Report No. 501

epa Research

The Impact of Extreme Weather Events on Ecosystems – Scoping Study (Extremes)

Authors: Mary Kelly-Quinn, Ashenafi Yohannes Battamo, Elke Eichelmann, John O'Sullivan and Md Salauddin

Lead organisation: University College Dublin

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Government of Ireland

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3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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What did this research aim to address?

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What did this research find?

Potential impacts on SACs and SPAs in Ireland were further explored through a questionnaire circulated among stakeholders. Responses highlighted that EWEs have varying degrees of impact across habitat groupings. A list of EWEs cited as having the largest impact on different habitat groups was compiled. Intense precipitation and flooding were reported to be particularly detrimental to rivers, streams, heaths and upland rocky habitats. Short periods of high temperatures exceeding 25°C were found to severely affect lakes, pools and standing waters. Prolonged droughts emerged as a critical threat to fens and turloughs, whereas wildfires and storm-force winds were reported to heavily impact forests and woodlands. Grasslands were reported to be particularly vulnerable to wildfires, while estuarine and marine habitats were notably affected by prolonged cold spells. Coastal habitats were found to face pronounced risks from tidal surges. Sensitivity to these climatic stressors varied substantially depending on habitat type. These findings highlight the urgent need to prioritise specific SACs and SPAs for detailed assessment of EWE impacts, and to inform future conservation and further research.

How can the research findings be used?

We identified a vulnerability assessment framework, comprising exposure, sensitivity and adaptive capacity indices, and tested its applicability in a case study on an Atlantic salt meadow habitat in Dublin Bay. The assessment revealed significant variation in exposure and impact severity, as indicated by the calculated Extreme Vulnerability Index scores. The framework has the potential to be applied at the national level to generate a vulnerability heat map for the various habitat groupings within SACs and SPAs and for more site-specific investigations required for identification of impact mitigation measures. Research needs relate to the production of national vulnerability maps and the identification of appropriate and measurable indicators for the three components of the vulnerability assessment framework. This may require both observational and experimental data collection, taking a multi-stressor, multi-scale perspective. Research is also needed to develop a robust analytical framework to test whether routine monitoring data can be used to detect impacts of climate change and EWEs. Based on the outcome of this analysis, it may be possible to identify how these monitoring programmes can be augmented to address the additional information needs.

Project code: 2022-CE-1152

EPA RESEARCH PROGRAMME 2021–2030

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(2022-CE-1152)

EPA Research Report

Independent scientific research funded by the Environmental Protection Agency

Prepared by

University College Dublin

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ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Climate, Energy and the Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely Aine O'Connor (National Parks and Wildlife Service), Mark Costello (Nord University, Norway), Katherine Dooley (EPA Technical Lead), Niamh McCarthy (EPA), Micheál O'Dwyer (EPA Climate Hub Lead), Rosemarie McDonald (Cork City Council) and Lorraine Bull (Fingal County Council), for their support and contributions over the duration of the project. The authors would also like to acknowledge the support of the Research Project Manager on behalf of the EPA, namely Karen Roche.

We also wish to thank research assistants Nadeem Naber, Arman Habib and Wenhui Wei, who worked on elements of the project. We are very grateful to many stakeholders who completed our two surveys and to Aine O'Connor, Grace Cott (University College Dublin) and Paul Brooks (University College Dublin) for their input into the focus discussion on the Dublin Bay case study.

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This report is based on research carried out/data from between March 2023 and June 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2021–2030

Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-80009-325-6 November 2025

Price: Free Online version

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Executive Summary

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1 Introduction

Evidence of accelerating pressures on ecosystems and biodiversity is mounting, particularly in terms of pollution and habitat fragmentation driven by a range of land use and other anthropogenic stressors, resulting in an unprecedented global decline in biodiversity across ecosystems. Climate change brings a suite of additional pressures to the existing multi-stressor environment that has the potential to alter ecosystems at every level of functioning, as outlined in Chapter 2. This will further challenge efforts to stem biodiversity loss and ecosystem degradation, and demands a rethink of how we address conservation goals and management of protected habitats and species. As noted by Folke *et al*. (2021), climate change and biodiversity loss are interconnected symptoms of the so-called Anthropocene and have implications for social, economic and cultural development. There is growing evidence that major biodiversity and ecosystem changes may be driven by extreme weather events (EWEs) (Harris *et al*., 2018).

The number of climate change-related EWEs has increased globally and is projected to increase further (Clarke *et al*., 2022). In terms of Ireland, Nolan and Flanagan (2020) predicted that by the middle of this century warming will be enhanced at the extremes (hot days and cold nights). Summer heatwaves are expected to occur more frequently, with the largest increases in the south, and precipitation is expected to become more variable, with substantial projected increases in the occurrence of both dry periods and heavy precipitation events. More recently, Thorne *et al*. (2023) noted that, although not formally studied, there is confidence that anthropogenic-induced climate change is enhancing the frequency and intensity of heat extremes and heavy precipitation events, and that these are likely to become more common under future climate scenarios. An increase in the frequency of EWEs was also highlighted by O'Loughlin (2023), and research by Meresa *et al*. (2022) on 37 catchments in Ireland projected increases in winter stream flows and decreases in summer flows. The increased intensity of a record rainfall event in County Cork in October 2023 has been attributed to climate change (Clarke *et al*., 2024). While projections for storm surges and extreme wave exposure are less certain, they too are expected to increase in magnitude and frequency as a result of climate change. These extreme events may influence the impact of other stressors. For example, extreme flooding and drought events in rivers are expected to interact with nutrient and fine sediment input to increase pressures on water quality (Murphy *et al*., 2023).

1.1 Defining Extreme Weather Events

Disturbances to ecosystems by climate change have been described in terms of a press (long-term changes) and pulse (extreme events) framework (Harris *et al*., 2018). The pulses, or EWEs, can be defined in various ways depending on the context. However, of relevance to this study are the meteorological events that are exacerbated by anthropogenic climate change and that present specific risks to Special Areas of Conservation (SACs) and Special Protection Areas (SPAs). These are likely to include heatwaves, forest and peatland fires, snowstorms, severe frosts, drought, intense precipitation, inland and coastal flooding, and storm surges (Herring *et al*., 2018; Stocker *et al*., 2013). Some of the key definitions from the literature are included in Table 1.1.

1.2 Policy Relevance

SACs, under the Habitats Directive (Directive 92/43/EEC), and SPAs focusing on wild birds (nesting, breeding and overwintering), as required by the Birds Directive (Directive 79/409/EEC), are part of the Natura 2000 network for protection of Europe's most valuable and threatened habitats (e.g. raised and blanket bogs) and species (e.g. the pearl mussel). These Directives are central to national, European and global efforts to protect representative habitats and threatened species and, in many areas, also provide vital ecosystem services. In Ireland, circa 441 SACs and 167 SPAs have been designated. Ireland's Prioritised Action Framework sets out priority measures needed to protect and restore SACs and SPAs (NPWS, 2021). The new EU Nature Restoration Law sets legally binding targets and deadlines for restoring habitats

Table 1.1. Selected definitions of "extreme event" that feature in the literature

Definition	Source
"An event that is rare at a particular place and time of year."	Seneviratne *et al.* (2021)
"... an event that is rare at a particular place and time of year … [it] would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations."	UNTERM (UN, 2023)
"... events that have extreme values of certain important meteorological variables … Extreme is generally defined as either taking maximum values or exceedance above pre-existing high thresholds."	Stephenson *et al.* (2008)
"... discrete episodes of extreme weather or unusual climate conditions, often associated with deleterious impacts on society or natural systems, defined using some metric to characterise either the meteorological characteristics of the event or the consequent impacts."	Stott *et al.* (2013)

and species listed in the Birds and Habitats Directives. The Nature Restoration Law was established under the EU Biodiversity Strategy for 2030, which aims to reverse biodiversity loss so that, by 2050, all of the EU's ecosystems are restored, resilient and adequately protected. The National Biodiversity Action Plan 2023–2030 (NPWS, 2024) also includes specific targets for enhanced conservation and restoration within the SAC and SPA network. Of relevance to these goals are the threats posed by climate change and the need to mitigate damage, especially in vulnerable, high-biodiversity areas.

A large extent of Irish SACs and SPAs can broadly be categorised as wetlands. The anaerobic conditions in wetland ecosystems provide potential for carbon sequestration and carbon storage. However, wetlands are usually also sources of methane, driving negative climate feedback, and careful management of these ecosystems is required to account for the complex interdependencies within their greenhouse gas (GHG) budgets (Petrescu *et al*., 2015; Regan *et al*. 2020). The Irish government's Climate Action Plan 2021 recognises wetlands as a focus area in terms of managing emission mitigation and carbon sink potential in the land use, land use change, forestry and the marine sectors, with SACs on raised bogs being specifically mentioned. While many SAC and SPA habitats (e.g. saltmarshes and other coastal ecosystems) are not currently included in the Irish Nationally Determined Contributions within the scope of the Paris Agreement, there is increasing recognition of the potential for climate change adaptation and mitigation through these types of ecosystems within policy frameworks (Cott *et al*., 2021).

The impact of extreme events on the precarious balance of GHG emissions and uptake, and the resulting carbon budgets in wetland ecosystems, has been documented (Chamberlain *et al*., 2020; Zhang *et al*., 2018). To realistically account for the GHG sink or source potential of SACs and SPAs within our national inventories and emission targets, we need a better understanding of the impacts of EWEs on these ecosystems' GHG balances and their vulnerability to such events, especially when combined with sustained warming.

