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Qualitative Assessment of Complex and Interacting Climate Risks

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Presented to the Actuaries Institute
2024 All-Actuaries Summit
1-3 May 2024

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Abstract

We traditionally quantify climate change risks as a function of the risk determinants of hazard, exposure, and vulnerability. Traditionally, insurers have been concerned with the built environment domain, focusing on assessing the damage to properties and buildings from natural disasters. Many practitioners are extending climate risk assessments to other domains to look at climate risk more holistically, as climate change not only impacts the built environment, but also the social, natural, and economic domains.

However, there are limitations to relying solely on a quantitative assessment, as climate change risk is extremely complex, interacting both internally between the determinants of risk, and externally with many other risks. This can lead to cascading and compounding events, with widespread systemic risk impacts.

For example, vulnerabilities in one domain can stem from multiple hazards, leading to exposures in other domains, whilst exposures that change over time can create changing vulnerabilities across domains. Hazard interactions from disasters may cause feedback loops that lead to untenable capacity to support social, economic, natural and built domains.

A qualitative risk assessment can help identify the interactions between hazard, vulnerability, and exposure that a quantitative assessment typically fails to capture. Our methodology for qualitative assessment refers to reports aggregated from community interviews, which involves decision-makers, local officers, emergency response officers, and other stakeholders. The methodology combs through the main conclusions from the reports to form our basis for the interactions between hazard, vulnerability, and exposure under the four domains (built, social, economic, and natural). The confidence of the interaction increases where there are multiple instances of the same interaction being noted across different reports, or sometimes across similar themes within the same report.

The output from our qualitative assessment is multiple mapping diagrams that show the interactions captured within the reports within and between domains. We draw conclusions from these mapping diagrams, which can be used to supplement quantitative risk assessments.

Keywords: climate risk assessments; qualitative risk assessments; complex risks; hazard; vulnerability; exposure; feedback loop; cascading risks; interacting risks; compounding risks; systems thinking.

1 Introduction

1.1 Climate risk assessments

Climate risk assessments can be undertaken to identify and assess climate risks to different entities and individual companies, such as through climate risk disclosures under the International Accounting Standard Board (ISSB), and also on a global basis through Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC). In this paper, we consider climate physical risk assessments at a national level. Such assessments can be performed both qualitatively and quantitatively, and Section 1.2 provides some examples.

Climate physical risks are risks resulting from climate change that can be event-driven (acute physical risk) or from longer-term shifts in climatic patterns (chronic physical risk). Acute physical risks arise from weather-related events such as storms, floods, drought, or heatwaves, which are increasing in severity and frequency. Chronic physical risks arise from longer-term shifts in climatic patterns including changes in precipitation and temperature which could lead to sea level rise, reduced water availability, biodiversity loss, and changes in soil productivity. Climate physical risk assessments typically consider hazards such as bushfires, storms, floods, cyclones, coastal inundation, coastal erosion, and heat stress.

One motivation for climate physical risk assessments is to prioritise risks or geographic regions to prioritise future risk treatment through adaptation or mitigation. For example, the NSW State Disaster Mitigation Plan (State Disaster Mitigation Plan, 2024) considers the relative risk from disasters in each geographic region of the state. This is often accomplished using either quantitative measures or other categorisation of risks into a scale.

We consider a framework for the qualitative and quantitative assessments of risk that includes the determinants of hazard, exposure and vulnerability, as shown in Figure 1.1. Risk is considered as the expected adverse consequences of climate-related disasters, and is the combination of the following three *determinants* (O'Niell, 2021):

- *Hazards* – the natural physical events that may cause loss of life, injury (or other health impacts), as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources
- *Exposure* – the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected
- *Vulnerability* – the propensity or predisposition to be adversely affected by a hazard. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Figure 1.1 – Risk assessment model

This model of risk is widely used in assessment frameworks for disaster and climate risk, including in:

- The IPCC assessments of climate risk (O'Niell, 2021)
- The United Nations Office for Disaster Risk Reduction's Sendai Framework (UNDRR, 2015)
- The Commonwealth Government's National Disaster Risk Framework (NRTF, 2018)
- The National Climate Change Risk Assessment for New Zealand (NZ Ministry for the Environment, 2020)
- NSW Treasury's Disaster Cost-Benefit Framework (NSW Treasury, 2023)

