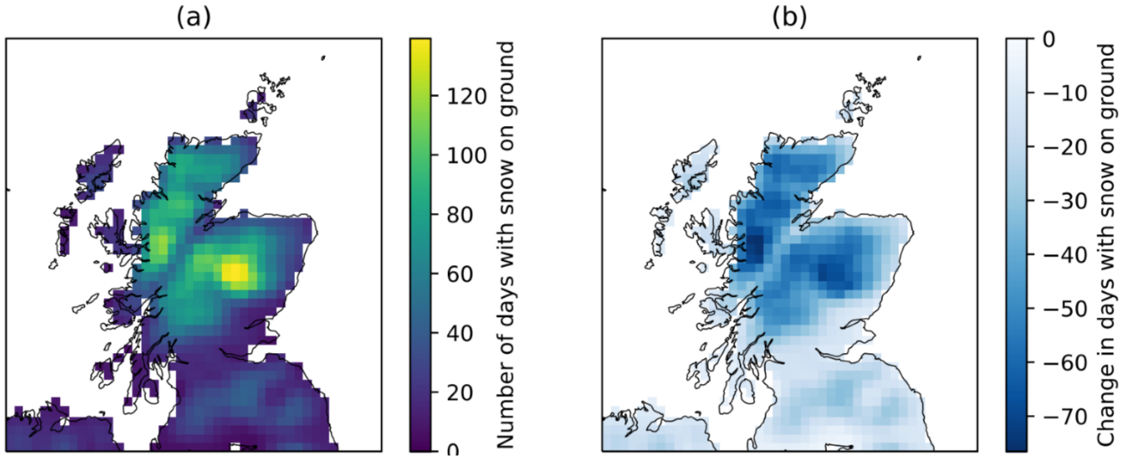

***Figure A.3.** (a) Number of days with snow on the ground averaged over the baseline 1981-2010, (b) Percentage change in days with snow on the ground projected for future period (2031-2060)*

# Appendix 3: CCRA3 2022 priority risks (UK-wide)

***Table A.2.*** *Highest UK-wide priorities for further adaptation in the next two years adopted by CCRA3 (HM Government, 2022) identifying eight priority risk areas (#1-8) that require the most urgent attention. Changing magnitude is shown up to 2100 for the highest scenario assessed in the CCRA3 Technical Report for the relevant risks for that theme [adapted from Climate Change Committee (2021)].*

| **Highest priority risks** | | **Magnitude of risk in time periods** | | | **Key policy areas** |
|---|---|---|---|---|---|
| | | **2020** | **2050** | **2100** | |
| **1** | Risks to the viability and diversity of terrestrial and freshwater habitats and species from multi-hazards | High | High | High | Biodiversity, soil and water protection and restoration, environmental management, sustainable farming and forestry, Net Zero, green finance |
| **2** | Risks to soil health from increased flooding and drought | Medium | High | High | |
| **3** | Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions | Medium | High | High | |
| **4** | Risks to crops, livestock and commercial trees from multiple climate hazards | Medium | High | High | |
| **5** | Risks to supply of foods, goods and vital services due to climate related collapse of supply chains and distribution chains | Medium | High | High | Public procurement, business resilience |
| **6** | Risks to people and the economy from climate-related failure of the power system | High | High | High | Infrastructure, energy, Net Zero |
| **7** | Risks to human health, wellbeing and productivity from increased exposure to heat in homes and other buildings | High | High | High | Building regulations and strategies, planning reform |
| **8** | Multiple risks to the UK from climate change impacts overseas | High | High | High | National resilience, overseas aid, research and capacity building |

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