It is clear that protected habitats and species in SACs and SPAs are vulnerable to the forecasted climate extremes. Furthermore, most (85%) Irish habitats listed in the Habitats Directive are in unfavourable status, and almost half are demonstrating ongoing decline (NPWS, 2019). Thus, those with responsibility for protected areas are challenged to adopt effective ecosystem and species management in the face of climate change and the uncertainty associated with biological responses against this background of unfavourable status. Equally challenging is the prevention of further deterioration and damage. As outlined by Reside *et al*. (2018), conservation protection and restoration planning must be cognisant of the range of climate change pressures (pulse and press), both current and projected, on biodiversity, ecosystems, ecological processes and geophysical diversity.

1.3 Aims and Objectives

The overall aim of this scoping study was to identify the potential impacts of EWEs on SACs and SPAs in Ireland and inform research needs. This was addressed through the following specific objectives:

- review and synthesise the likely range and nature of extreme climate events of relevance to Ireland;
- explore and identify the range of potential impacts of extreme climate events on SACs and SPAs in Ireland;
- assess the vulnerability of SACs and SPAs to climate change and the risk it poses;
- identify key knowledge gaps that need to be addressed by future research priorities.

In Chapter 2 we provide a synthesis of the key findings of the literature review. Chapter 3 seeks to address the second objective listed here, outlining the results obtained through engagement with stakeholders. A key output from this project is the exploration of a vulnerability assessment approach in Chapter 4. Finally, in Chapter 5 we present the key knowledge gaps and future research needs identified.

2 Potential Impact of Extreme Weather Events: Insights from the Literature

2.1 Global Background

EWEs, such as droughts, extreme temperature anomalies, flooding and storms, have been shown to have far-reaching consequences for ecosystems. As a result of extreme events, vertebrate and invertebrate populations globally have experienced resource bottlenecks, leading to extirpation events and significant population-level declines (Maron *et al*., 2015). The authors also identified droughts and storms as providing particular challenges for certain taxa (amphibians, mammals and reptiles, and birds, respectively) (Maron *et al*., 2015). Regional extirpation and large reductions in population size and species richness were also reported in a global review of the conservation implications of extreme events by Maxwell *et al*. (2019). However, the study also reported positive outcomes – for example, species responding to increased resource availability in the aftermath of floods (Maxwell *et al*., 2019). Similarly, Neilson *et al*. (2020) reported both negative and positive impacts on species from EWEs and specifically noted that some species compensated either behaviourally, physiologically or demographically in the face of extreme weather – reducing potential impacts by up to 86%. These studies highlight the diverse impacts that extreme events can have on species and ecosystems and draw attention to the need to understand potential risks to Irish ecosystems of important conservation value.

2.2 Methodology

Our literature review synthesised the reported impacts of EWEs, as opposed to more gradual climate change, on the biota of aquatic and terrestrial habitats protected in SACs and SPAs.

Environmental/ecological and meteorological/climatic terms and phrases identified as being of key importance were used to construct a search matrix, grouping terms depending on the type of event, the ecological measure or index that was impacted, and the level at which the impact was studied (from population to ecosystem). Based on this search matrix, a number of literature searches were conducted using the Web of Science and Scopus databases, initially identifying 191,336 publication records. This was reduced via successive screening with inclusion/exclusion criteria to 251 studies, which were included in the literature review (Figure 2.1).

2.3 Summary of Key Findings from the Literature

Here we summarise a number of the key findings of the literature review. The full review has been published elsewhere (Eichelmann *et al*., 2025). The existing literature on the impacts of EWEs on freshwater, terrestrial and marine ecosystems revealed that impacts are highly context specific. The impact of flooding on freshwater ecosystems has been intensively studied (Figure 2.2), whereas research on terrestrial biomes (including forests and grasslands) has mostly focused on heatwaves and droughts (Table 2.1). Research on marine and coastal ecosystems, on the other hand, has mostly centred on the impact of extreme storm events. Many studies also investigated coupled or compound events, making it difficult to attribute impacts to a specific event type. Additionally, the impact of EWEs is species dependent, with different species, even within the same taxon, showing divergent responses to the same event. Similarly, species' and communities' resilience and resistance to, and recovery from, extreme events are variable and depend on the species, species composition, availability of refuge area and existence of additional (long-term) pressures, among other things. For these reasons, drawing generalised conclusions from the existing literature and extrapolating these to an Irish context is difficult.

However, several studies across different ecosystems showed that increased diversity helps improve resilience and resistance to, and/or recovery from, extreme events (Bartha *et al*., 2022; Domec *et al*., 2015; Marcotti *et al*., 2021; Wiesner *et al*., 2020). Furthermore, additional anthropogenic pressures generally lead to more negative outcomes

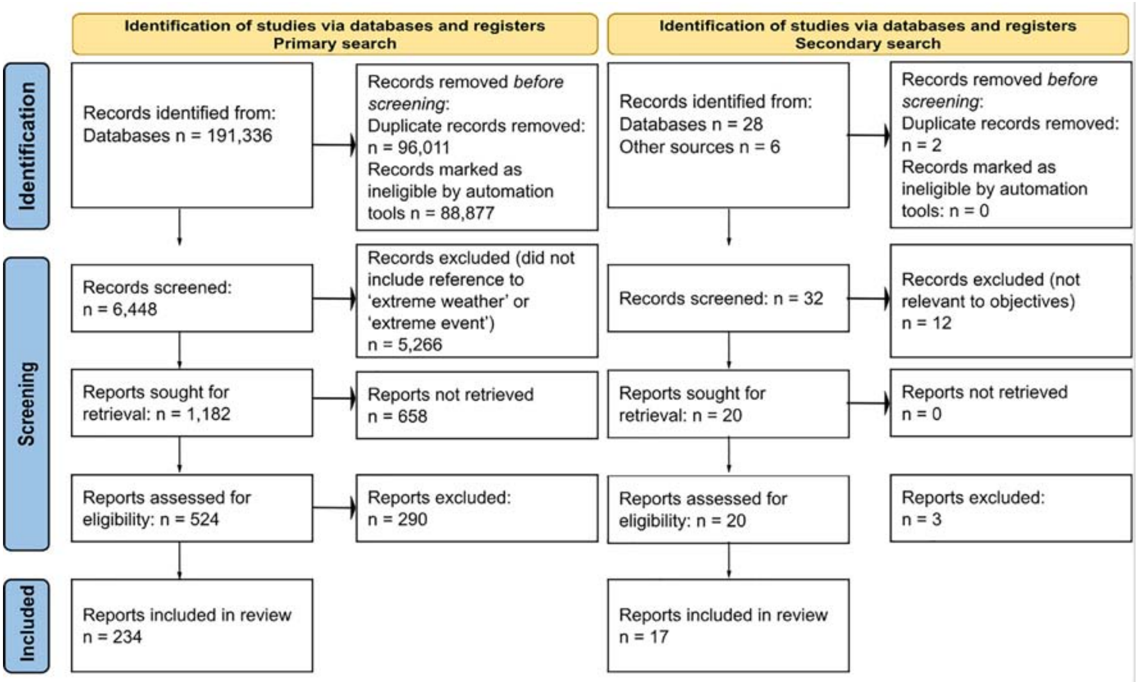

Figure 2.1. Flow chart of the inclusion and exclusion process for the primary literature review and the secondary search focusing on Irish ecosystems, following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) framework (Page *et al*., 2021). The sum of the two final figures is the number of studies included in the review (n = 251).

Figure 2.2. Stream bed and banks (A) before and (B) after the extreme flooding event described by Feeley *et al*. (2012). Reproduced from Feeley *et al*. (2012); licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Table 2.1. Number of studies covering specific ecosystems, communities and extreme events studied

Ecosystem	Community studied	Total no. of studies	Type of extreme event				
			Flood	Extreme temperature (heat or cold wave)	Drought	Storm (including hurricane, cyclone, tsunami, typhoon)	Other
Freshwater	Fauna	53	28	10	19	4	0
	Flora	8	4	2	0	5	0
	Total no.	67	34	11	21	9	4
Coastal and marine	Fauna	41	2	13	2	21	5
	Flora	22	0	6	2	13	1
	Total no.	60	2	17	3	33	6
Terrestrial	Fauna	52	13	24	13	5	1
	Flora	30	8	9	22	0	3
	Total no.	82	21	32	35	5	4
Forest	Fauna	5	0	4	2	1	0
	Flora	46	5	16	25	5	3
	Total no.	46	5	16	25	5	3

Individual columns/rows do not necessarily add up to the respective total, since some studies covered multiple ecosystems or event types, while others covered non-specific extreme events.

(Côté-Laurin *et al*., 2017; Crozier *et al*., 2020; Mouthon and Daufresne, 2015). Coupled events tend to have a synergistic effect, causing more negative outcomes than single events, except in instances where the same type of event recurs, which can lead to adaptations and increase resistance and/or resilience (Backhaus *et al*., 2014; de Long *et al*., 2019). The review also highlighted several areas that are highly understudied, such as open water marine ecosystems and marine/coastal microbial communities. Overall, EWEs are expected to occur with increasing frequency and severity, and more research is needed on how this will affect Irish ecosystems specifically.