When discussing risk in the assessment, we have adopted the definition of climate risk in line with the IPCC's sixth assessment report by (O'Niell, 2021). In previous IPCC assessment reports, the risk approach is divided risk into individual sectors, regions or asset classes, or types of response options, ignoring interactions between risks. This component-oriented, rather than interaction-oriented, approach can miss important interactions that can amplify, reduce, or generate additional climate risks (Simpson, et al., 2021).

The AR6's definition of climate risk incorporates the work of (Simpson, et al., 2021) on complex risk. Climate risks are becoming increasingly complex as they can occur simultaneously, and can interact with other climatic and non-climatic risks, creating compounding overall risk that cascades across sectors and regions (Simpson, et al., 2021). (O'Niell, 2021) integrate the complex risk framework in the AR6 to identify a broad range of climate-related key risks and an analysis of clusters of key risks.

As stated in the National Climate Risk Assessment Methodology, (O'Niell, 2021) provides a valuable framework for Western science to conceptualise the cascading, compounding and aggregating climate risks. It is the use of this in conjunction with First Nations' knowledge that will form a complete assessment of complex risk in Australia (Department of Climate Change, Energy, the Environment and Water, 2023).

While quantitative risk assessments can be more tractable and, for example, feed into cost-and-benefit frameworks more readily, the demands of quantitative modelling can be onerous, and lead to computational complexity. Examples of such quantitative models include catastrophe models used by insurers to price coverage for disasters such as cyclones, floods, bushfires and storms (John Seo, 2009). Simpler models can be linear in nature, such as those that take the product of measures for exposure, hazard and vulnerability. Such linear models can fail to identify systemic risks or feedback loops caused by non-linear cause-effect relationships (Seth Westra, 2023). There is often a lack of data from which to robustly parameterise such models or to make assumptions. Though qualitative assessments provide limited quantification of the relative size of risks, we argue in this paper that they can be used to understand and assess the limitations of quantitative models, providing insight into the complex interactions that are not captured well in linear frameworks.

One of the key reasons we assess risk is to form treatments to minimise it. A risk assessment aims to identify relevant treatment options, however, as noted in (Simpson, et al., 2021), responses to climate risk can themselves bring about risks because treatments that do not account for complex risk may result in unintended consequences. The collapse of Grenfell Tower exemplifies this, where a retrofit to improve the insulation of the tower was conducted without considering the impact on the fire risk of the building, resulting in external walls that ‘actively promoted’ the spread of fire (Jessel, 2019). The IPCC has identified maladaptation practices around the world in response to complex climate risks; for example, Australia’s response to drought-induced changes in water harvesting and storage unintentionally resulted in increased breeding sites for mosquitoes (O'Niell, 2021).

In Section 2, we describe our approach to qualitative assessment of complex risks affecting states in Australia by surveying the results of major inquiries and assessments of climate risk. In Section 3, we describe the key results and conclusions. In Section 4, we consider the key findings and make recommendations for future work.

1.2 Risk assessments and qualitative frameworks

Traditionally, insurers have been concerned with the built environment domain, focusing on assessing the damage to properties and buildings from natural disasters. Over time, qualitative assessments that explore complex problems have been employed by a range of academics, governments and bodies. Systems thinking approaches are increasingly being applied to model complexities, particularly non-linear interactions between cause and effect, with relationships that change over time and are difficult to predict (Hovmand, 2014). First Nations communities apply a systems thinking lens to the parts of an ecosystem or set of knowledges -how they are interrelated, and how the elements of the systems are defined and shaped by these interrelationships (Glynn-McDonald, 2022). While “systems thinking” is an ideology that has been consumed by Western disciplines of social change and systems change theory, First Nations communities are the original systems thinkers.