3 Potential Impact of Extreme Weather Events on Special Areas of Conservation and Special Protection Areas in Ireland

3.1 Context and Rationale

The review work in Chapter 2 of this report draws attention to a mounting evidence base on the potential impacts of climate change on various aquatic and terrestrial ecosystems and the key ecological processes that underpin the functioning of these ecosystems. However, as noted by Maxwell *et al.* (2018), much of this research is focused on the responses of species and ecosystems to long-term means rather than on the impact of extreme events, despite the increased frequency of EWEs and the growing concern about the potential impacts on sensitive ecosystems that is evident in the literature (see, for example, Harris *et al.*, 2018; Sabater *et al.*, 2023). Therefore, there remains a gap in our understanding of the potential impacts of EWEs on sensitive habitats more generally, but also, specific to Ireland, on sensitive habitats protected within SACs and SPAs, which were the focus of the Extremes project.

The primary objective of the work in this chapter was to access and compile data and information, through stakeholder input, in order to explore and identify the range of potential impacts of EWEs on selected and representative SACs and SPAs in Ireland. A further objective of the stakeholder engagement in this chapter was to inform the choice of habitat for the case study and the presentation of the vulnerability analysis that is outlined in Chapter 4.

3.2 Methodology

3.2.1 Research method

Consideration was given by the project team to the most appropriate method for engaging with stakeholders to meet the specific objective of this project task. Both qualitative (e.g. focus groups) and quantitative (e.g. questionnaires) research methods were considered, but, based on the potential for wider outreach, the use of an anonymous, online self-completion questionnaire was adopted.

The format of the questionnaire evolved through extensive consultation with the EPA technical steering group for the Extremes project. Prior to developing the questionnaire, consideration was given to the range of EWEs that should be considered and the sensitive habitats that should be assessed. The eight EWEs in Table 3.1 were identified for inclusion in the questionnaire based on the results of the literature review in Chapter 2, and by recognising EWEs that are increasing in frequency in Ireland, and could therefore be expected to be most relevant to the functioning of sensitive habitats over longer-term time horizons. Definitions of these EWEs are included in Appendix 1.

Identifying sensitive habitats for inclusion in the questionnaire was a key task in developing a suitable survey instrument. The process commenced with a review of the Natura 2000 SAC sites in Ireland and the habitats listed in Annex I to the Habitats Directive that these are designated to protect. Irish SACs protect 59 different Annex I habitats, so a survey of each habitat type was impractical. To rationalise the survey, habitats were categorised as one of nine habitat groupings (Table 3.2).

Table 3.1. EWEs identified for assessment in the questionnaire

No.	Extreme weather event
1	Heavy precipitation and/or flooding
2	Prolonged drought conditions
3	Prolonged cold spells
4	Short periods of high temperatures (>25°C)
5	Short periods of low temperatures (<0°C)
6	Tidal surges
7	Storm-force winds
8	Wildfires

Table 3.2. The nine habitat groupings included in the questionnaire

No.	Habitat grouping
1	Rivers and streams
2	Lakes, pools and standing waters
3	Bogs
4	Fens and turloughs
5	Heaths and upland rocky habitats
6	Grasslands
7	Forests and woodlands
8	Estuarine and marine habitats
9	Coastal habitats

Following the identification of the key EWEs and habitat groupings to be considered, a structured online self-completion survey was developed using Survey Monkey. The questionnaire adhered to the key principles of questionnaire design, with the majority of questions being short and of a pre-coded and prompted nature. Precise and unambiguous questions were utilised to minimise misunderstanding. Both open-ended and closed-form questions were included in the questionnaire. Closed-form questions were designed with a meaningful scale that was selected to provide a good spread of answers. Where appropriate, scales comprised equal intervals between equivalent end points. The questionnaire contained nine sections, one for each of the habitat groupings. For each of the nine groupings, the respondent's opinions on how each of the eight EWEs impacted the habitat grouping were sought; therefore, the questionnaire contained 72 core questions. A final open-ended question (question 73) was included to provide respondents with an opportunity to provide any additional information to the project team that was not captured in the core survey questions. Filters were used, where appropriate, to guide respondents through the questionnaire. A sample of the questionnaire for a specific habitat grouping and EWE (rivers and streams and heavy precipitation and/or flooding) is included in Appendix 2.

3.2.2 Distribution of the questionnaire survey

A process of stakeholder mapping using a level of influence/level of interest matrix (Newcombe, 2003) was undertaken to ensure that those working with, and with responsibility for, SACs and SPAs in Ireland would have an opportunity to engage with the consultation process through the questionnaire. Personnel in the National Parks and Wildlife Service, as well as those with responsibility for protected areas on the ground or at the planning and policy levels, were of particular interest to the project team.

A three-pronged approach for distributing the questionnaire was implemented. This involved the following:

1. Identifying a list of individuals across Ireland known to be working on or researching issues relevant to the protection of sensitive habitats in Ireland. The list included individuals (40 in total) from academic institutions and from relevant agencies, including the EPA, Coillte, Teagasc, BirdWatch Ireland, Sustainable Water Network Ireland, Bat Conservation Ireland, Irish Peatland Conservation Service, An Taisce and the Irish Whale and Dolphin Group. Individuals were contacted directly by the project team (via email) with an electronic link to the questionnaire and were encouraged to share the questionnaire link more widely.
2. Distributing the questionnaire via contacts of the technical steering committee of the EPA Extremes project.
3. Distributing the questionnaire via the Extremes project website (www.ucd.ie/extremes).

Responses to the questionnaire survey were sought over a 4-week period in March and April 2024. Ethics approval from the University College Dublin Research Ethics Committee was obtained prior to distribution of the questionnaire.

3.3 Key Results

In total, 23 survey responses were returned, and the majority of these were incomplete, with respondents choosing to answer some but not all parts of the questionnaire. The number of survey responses for each habitat grouping is summarised in Table 3.3.

The maximum number of responses returned for any habitat grouping was five (rivers and streams; lakes, pools and standing waters; and bogs). With the exception of rivers and streams (grouping 1), where all five responses dealt with heavy precipitation and/or flooding (EWE 1), response numbers for other habitat

Table 3.3. EWEs cited by respondents as having the largest impact on the different habitat groupings

No.	Habitat grouping	No. of responses	EWE cited as being the most impactful
1	Rivers and streams	5	Heavy precipitation and/or flooding
2	Lakes, pools and standing waters	5	Short periods of high temperatures (>25°C)
3	Bogs	5	Short periods of low temperatures (<0°C)
4	Fens and turloughs	3	Prolonged drought conditions
5	Heaths and upland rocky habitats	1	Heavy precipitation and/or flooding
6	Grasslands	3	Wildfires
7	Forests and woodlands	2	Wildfires; storm-force winds
8	Estuarine and marine habitats	2	Prolonged cold spells
9	Coastal habitats	4	Tidal surges

groupings and EWEs were typically in the range of one or two. However, in many cases, no responses were given to questions assessing the impacts of particular EWEs on habitat groupings. The EWEs that were cited by respondents as being particularly impactful across the nine habitat groupings are summarised in Table 3.3.

4 Vulnerability of Ecosystems to Climate Change and the Risk it Poses

4.1 Review of Vulnerability Assessment Methods

Vulnerability assessments provide a structured approach to identifying which habitats, species and ecosystem services are at the most significant risk, allowing for the development of targeted adaptation and mitigation strategies for biodiversity conservation (Foden *et al*., 2019; Lecina-Diaz *et al*., 2021; Maxwell *et al*., 2019). This chapter synthesises various methodological approaches used in vulnerability assessments, examining their strengths and limitations. The research included an assessment of the applicability of a selected framework to a protected Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*) habitat in the North Dublin Bay SAC.

4.1.1 Methodological approaches to assess the vulnerability of protected habitats and species to extreme events

The assessment of the vulnerability of protected habitats and species to climate change is based on various theoretical and methodological underpinnings. These include conceptual frameworks, indicator-based approaches, species distribution and habitat suitability modelling approaches, participatory and stakeholder-driven approaches, and hybrid approaches (Advani, 2023; Foden *et al*., 2013; Foden and Young, 2016; Lecina-Diaz *et al*., 2021; Maxwell *et al*., 2019; Pacifici *et al*., 2015). The literature identifies three primary methods for assessing species vulnerability to climate change: correlative, mechanistic and trait-based (Advani, 2023; Foden *et al*., 2013; Foden and Young, 2016; Pacifici *et al*., 2015). These are detailed here, along with a hybrid method.

Trait-based approach

Trait-based methods assess a species' sensitivity, adaptive capacity and exposure by considering its biological traits and its exposure to changes in weather and climate (Ameca y Juárez *et al*., 2012; Foden *et al*., 2013). This method has become a preferred assessment method among conservation organisations, including the World Wide Fund for Nature. Traits such as body size, dispersal ability and habitat affiliation are believed to determine the vulnerability of animals to natural hazards (IPCC, 2022; Schoener and Spiller, 2006; Spiller *et al*., 1998; Walker *et al*., 2023). Recently, traits such as primary diet, body mass, habitat/dietary specialisation, home range size, generation length, number of litters per year, mean group size, day journey length, diurnality and ecological redundancy have been used to quantify sensitivity (Leclerc *et al*., 2020; Zhang *et al*., 2019). Additionally, diet breadth, habitat breadth (number of different habitats used), use of habitat, dispersal velocity, geographical isolation, presence of protected areas and phylogenetic distinctiveness are used to quantify adaptive capacity (Leclerc *et al*., 2020; Zhang *et al*., 2019).

In 2019, Zhang *et al*. (2019) utilised a trait-based approach to evaluate the susceptibility of 607 primate species worldwide to extreme climate events. They assessed the vulnerability of species based on exposure, sensitivity and adaptive capacity. However, vulnerability was further categorised into exposure and susceptibility dimensions. The research used high sensitivity and low adaptive capacity traits to assess inherent susceptibility. More recently, Walker *et al*. (2023) applied a trait-based approach to ascertain the vulnerability of large herbivores and carnivores in Mozambique to the intense tropical Cyclone Idai. Additionally, Coldrey *et al*. (2022) employed a similar approach to evaluate the vulnerability of protected areas to climate change in South African national parks.

Other studies, such as Auber *et al*. (2022), introduced a functional vulnerability framework that incorporated uncertainty and reference conditions into a generalisable tool, and demonstrated its relevance and operability through case studies on marine fish and mammals. Barry *et al*. (2023) investigated the vulnerability of Ireland's freshwater fish to climate change using a trait-based approach based on exposure, sensitivity and adaptive capacity. Leclerc *et al*. (2020) studied the vulnerability of native island mammals to climate change using a trait-based and quantitative vulnerability framework that had three vulnerability components: exposure, sensitivity and adaptive capacity.

Correlative approach

Correlative models use the geographical distribution of a particular species and the range of climatic variation within that distribution to predict the species' potential future range. Although commonly used to assess species' vulnerability to climate change, it has limitations due to uncertainties in climate projections, variations in modelling methods and reliance on the species' current realised niche to determine its fundamental niche (Advani, 2023; Pacifici *et al*., 2015).

Another challenge is the limited understanding of a species' realised dispersal ability, particularly over multiple generations. Realised dispersal, influenced by complex ecological interactions, landscape connectivity and behavioural traits, is critical to determining whether a species can colonise suitable habitats that emerge under changing climatic conditions. This is further complicated by a general lack of empirical data on species' dispersal capacities at generational scales, particularly under novel environmental pressures. As a result, correlative models may overestimate or underestimate a species' ability to track shifting climatic conditions, thereby introducing additional uncertainty into vulnerability assessments.

Mechanistic approach

Mechanistic models are highly useful, especially when detailed information on a species' physiology is available, for determining its tolerance limits, and have the potential to be used for evaluating their vulnerability to EWEs. However, due to lack of data, this approach is currently applicable to only a few species (Advani, 2023; Pacifici *et al*., 2015).

Hybrid approach

Hybrid modelling integrates and synthesises elements from different vulnerability assessment approaches. Recognising the limitations of individual vulnerability assessment methods, recent research has advocated for hybrid modelling approaches that integrate multiple assessment methods to capture the multi-dimensional nature of ecosystem vulnerability (Advani, 2023; Foden *et al*., 2013; Foden and Young, 2016; Lecina-Diaz *et al*., 2021; Maxwell *et al*., 2019; Pacifici *et al*., 2015).

Applying the combined vulnerability assessment approach described below (i.e. integrating the framework recommended by the Intergovernmental Panel on Climate Change (IPCC) with the functional trait-based approach) provides a comprehensive means for estimating the extent and nature of EWE impacts on habitats and species. In this study we focused on testing a hybrid approach, using standardised indicators and improving data integration through engagement with stakeholders. By using a hybrid vulnerability assessment framework and involving stakeholders in the process, practitioners or responsible authorities can better guide adaptive management practices to address the complex challenges of EWEs. Moving forward, there is a clear need for interdisciplinary approaches that integrate ecological, climatic and socio-economic dimensions to provide a holistic understanding of ecosystem vulnerability.

4.2 Vulnerability Assessment Method Adopted in This Study

Before introducing the vulnerability assessment methodology adopted in this study, consideration of why protected habitats and species are treated differently to other habitats and species is required, and of why a specific vulnerability assessment is required for EWEs. Protected habitats and species within SACs and SPAs are designated based on criteria such as observed declines (in structure and function or population), perceived threats, global responsibility (because their distribution is centred on parts of Europe) and sensitivity to anthropogenic and environmental pressures. While some habitats or species may be widespread or abundant, their legal protection reflects broader conservation obligations and ecological significance, necessitating tailored approaches to vulnerability assessment. The theoretical foundation of the vulnerability assessment adopted in this study is rooted in the IPCC vulnerability framework, which defines vulnerability as a function of exposure, sensitivity and adaptive capacity (McCarthy, *et al*., 2001; Parry, *et al*., 2007) (Figure 4.1). However, the existing definitions of the key elements of vulnerability (exposure, sensitivity and adaptive capacity) require modification when applied to protected habitats and species. The following section outlines how each vulnerability component is conceptualised and assessed in the context of protected habitats.

4.2.1 Exposure

The IPCC defines exposure as “the nature and degree to which a system is exposed to significant gradual climatic variations” (McCarthy *et al*., 2001: Annex B). However, for protected habitats and species, exposure must encompass not only gradual climatic variations but also associated EWEs. Therefore, we define exposure of protected habitats to extreme events as the extent to which an identified habitat or its ecological value – encompassing biodiversity, ecosystem functions and conservation priorities – is subjected to extreme climatic variations and their related ecological impacts. This exposure is influenced by macro- and micro-scale environmental conditions, including the habitat’s physical characteristics, ecological structure and function, geographical location and broader environmental context.

4.2.2 Sensitivity

The IPCC defines sensitivity as “the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli” (McCarthy *et al*., 2001: Annex B). In this study, we have adapted the IPCC definition such that sensitivity is defined as the degree to which EWEs affect an identified habitat or ecological value, either positively or negatively. Sensitivity may be affected at the level of individual species, communities, ecosystem functions or habitats. Understanding sensitivity requires a detailed evaluation of the species’ composition, habitat conditions and ecological interactions, and the habitat’s historical response to extreme climatic variations.

4.2.3 Adaptive capacity

The IPCC defines adaptive capacity as “the ability of a system to adjust to climate change (including

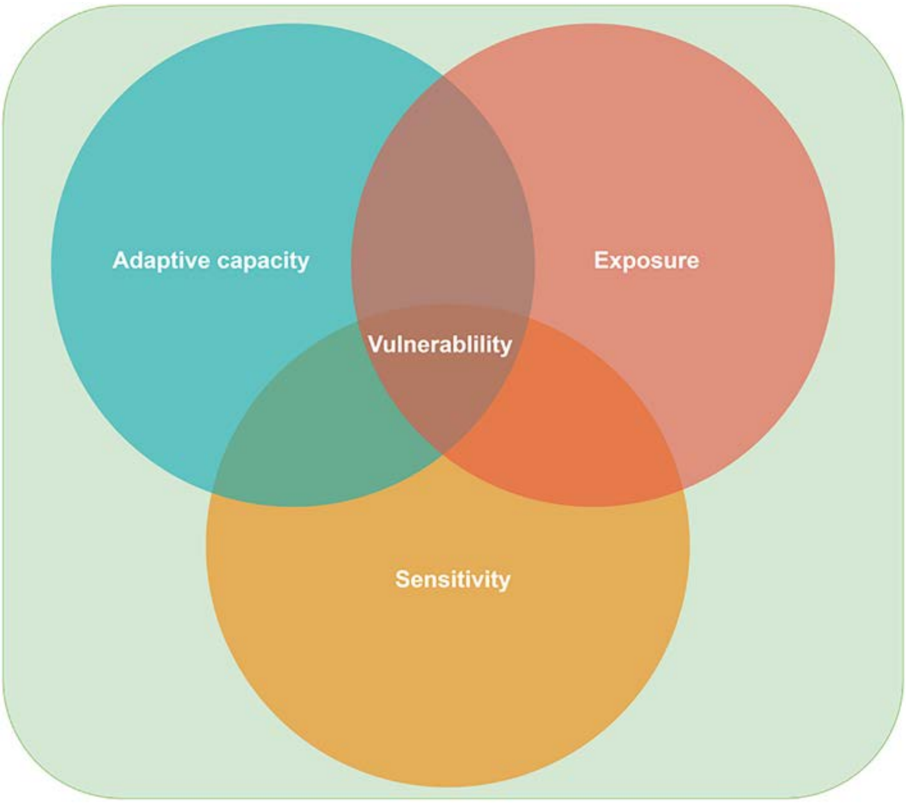

Figure 4.1. Elements of vulnerability from the IPCC Fourth Assessment Report (2007). Figure produced by the authors using information from Parry *et al.* (2007).

climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (McCarthy *et al*., 2001: Annex B). In this study, we have adapted the IPCC definition such that adaptive capacity is defined as the ability of habitats and/or species to withstand and recover from EWE stressors. Adaptive capacity is shaped by ecological processes, species-specific traits, management practices and conservation policies, all of which influence the potential for persistence and functionality under changing environmental conditions.

4.2.4 Vulnerability

Drawing from the IPCC's framework, the vulnerability of protected habitats is defined as the degree to which a habitat or ecological value is susceptible to, or will be adversely affected by, extreme climate variability and events. Vulnerability (V) is a function of exposure (E), sensitivity (S) and adaptive capacity (AC), and can be expressed by the following equation: $V = (E + S) - AC$ (Figure 4.2).