Intersectionality, a term coined by Kimberlé Crenshaw, is another lens that is frequently employed in social policy. While more commonly used to assess inequity, it can be useful in risk assessments to analyse who is at the intersections of multiple vulnerabilities (Crenshaw, 1991). Marginalisation can be based on attributes such as Aboriginality; age; disability; ethnicity; gender identity; socio-economic status; race; religion; and sexual orientation. The Victorian Government Gender Equality Commission uses an intersectional lens to recognise that the drivers of disadvantage or discrimination do not exist independently – there are interactions and overlaps. These compound the severity and frequency of the impacts of marginalisation, while also hindering access to support. In a risk assessment, it is critical to examine the experiences of Indigenous people, people of colour, and sexual, and gender minority populations within an intersectional framework to identify how these experiences relate to risk and resilience (Richard T Liu, 2023).

As stated previously, the IPCC AR6 identified and analysed a range of climate-related key risks, isolating which key risks and representative risks would significantly impact specific regions. Broadly, Australasia was said to have two key risks that are of particular concern; risk of wildfire and loss of cultural heritage (O'Niell, 2021). The IPCC (O'Niell, 2021) highlights that coastal settlements in Australia and New Zealand are at risk of sea level rise, with the estimated value of coastal urban infrastructure at risk amounting to between $AUD164-226 billion. Australia was also frequently mentioned to be impacted by ecological and agricultural drought, with ensuing risks to water scarcity, induced tree mortality and mass animal mortality due to heatwaves and biodiversity loss (O'Niell, 2021).

When applying systems thinking in the context of risk of disasters in Australia, we can refer to the National Resilience Taskforce initiated to help prioritise our collective efforts to reduce loss and harm across society. The Taskforce recognised that we can learn from the experience of Indigenous peoples about their relationship with nature, local knowledge, cultural practices, skills and knowledge of materials to better understand the reasons for their success in surviving or coping with disasters over centuries (NRTF, 2018).

In New Zealand, The Ministry of the Environment of New Zealand published its first national climate change risk assessment in 2020, calling out risk in the natural environment domain. With this assessment, the Ministry published a guide to local climate change risk assessments (NZ Ministry for the Environment, 2020). The guide sets out a risk assessment framework addressing the interdependencies between sectors influencing climate risk national adaptation planning and legislation. The guide was developed via workshops with a Local Government Working Group and Māori caucus and panel. The aim of the guide was to inform adaptation planning and to work with iwi/Māori as Treaty partners on a range of priorities (social, cultural, economic, and environmental). The guide also emphasised that when planning an assessment, that the needs of iwi/Māori must be considered through early dialogue. For example, identifying physical risks to iwi/Māori relies on working with local representatives and understanding their views on both physical and spiritual wellbeing as they are interconnected.