4.3 Case Study Demonstration of Vulnerability Analysis

4.3.1 Approach

In the following sections the key steps in applying the vulnerability assessment framework shown in Figure 4.1 to the project case study are described. The case study focused on the Atlantic salt meadows on North Bull Island, which is located within the North Dublin Bay SAC (site code 000206) and the North Bull Island SPA in Dublin. The SAC includes important coastal habitats such as sand dunes, salt marshes, tidal mudflats and salt meadows (Table 4.1). These habitats are of significant ecological importance, as they support a wide range of flora and fauna, some of which are protected under the Habitats Directive. North Bull Island formed in the 18th and 19th centuries after the construction of the South Wall and the Bull Wall to protect Dublin Port, which impacted tidal currents and caused the accumulation of sediment in the area (NPWS, 2013). The saltmarsh habitat is located on the landward site of the island (Figure 4.3). North Dublin Bay SAC is recognised nationally and internationally as being of high conservation value, and the area provides essential services, from biodiversity conservation and carbon sequestration to coastal protection and recreation.

The Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*), a coastal habitat providing essential ecosystems services such as coastal protection, carbon storage and water filtration, are under significant threat from the combined pressures of human activity (Brophy *et al*., 2019; NPWS, 2021; Penk and Perrin, 2022; Perrin *et al*., 2020) and climate change (Brooks *et al*., 2016; Schertenleib *et al*., 2023). Despite its ecological importance,

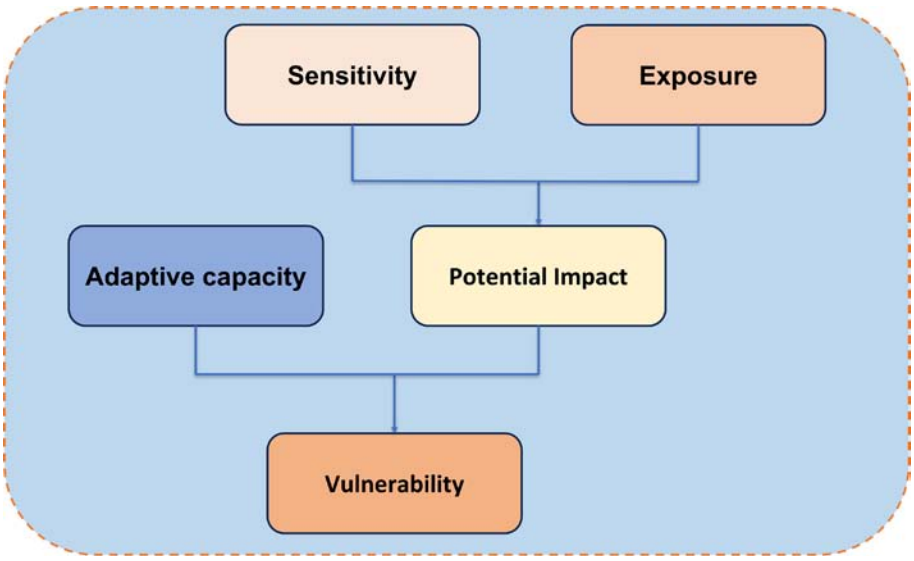

Figure 4.2. Vulnerability assessment conceptual framework based on the IPCC Fourth Assessment Report. Figure produced by the authors using information from Parry *et al.* (2007).

Table 4.1. Ten habitats listed in Annex I to the Habitats Directive that were identified in the North Dublin Bay SAC

Habitat e-code	Habitat	Cover (ha)
1140	Mudflats and sandflats not covered by seawater at low tide	577.73
1210	Annual vegetation of drift lines	0.11
1310	Salicornia and other annuals colonising mud and sand	29.10
1320	Spartina swards (*Spartinion maritimae*)	73.75
1330	**Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)**	**82.27**
1410	Mediterranean salt meadows (*Juncetalia maritimi*)	7.98
2110	Embryonic shifting dunes	6.07
2120	Shifting dunes along the shoreline with *Ammophila arenaria* (“white dunes”)	3.18
2130	Fixed coastal dunes with herbaceous vegetation (“grey dunes”)	104.80
2190	Humid dune slacks	12.11

Source: Reproduced from https://eunis.eea.europa.eu/sites/IE0000206; licensed under CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/).

Figure 4.3. The north lagoon saltmarsh area of North Bull Island on the landward side of the island. The Dublin neighbourhood of Kilbarrack is visible in the background. Source: the authors.

the overall conservation assessment for habitat 1330 was either unfavourable–bad (NPWS, 2006) or unfavourable–inadequate (Brophy *et al*., 2019). The conservation status of Atlantic salt meadows in Ireland has been persistently classified as inadequate over the last three reporting cycles (Table 4.2), with further decline noted in 2019 (NPWS, 2021). Anthropogenic pressures, such as intensive livestock grazing, reclamation and infilling for agricultural and developmental purposes, have led to habitat loss and fragmentation (Brophy *et al*., 2019; NPWS, 2021; Penk and Perrin, 2022; Perrin *et al*., 2020). High-intensity grazing affects 78% of surveyed sites, degrading soil stability and vegetation cover, while invasive species such as *Spartina anglica* further displace native flora and diminish habitat quality (Brophy *et al*., 2019; NPWS, 2021; Penk and Perrin, 2022; Perrin *et al*., 2020).

Climate change exacerbates these threats to the Atlantic salt meadows habitat, particularly through

Table 4.2. Current status of habitats listed in Annex I to the Habitats Directive

Code	Short/common name	2007	2013	2019
1330	Atlantic salt meadows	Inadequate	Inadequate=	Inadequate↓
1410	Mediterranean salt meadows	Inadequate	Inadequate=	Inadequate↓
2130	Fixed dunes (grey dunes)*	Bad	Bad=	Bad↓
21A0	Machair*	Bad	Bad=	Inadequate=
6130	Calaminarian grasslands	Inadequate	Inadequate=	Inadequate↓
6210	Orchid-rich calcareous grassland*	Bad	Bad=	Bad↓
6230	Species-rich Nardus grassland*	Bad	Bad↓	Bad=
6410	Molinia meadows	Bad	Bad↓	Bad↓
6430	Hydrophilous tall herb	Inadequate	Bad=	Bad↓
6510	Hay meadows	Bad	Bad=	Bad↓

***Priority habitat.**
↓ (declining): status has deteriorated compared with the previous reporting period.
= (stable): status has remained the same compared with the previous reporting period.
Source: Table generated using information from NPWS (2019).

EWEs (Cunha *et al*., 2024; Lubińska-Mielińska *et al*., 2023; Parry and Hendy, 2022), making its conservation and restoration a priority for maintaining ecological balance, as climate change will degrade the ecological status of Dublin Bay (Brooks *et al*., 2016; Schertenleib *et al*., 2023).

4.3.2 Step 1: Define the scope and objectives of the assessment

The first step in applying the vulnerability assessment framework involves identifying the protected habitats and species under consideration, the scale of the assessment (local, regional or landscape level) and the primary EWEs that may affect these habitats and species. This process is inherently context dependent, as ecological characteristics, conservation priorities and data availability vary significantly across systems. While the goal is to achieve a comprehensive understanding of threats to a given system, this is guided by the spatial, temporal and ecological context of the assessment. This requires details of the habitat's spatial boundaries, species composition, ecosystem services and conservation status, and these are typically assessed using input from experts in the field. Where data are lacking, expert field surveys and ecological assessments are recommended for establishing the baseline conditions.

Stakeholder engagement in step 1 serves a complementary role by aligning the assessment with ecological, social and economic priorities. Conservation managers, local communities, policymakers and researchers contribute valuable site-specific knowledge and perspectives on conservation strategies and socio-economic dynamics, and access to collaborative networks. This engagement helps to ensure that the vulnerability assessment is both scientifically robust and contextually relevant, ultimately supporting the effective implementation of conservation measures. As mentioned above, we limited our work in the Extremes project to the North Dublin Bay SAC case study.

4.3.3 Step 2: Identify a conceptual framework and meaningful parameters

In this study, we adopted the aforementioned IPCC vulnerability assessment framework, which emphasises the interplay between exposure, sensitivity and adaptive capacity (Figure 4.1). This often involves collecting data from diverse sources, including field observations, surveys, historical climate records, projections of future conditions, ecological studies, stakeholder input and remote sensing data. Site visits and consultations with experts and stakeholders are essential for capturing dynamic interactions between habitat components and their environmental contexts. The components of vulnerability in the case study, including the indicators related to each, are shown in Figure 4.4.

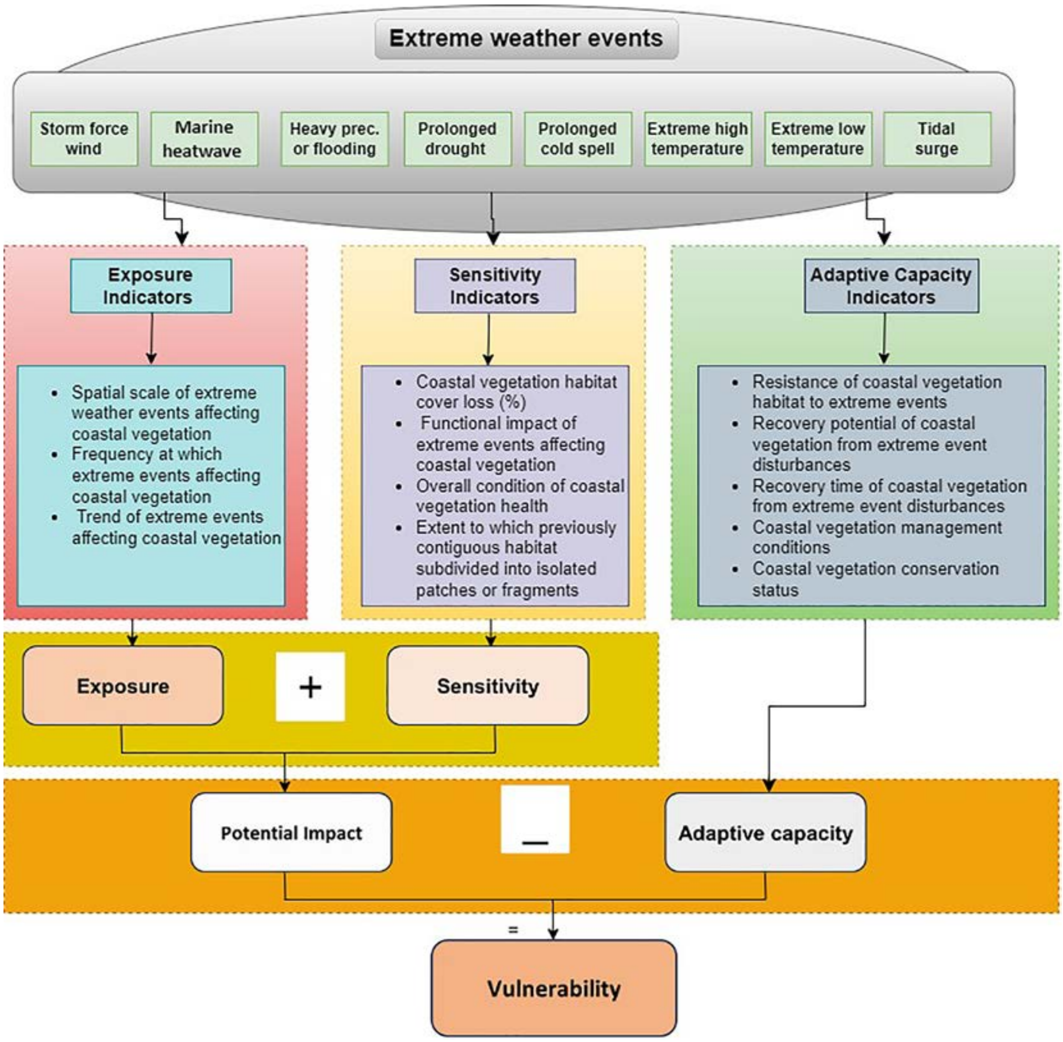

Figure 4.4. Vulnerability assessment conceptual framework implemented in the case study on the Atlantic salt meadows habitat in the North Dublin Bay SAC. Prec, precipitation.

4.3.4 Step 3: Assess data availability, select indicators and collect data

Prior to establishing an appropriate data collection strategy for a particular application of the vulnerability framework, the availability of relevant datasets and information sources is evaluated. A set of indicators is essential to quantify exposure, sensitivity and adaptive capacity effectively. Indicators are selected to measure key aspects of exposure, sensitivity and adaptive capacity, providing a quantifiable basis for assessing vulnerability. The choice of indicators is context specific, reflecting the unique characteristics and stressors of each habitat and species. Examples include indicators of habitat health (e.g. vegetation cover), exposure (e.g. spatial scale, frequency of and trends in extreme events) and adaptive capacity (e.g. management interventions). Data collection methods should be varied, integrating remote sensing, field surveys, ecological modelling, expert surveys, stakeholder interviews, historical data analysis and future predictions. Using a mix of qualitative and quantitative data can provide a more nuanced understanding of habitat vulnerability. In this case study, we selected the indicators shown in Figure 4.4, based on the project's literature review.

4.3.5 Step 4: Develop exposure, sensitivity and adaptive capacity indices

A composite index construction approach was used to combine the data gathered in the previous steps and develop exposure, sensitivity and adaptive capacity indices (Figure 4.4). Data were collected for each indicator and used for calculating index values for exposure, sensitivity and adaptive capacity.

This involved normalising, weighting and aggregating indicators to create composite indices as follows:

- **Normalisation.** Convert indicators into a common scale (e.g. 0 to 1) to facilitate comparison. This often involves using min–max normalisation.
- **Weighting.** Assign a weight to each indicator based on its relative importance to the overall vulnerability. Weighting can be determined using expert consultation, stakeholder surveys or statistical methods.
- **Aggregation.** Combine the normalised, weighted indicators to generate indices for exposure, sensitivity and adaptive capacity. This can be done using arithmetic or geometric means, ensuring consistency across different vulnerability components.

The choice of indicators and their weighting should be context specific, reflecting the unique ecological and socio-economic attributes of the protected area or species assessed.

Vulnerability components – index calculations

The following equations were adopted from a number of sources (Battamo *et al*., 2021, 2022; Coldrey *et al*., 2022; Losciale *et al*., 2024) to calculate the exposure, sensitivity, adaptive capacity and vulnerability indices based on the IPCC vulnerability conceptualisation (Parry *et al*., 2007).

Exposure (*ExP*)

$$ExP = \frac{1}{N}\sum_{i=1}^{N} ExP_i = \left(\frac{SS + FR + TR}{3}\right) \quad (4.1)$$

Sensitivity (*SeS*)

$$SeS = \frac{1}{N}\sum_{i=1}^{N} SeS_i = \left(\frac{HL + FI + VH + HF}{4}\right) \quad (4.2)$$

Adaptive capacity (*AdC*)

$$AC = \frac{1}{N}\sum_{i=1}^{N} AdC_i = \left(\frac{RE + RP + RT + VM + CS}{5}\right) \quad (4.3)$$

Extreme event vulnerability index (*EVI*)

$$EVI = AdC - \left(ExP + SeS\right) = \left(\frac{1}{N}\sum_{i=1}^{N} AdC_i\right) - \left(\left(\frac{1}{N}\sum_{i=1}^{N} ExP_i\right) + \left(\frac{1}{N}\sum_{i=1}^{N} SeS_i\right)\right) \quad (4.4)$$

$$\mathbf{EVI = (w * exposure) + (w * sensitivity) - (w * adaptation)} \quad (4.5)$$

where w can be assumed to be the confidence score.[1]

4.3.6 Step 5: Assess vulnerability by combining indices into the conceptual model

This step involved aggregating the three indices – exposure, sensitivity and adaptive capacity – into an overall vulnerability score, identifying areas and species at greatest risk. To synthesise the information gathered, a vulnerability index was developed as a useful way to integrate the three dimensions of vulnerability (Equation 4.5 and Table 4.3). Ideally, a single, interpretable metric should be computed that can be used for comparison across different habitats or species.

Aggregating vulnerability components. Use the conceptual model (e.g. vulnerability = (exposure + sensitivity) − adaptive capacity) to combine the indices (Figure 4.4). High exposure and sensitivity coupled with low adaptive capacity results in higher vulnerability.

Resulting extreme event vulnerability index (EVI) scores were calculated to indicate the overall susceptibility of the studied habitat to EWEs,

1 Mathematical notation for the above equations: CS, coastal vegetation conservation status; FI, functional impact of extreme events affecting coastal vegetation; FR, frequency at which extreme events are affecting coastal vegetation; HF, extent to which previously contiguous habitat is subdivided into isolated patches or fragments; HL, coastal vegetation habitat cover loss (%); RE, resistance of coastal vegetation habitat to extreme events; RP, recovery potential of coastal vegetation from extreme event disturbances; RT, time of coastal vegetation from extreme event disturbances; SS, spatial scale of EWEs affecting coastal vegetation; TR, trend of extreme events affecting coastal vegetation; VH, overall condition of coastal vegetation health; VM, coastal vegetation management conditions.

Table 4.3. Example of the EVI calculations from the case study on the Dublin Bay Atlantic salt meadows

Extreme event	Vulnerability elements			EVI	
	Exposure	Sensitivity	Adaptation	EVI	EVI (normalised)
Tidal surges	2.33 (1.33)	2.00 (1.00)	2.00 (1.00)	3.11	0.84
Storm-force winds	2.33 (1.67)	2.00 (1.00)	2.00 (1.00)	3.89	1.00
Heavy precipitation and/or flooding	1.67 (1.67)	1.00 (1.00)	3.00 (1.00)	0.78	0.36
Short periods of high sea surface temperatures (>25°C)	1.50 (1.50)	1.00 (1.00)	3.00 (1.00)	0.25	0.26
Marine heatwaves	1.50 (1.00)	1.00 (1.00)	3.00 (1.00)	–0.50	0.10
Prolonged drought conditions	1.33 (1.33)	1.00 (1.00)	3.00 (1.00)	–0.22	0.16
Short periods of low temperatures (<0°C)	1.00 (1.00)	1.00 (1.00)	3.00 (1.00)	–1.00	0.00
Prolonged cold spells	1.00 (1.00)	1.00 (1.00)	3.00 (1.00)	–1.00	0.00

Weight/confidence is presented in brackets.

with values near to +1 signifying high vulnerability and a value proximal to 0 indicating low vulnerability or higher resilience. Table 4.3 includes these metrics for the case study of the Dublin Bay Atlantic salt meadows.

4.3.7 *Step 6: Validation and sensitivity analysis*

Validation is a critical step in ensuring the reliability of the vulnerability assessment. This involves cross-referencing the results with empirical data, such as observed climate impacts on habitats or changes in species distributions. Sensitivity analysis tests the influence of individual indicators on the overall vulnerability index, identifying areas where improved data or additional research are needed.

In the Extremes project, we held focus group discussions with marine science experts, who provided information with regard to coastal and marine habitats, to better understand the inherent complexity of the systems being studied. These discussions provided critical insights for validating indicators and refining the methodology. While the primary focus was on coastal and marine habitats, the insights gained from the validation process are transferable to other habitats with adequate empirical data. This multi-faceted approach ensured that the framework was robust and applicable across diverse habitats.