2 Methods for qualitative assessment

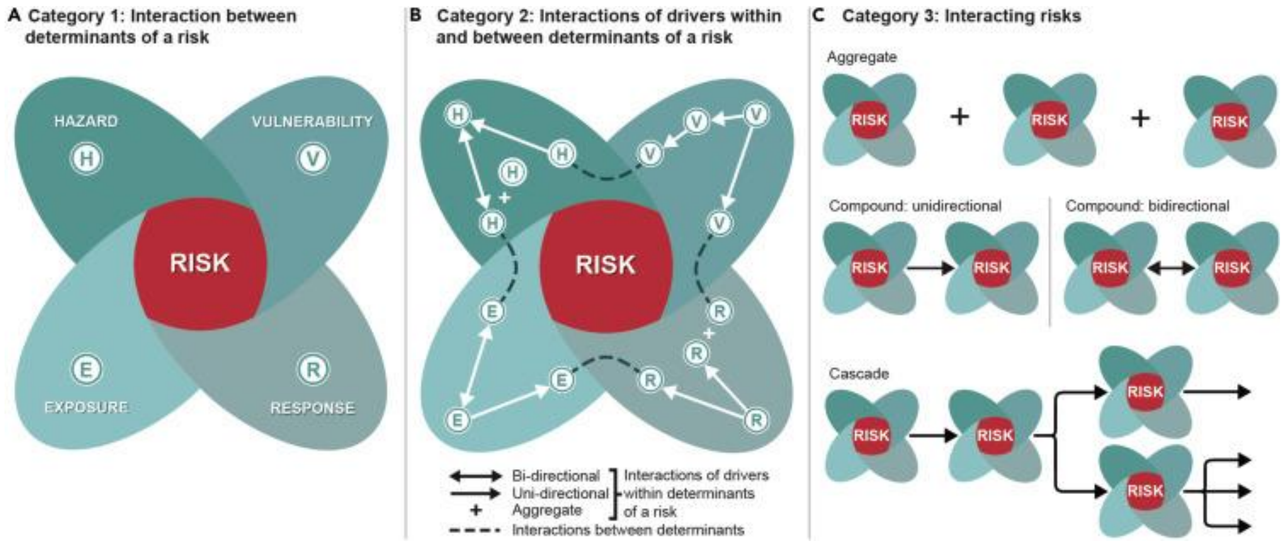
2.1 Purpose of qualitative assessment

A qualitative risk assessment can help identify these interactions between hazard, vulnerability and exposure that the quantitative assessment typically fails to capture. We ignore any risk interactions that are explicitly included within the typical quantitative assessment model as our calculated risk is, by definition, the dynamic interaction between climate-related hazards with exposure and vulnerability. For example, part of the built risk depends on interactions between bushfire (hazard), roof and wall type (vulnerability), and the location of the building (exposure).

2.2 Approach

We use a framework for complex climate change risk assessment as discussed in (Simpson, et al., 2021), and identify complex risk interactions through a review of post-disaster discussions and reports. Figure 2.1 shows the different types of risk interactions that can arise, and provides categories of these interactions.

Figure 2.1 – Framework for complex climate change risk assessment



In our approach we consider the following *domains*:

- *Built Environment* – the risk of physical damage to residential and commercial property, industrial facilities and public and private infrastructure
- *Natural* – the risk of damage to the natural environment
- *Economy* – the risk of disruption to the economy
- *Social* – the risk of loss or harm to human lives and communities

Vulnerabilities in one domain, stemming from multiple hazards, can lead to exposures in other domains, whilst exposures that change over time can create changing vulnerabilities across domains. Hazard interactions from disasters may cause feedback loops that lead to untenable capacity to support social, economic, natural, and built domains.

For each domain we have considered the three risk determinants of hazard, vulnerability and exposure, as discussed in section 1.1. (Simpson, et al., 2021) also considers drivers of each of these risk determinants, and labels interactions between the determinants of a risk as Category 1. Category 2 then consists of interactions between drivers of risk both within a risk determinant and between different risk determinants. Category 3 then considers interactions between different risks, including aggregate, compound and cascading risks.

Our approach differs from (Simpson, et al., 2021) in two ways:

- A full risk assessment would consider the interactions between drivers within each determinant. However, for this paper, we have only considered the interactions between the determinants, i.e. the hazard, vulnerability, and exposure.
- We have not considered the response determinant because our risk assessment is on an *inherent* risk basis, i.e. before consideration of any risk response or controls.

2.3 Scope

Our methodology for qualitative assessment refers to reports aggregated from community interviews, which involves decision-makers, local officers, emergency response officers, and other stakeholders. The list of reports included in our scope is shown in Table 2.1. We have chosen to focus our analysis on bushfire and flood hazards, as historically these hazards have caused the most devastation to each domain, both independently and interactively through compounding and cascading events.

Table 2.1 – Referenced reports for qualitative assessment

A	Community experiences of the January – July 2022 floods in New South Wales and Queensland, Summary Report (Natural Hazards Research Australia , 2023)
B	Western Enabling Regional Adaptation, Central West and Orana region report (State of New South Wales and Office of Environment and Heritage, 2017)
C	Western Enabling Regional Adaptation, Far West region report (State of New South Wales and Office of Environment and Heritage, 2017)
D	Final Report of the NSW Bushfire Inquiry (Owens & O'Kane, 2020)
E	Black Summer – How the NSW Community Responded to the 2019-20 Bushfire Season: Research for the NSW Rural Fire Service (Whittaker J, 2021)
F	NSW Flood Inquiry Volume 1 Summary Report (2022)
G	Western Enabling Regional Adaptation, New England North West region report (State of New South Wales and Office of Environment and Heritage , 2017)
H	Western Enabling Regional Adaptation, Riverina Murray region report (State of New South Wales and Office of Environment and Heritage, 2017)
I	Bushfire-affected waterways (NSW Department of Planning and Environment , 2023)
J	Integrated Regional Vulnerability Assessment: North Coast of New South Wales, Volume 1: Assessment Report (NSW Government, Office of Environment and Heritage, 2016)
K	Urban Heat Climate Change Impact Snapshot (NSW Government Office of Environment and Heritage , 2015)
L	Sydney Air Quality Study Stage 2 Fact Sheet (NSW Government Department of Planning and Environment , 2023)
M	Understanding the experiences of women in disasters: lessons for emergency management planning (Australian Institute for Disaster Resilience, 2022)
N	Women's health-related vulnerabilities in natural disasters: a systematic review protocol (Riyad Fatema S, 2019)
O	Cultural Flows, A Guide for First Nations (Murray Darling Basin Authority, 2010)
P	10 Years Beyond Bushfires Report (Gibbs L, 2020)

We acknowledge that this list of reports is not exhaustive of all possible sources of climate risk interactions. There is vast ongoing research, on top of many past inquiries, and our selected reports are not conducive to a fully comprehensive qualitative assessment.

2.4 Method

Our method involves reviewing the main conclusions or findings from each of these reports to identify interactions between hazard, vulnerability, and exposure under the four domains. We then analyse these observations to find patterns within the interactions. The confidence of the interaction increases where there are multiple instances of the same interaction being noted across different reports, or sometimes across similar themes within the same report. The output from our qualitative assessment is multiple mapping diagrams that show the interactions captured within the reports within and between domains. We then draw conclusions from the mapping diagrams, which can be used to supplement quantitative risk assessments. Figure 2.2 below provides a high-level overview of the steps we took to perform the qualitative risk assessment, followed by detail in Figure 2.3.

Figure 2.2 – High-level process for qualitative risk assessment

Figure 2.3 – Detailed process for performing qualitative risk assessment

Collect observations from reports

- For each report, find evidence of interaction noted between and within risk domains (built, social, economic, natural) and determinants (hazard, vulnerability, exposure).
- Document observations in database, noting the type of interaction and the direction (lessen or worsen). An example of an interaction is: Storm (hazard) worsens (direction of interaction) bushfire (hazard).
- Document other attributes of the interaction: report (denoted by alphabet) and page number for traceability.
- A report can have no observations noted, but for completeness, they are still included in the list of reports referred to.

Summarise observations into interactions and assign unique labels

- Summarise the database by grouping observations into interaction type, then assign them a catalogue number. For example, all observations about storm worsening bushfires are given the same catalogue number (e.g. 7 in our case).
- Count the number of times each interaction (by referring to its assigned catalogue number) appears in the database. If the interaction appears more than once, we consider this a high confidence interaction, otherwise, a low confidence interaction.
- We refer to the combination of catalogue number and alphabet as our unique label number e.g. 7D refers to the interaction between storm and bushfires, which comes from report D.
- The output from this process is a “table of interactions”, which contains labels, interactions, confidence, report, and page number where observation was noted.

Map interactions onto diagrams

- Build diagrams bottom-up for each domain.
- Separate the “table of interactions” into domains, then for the interactions noted in each domain, build mapping diagrams that show the interactions.
- Denote high-confidence interactions with a unbroken line and low-confidence interactions with a dotted line.
- Show determinants as red, orange, or green depending on whether they are typically captured in typical linear quantitative assessment models. This is useful to identify gaps from a typical quantitative assessment.
- If interactions span between domains, denote that by drawing a line between the main domain and other domain.