4.3.8 *Step 7: Identify adaptation and management strategies*

Based on the vulnerability assessment results, an application of a framework of the type presented can guide and support the development of targeted adaptation and management strategies for sensitive habitats. These may include habitat restoration, assisted species migration, establishment of ecological corridors, climate-resilient land use planning and adaptive management practices. Engaging stakeholders and local communities in co-developing these strategies can enhance the process and ensure that strategies and individual mitigation measures are contextually appropriate and supported by the individuals and groups most affected. This was not a goal of the present case study.

4.3.9 *Step 8: Communicate results and refine through iterative stakeholder review*

The final step involves presenting the assessment results to stakeholders for review and feedback. Effective communication of the assessment results is vital for informed decision-making, policy formulation and adaptive management. The framework emphasises the need for an iterative process in which vulnerability assessments are regularly updated as new data and insights become available. This process validates the findings and ensures that they are contextually relevant. Results are communicated through reports, visual summaries (e.g. colour-coded vulnerability rankings) and direct engagement with stakeholders to facilitate adaptive management strategies tailored to the habitat's or species' specific needs. This adaptive management approach allows for the continuous refinement of conservation strategies, accommodating changes in climate, ecological conditions and socio-economic dynamics.

The primary objective of this pilot study was to develop and test the methodological framework for assessing protected habitat vulnerability, rather than to engage in full-scale policy implementation or stakeholder-driven planning. As a result, this was not a relevant step for the current pilot case study. However, we acknowledge that future iterations of the framework, particularly when applied to site-specific conservation planning, will require stakeholder engagement to ensure practical relevance and to facilitate adaptive management.

4.4 Key Findings

The vulnerability assessment of the Atlantic salt meadow habitats in Dublin Bay to EWEs revealed significant variation in exposure and impact severity, as indicated by the calculated EVI scores (Table 4.3). Storm-force winds received the highest EVI scores, followed by tidal surges, reflecting the significant exposure and sensitivity of coastal habitats such as saltmarshes and estuaries to sea level fluctuations and extreme tidal conditions.

In contrast, Atlantic salt meadows were shown to be moderately vulnerable to events such as heavy precipitation and flooding (EVI score of 0.36) and short periods of high sea surface temperatures (EVI score of 0.26). While these events are less impactful than tidal surges or storm-force winds, their combined effects over time could lead to significant cumulative stress levels on habitats, influencing both species composition and ecosystem function.

Marine heatwaves and prolonged drought conditions show relatively low EVI scores of 0.10 and 0.16, respectively. Despite the predicted lower vulnerability of habitats to these events, they may still contribute to long-term habitat degradation, particularly in regions where climate change is driving shifts in baseline temperature and moisture regimes.

Notably the EVI scores indicate that short periods of low temperatures (below freezing) and prolonged cold spells have minimal to zero impact on the habitats assessed. This suggests a lower sensitivity of these ecosystems to cold extremes, possibly due to the historical climate conditions in which these habitats have evolved. While this finding may not be unexpected, it provides a critical baseline for comparing the relative vulnerability of these ecosystems. These results also reinforce the reliability of the methodological framework, demonstrating its ability to capture expected patterns of habitat sensitivity.

Overall, the results of this case study underscore the multi-faceted nature of habitat vulnerability to EWEs. The high EVI scores associated with storm-force winds and tidal surges for Atlantic salt meadows in Dublin Bay indicate that management strategies should prioritise an exploration of potential mitigation measures for the specific events. Additionally, the moderate to low scores for other weather phenomena highlight the need for a comprehensive vulnerability assessment approach that takes into account both short-term and long-term climatic trends. This detailed understanding of vulnerability forms the basis for evidence-based policymaking and adaptive management practices to protect habitats in the face of climate change. The vulnerability framework developed in this study can be used as a quick and repeatable exercise to understand the vulnerability of saltmarsh habitats to extreme events. While this framework can be adapted to assess the vulnerability of similar habitats, it is important to note that the results were based on a small sample size (low survey responses).

5 Knowledge Gaps and Research Needs

In this chapter we use the information garnered through the literature review, stakeholder engagement and case study to highlight information gaps and research needs (highlighted in bold type). While there is a growing body of evidence of the impact of climate change on species and habitats, a significant gap remains in our understanding of the potential impacts of EWEs associated with climate change on sensitive habitats more generally, and, specific to Ireland, those habitats protected in SACs and SPAs, which merit particular attention, as emphasised in Chapters 2 and 3. Furthermore, we do not know whether these events would lead to habitat loss or species extirpation in certain areas, or the potential for species and habitats to reestablish themselves post disturbance. Disturbances to species and habitats by climate change have been described in terms of a press (long-term changes) and pulse (extreme events) framework (Harris *et al*. 2018). EWEs thus sit within the context of more gradual climate change-mediated impacts and, in this context, can be difficult to disentangle from longer-term climate changes.

A key first step is identifying a methodological framework that can facilitate identification of species and habitats, in particular those protected in SACs and SPAs, that are vulnerable to EWEs, thereby enabling management to consider possible mitigation measures. The framework selected in this study can be employed at both national and local scales, but data requirements may differ. **At the national level, research is needed to generate a vulnerability heat map to enable more detailed vulnerability assessments at sites identified as having the highest vulnerability.**

The vulnerability assessment framework, as outlined in Chapter 4, has three components (exposure, sensitivity and adaptive capacity), and each contains a number of indicators of these elements. Effectiveness of the framework is highly dependent on the selection of appropriate and measurable indicators. The indicators will differ depending on whether the framework is to be used for national vulnerability screening or at a more local level for mitigation management. The indicators need to be reflective of the potential impact and easily measured, either within existing monitoring programmes or in more targeted studies. For example, the measurement of "habitat cover loss" in the present case study may require unreasonably high resources. Research is therefore needed to identify effective indicators for vulnerability assessment at the national and local levels.

The number of Natura 2000 SAC sites in Ireland, including habitats listed in Annex I to the Habitats Directive, is extensive, encompassing 59 habitat types. Clearly, a vulnerability assessment of each habitat would be impractical. We suggest that **the initial research vulnerability analysis and associated heat map generation should target coastal systems such as the Atlantic salt meadows and inland peatlands.** Both habitats are particularly important in terms of carbon sequestration and cover a substantial area of the country. However, consultation with stakeholders should be carried out to agree on the priority habitats for research on vulnerability to EWEs.

The potential response of ecological components to EWEs (pulse) will depend on the events' magnitude, duration, frequency, timing and spatial profile, but also on more gradual, long-term ongoing climate changes (press), both of which are operating simultaneously and alongside other pressures (Harris *et al*. 2018; Malhi *et al*. 2020). In effect, extreme events have the potential to exacerbate or amplify the impact of more gradual changes and, as noted by Harris *et al*. (2018), may push ecosystems to tipping points. Spatial scale may influence the potential for recovery, a factor that may not be of relevance to SACs and SPAs, as many are not spatially extensive. **Thus, future research must adopt a multi-stressor, multi-scale perspective to scope how climate change and other stressors interact to drive potential change and recovery, which may also be influenced by lag and legacy effects. Research is needed to consider how multiple stressors can be incorporated into the framework adopted in this study.** As noted by Maxwell *et al*. (2019), interactions with other stressors should be considered within the context of vulnerability. They note that those other stressors may be co-occurring EWEs or other anthropogenic stressors such as pollution. The results may help to inform more dynamic management and assessment frameworks for protected areas and inform whether proactive interventions are needed to mitigate impacts.

In addition to the paucity of studies investigating the impact of EWEs on Irish habitats and species, existing monitoring programmes are unlikely to yield data that can provide adequate evidence of the nature and extent of potential impacts. A perusal of the available datasets for SACs and SPAs, and of the national water quality monitoring programme and citizen science monitoring of bee and butterfly populations, highlights that the spatial and temporal scales may not capture the impacts of EWEs given their general unpredictable nature. **Research is needed to develop a robust analytical framework to test whether routine monitoring data can be used to extract impacts of climate change and, more specifically, EWEs**, such as the study undertaken by Feld *et al*. (2016) for multiple stressors in freshwater habitats. Based on the outcome of this analysis, it may be possible to identify how these monitoring programmes can be augmented to address the additional information needs. Furthermore, **it is recommended that consideration be given to tracking climate change impacts in the monitoring of the Nature Restoration Plan.** Research gaps should not delay the implementation of post-restoration monitoring, but should instead inform the review and adaptation of monitoring and conservation plans and measures.

Where it is not possible to link cause and effect due to insufficient data, studies employing **experimental simulation of EWEs may be required to confirm potential impacts and provide insights into the mechanisms underpinning impacts on species survival, ecological processes, biotic interactions and, ultimately, ecosystem resistance and resilience.** Timing is important, as the impact can vary depending on when the extreme event occurs in the life cycle of the organism and on community dynamics. **Research is needed to identify the vulnerable periods in the life cycles of species that constitute the various SPA and SAC habitats**, a gap also identified by Cinto Mejía and Wetzel (2023). An enhanced focus on the timing of extreme weather in climate change research will reveal how and when EWEs are altering ecosystems, the possible mechanisms behind these impacts, and what ecosystems or species are most vulnerable to EWEs, helping us to make more informed predictions about the ecological consequences of climate change. **Furthermore, assessing the vulnerability of keystone species would offer deeper insights into the resilience of the broader ecosystem. Finally, assessment of factors enabling the re-establishment of species and communities requires further study.** In some cases, new habitats may arise or the location of a specific habitat may be changed by the occurrence of EWEs.

6 Concluding Comments

The overall aim of this scoping study was to identify the potential impacts of EWEs on SACs and SPAs in Ireland and inform research needs. Apart from highlighting significant knowledge gaps in relation to the impact of EWEs on these habitats, the key output from this project was the identification of a vulnerability assessment framework that can be deployed at the national and local levels. A research priority is to generate a vulnerability heat map for priority habitats. This will entail the identification of appropriate and measurable indicators for the three components of the analysis framework. In addition, the data acquisition strategies to populate these indicators need to be identified. Observational data collected in the field may need to be supplemented with experimental simulation of extreme events to confirm potential impacts and provide insights into the mechanisms underpinning impacts on species survival, ecological processes, biotic interactions and, ultimately, ecosystem resistance and resilience. A key challenge is disentangling the impacts of longer-term climate changes from those of EWEs and interactions with other stressors. So-called impact attribution has been poorly studied. Extreme event attribution has generally been used to estimate how human-induced climate change has led to more severe weather events. A recent study by Noy *et al*. (2024) extended the methodology to extreme event impacts attribution, albeit in a socio-economic context. Finally, we recommend that consultation with stakeholders be carried out to prioritise the habitats for research based on their vulnerability to EWEs.

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Appendix 1 Quantitative Definitions of Extreme Weather Events

Quantitatively defining an EWE is far from straightforward. There is no universally accepted, unique definition of what constitutes an EWE.

While EWEs are generally easy to recognise, they are difficult to quantitatively define. This complexity arises from the multi-dimensional nature of these events. EWEs possess a variety of attributes that cannot be fully encapsulated by a single number. Such attributes include the rate (probability per unit time) of occurrence, magnitude (intensity), temporal duration and timing, spatial scale (footprint) and multivariate dependencies (Stephenson *et al.*, 2008).

In an attempt to quantitatively define EWEs, the following definitions, based on various sources of information relevant to Ireland, are proposed (IPCC, 2023; Stephenson and Murnane, 2008).

No.	Extreme weather event	Definition	Reference
1	Heavy precipitation and/or flooding	"Floods of rivers, lakes, coasts, etc., due to severe weather conditions; for example, river floods caused by intense precipitation over a short period (e.g. flash floods) and persistent/recurrent precipitation over many days (e.g. wintertime floods in northern Europe), river floods caused by rapid snowmelt due to a sudden warm spell, or coastal floods caused by high sea levels due to wind-related storm surges."	Stephenson *et al.* (2008)
		"Flood is the overflowing of the confines of a stream or other water body, or the accumulation of water over areas that are not normally submerged."	IPCC (2023)
		"A very heavy precipitation day is a day on which 20 mm or more rainfall is recorded."	https://www.met.ie/cms/assets/uploads/2017/08/Nov2009_rain.pdf
		"In July 25th/26th 1985, in Ireland many areas recorded over 50 mm of rainfall in the 24 hours period…"	https://www.met.ie/cms/assets/uploads/2017/08/July1985_Thunderstorm.pdf
		Daily rainfall > 30 mm within 24 hours and/or water levels rising above 0.5 m above normal levels, causing significant runoff or inundation.	Proposed quantitative definition
2	Prolonged drought conditions	"Drought is defined usually on the basis of the degree of dryness (in comparison to some 'normal' or average amount) and the duration of the dry period. Simple definitions relate actual precipitation departures to average amounts on monthly, seasonal, or annual timescales."	Stephenson *et al.* (2008)
		"Drought is an exceptional period of water shortage for existing ecosystems and the human population (due to low rainfall, high temperature and/or wind)."	IPCC (2023)
		"An absolute drought is a period of 15 or more consecutive days with daily precipitation of less than 0.2 mm (that is, a daily rainfall total < 0.2 mm)."	https://www.met.ie/cms/assets/uploads/2020/06/Summer2018.pdf
		A period of at least 15 consecutive days where the mean daily rainfall does not exceed 0.2 mm.	Proposed quantitative definition
3	Prolonged cold spells	"Cold waves/spells (e.g. extremely cold days or a succession of frost days with minimum temperatures below 0.8°C)."	Stephenson *et al.* (2008)
		The Extreme Cold Spell of November – December 2010 in Ireland is a good example. "Both Dublin Airport (–8.4°C) and Casement Aerodrome (–9.1°C) had their lowest November temperatures on record on the 28th."	https://www.met.ie/cms/assets/uploads/2017/08/ColdSpell10.pdf
		Consecutive days (≥ 5) with minimum daily temperature < –5°C.	Proposed quantitative definition

No.	Extreme weather event	Definition	Reference
4	Short periods of high temperature/ heatwave	"Heat wave is a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months."	IPCC (2023)
		"In Ireland, the current definition of a heatwave is classified as 5 consecutive days with a maximum temperature in excess of 25°C (that is, a daily maximum screen air temperature > 25°C)."	https://www.met.ie/cms/assets/uploads/2020/06/Summer2018.pdf
		Daily maximum temperature exceeding 25°C for at least 5 consecutive days.	Proposed quantitative definition
5	Short periods of low temperature	The Extreme Cold Spell of November – December 2010 in Ireland is a good example. "Both Dublin Airport (–8.4°C) and Casement Aerodrome (–9.1°C) had their lowest November temperatures on record on the 28th"	https://www.met.ie/cms/assets/uploads/2017/08/ColdSpell10.pdf
		Daily minimum temperature below 0°C for at least 2 consecutive days.	Proposed quantitative definition
6	Tidal surges	"Tidal ranges on the Malin Shelf from 0.5 m on a neap tide (1 m on a spring tide) in the Sound of Jura just south of the amphidromic point south of Islay, to 1.6 m on a neap tide (4.5 m on a spring). Further offshore and north of Skye the tidal range is reduced. Within the Irish Sea maximum tidal ranges occur on the Lancashire and Cumbria coasts where the mean spring tides have a range of 8 m, contrasting with Carnsore Point on the south eastern Irish coast where the range is only 1.75 m."	https://www.marine.ie/site-area/data-services/real-time-observations/tidal-flows-around-ireland
		Sea level rise exceeding 1.5 m above mean high tide due to atmospheric pressure and wind effects.	Proposed quantitative definition
7	Storm-force winds	Examples: • 120 km/h (hurricane force), Galway (Mace Head) 12th 2014. • 111 km/h (violent storm) Cork (Roches Point) 19th 2020 Ellen.	https://www.met.ie/climate/weather-extreme-records
		Sustained wind speeds ≥ 90 km/h (Beaufort scale category 10) or gusts exceeding 100 km/h.	Proposed quantitative definition
8	Wildfires	Examples: In 2022, Ireland experienced a record number of wildfires, with over 3400 hectares of land damaged. In 2023, 117 wildfires were mapped, covering over 5000 hectares. The majority of these fires occurred in upland heath areas, which are particularly vulnerable to wildfires.	https://www.breakingnews.ie/ireland/more-than-3400-hectares-damaged-as-record-number-of-wildfires-in-ireland-last-year-1471061.html; https://www.agriland.ie/farming-news/117-fires-covering-over-5000ha-mapped-in-ireland-in-2023/
		Uncontrolled fires affecting areas ≥ 1 hectare of land with varying intensities, often resulting in significant ecological and environmental damage.	Proposed quantitative definition

Appendix 2 Questionnaire Sample

'Extremes' Project Survey of Protected Habitats (Habitat Grouping #1: Rivers & Streams)

Habitat Grouping #1: Rivers & Streams - Heavy Precipitation and/ or Flooding

1. In your opinion, how sensitive are habitat conditions in rivers and streams to heavy precipitation and/ or flooding?

○ 1 Not sensitive ○ 2 ○ 3 ○ 4 ○ 5 Very sensitive

2. Have you observed/ recorded any impacts to habitat conditions in rivers and streams from heavy precipitation and/ or flooding?

○ Yes

○ No

Next

Habitat Grouping #1: Rivers & Streams - Heavy Precipitation and/ or Flooding

3. What were the observed/ recorded impacts? (select all that apply)

☐ Habitat degradation/ damage

☐ Reduction in species diversity

☐ Reduction in species abundance

☐ No impacts

☐ Habitat enhancement

☐ Increase in species diversity

☐ Increase in species abundance

☐ Other...

4. If your response is 'other' for the above question, what additional impacts might be considered?

Prev Next

Habitat Grouping #1: Rivers & Streams - Heavy Precipitation and/ or Flooding

5. When and where were these impacts observed/ recorded?

6. Are there species in habitats of rivers and streams that you believe are particularly vulnerable to heavy precipitation and/ or flooding?

7. Why are these species vulnerable?

8. Have you observed/ recorded recovery in the habitat conditions of rivers and streams following impact from heavy precipitation and/ or flooding?

- ○ Yes
- ○ No

Prev Next

Habitat Grouping #1: Rivers & Streams - Heavy Precipitation and/ or Flooding

9. The timeframe for this recovery was

- ○ Less than 1 year
- ○ Between 1 and 3 years
- ○ Between 3 and 5 years
- ○ Greater than 5 years

Prev Next

73. Please include any further comments relating to impacts in rivers and streams that you feel may be relevant to the Extremes project team

Prev Done

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Abbreviations

EVI	Extreme event vulnerability index
EWE	Extreme weather event
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
SAC	Special Area of Conservation
SPA	Special Protection Area

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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