Draw key results and learnings from diagrams

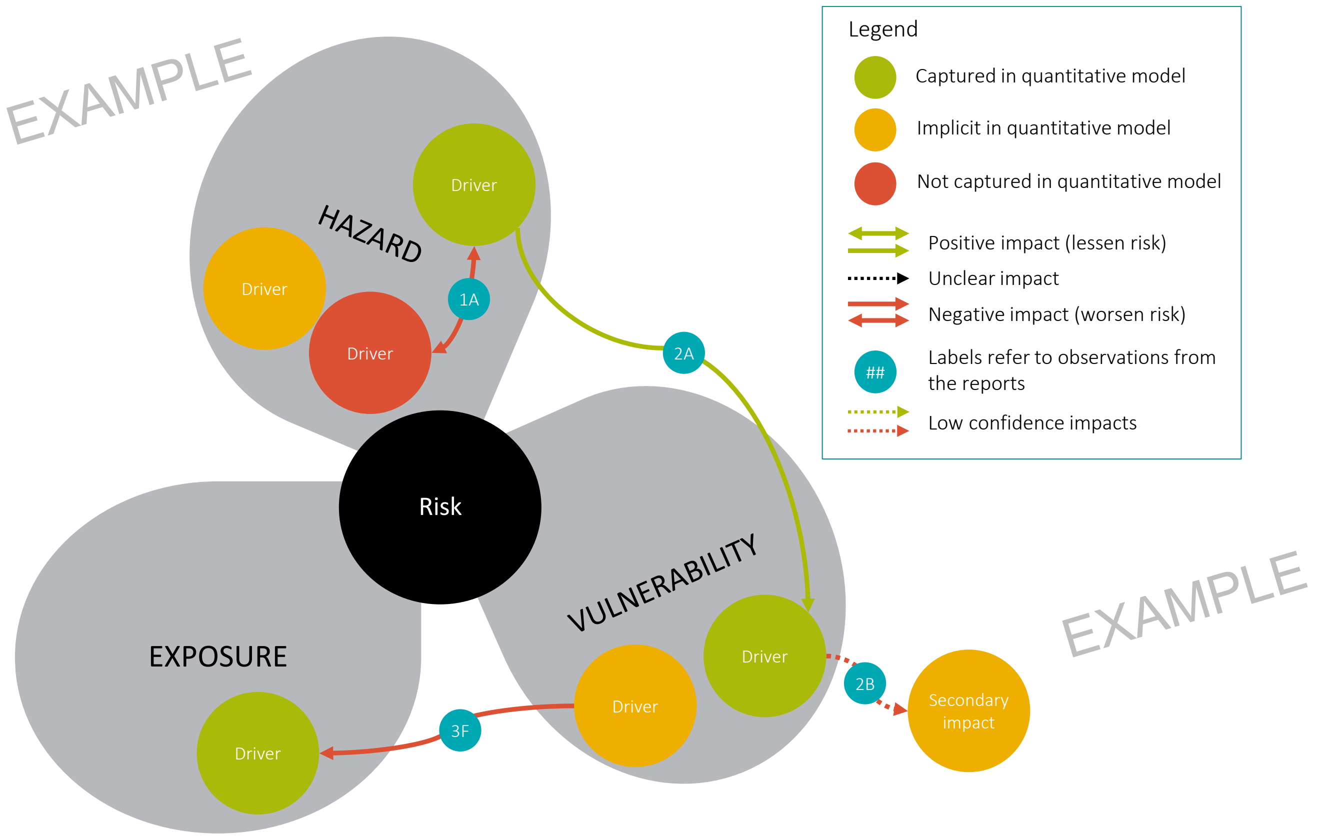
- Display qualitative risk assessment results by risk domain so that we maintain sufficient detail within the diagram to show meaningful results.
- Discuss overall results and learnings from each domain and across domains.
- Discuss results and learnings that apply to all domains e.g. interactions between the hazard determinant apply to all domains.
- Discuss results and learnings from looking at interactions within and from the built domain.
- Repeat for social domain.
- Repeat for economic domain.
- Repeat for natural domain.

We show an example of how we map the results from table to diagram below.

Table 2.2 – Table of interactions for a domain (example only)

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page Number*
1A	There is a two-way interaction between two drivers in the hazard determinant, where only one of these drivers are typically captured in a quantitative model. This interaction worsens risk so their relationship is represented by a red line. There were multiple observations from several reports to support this, hence the high confidence.	High	A	200
2A	A driver within the hazard determinant and a driver within the vulnerability determinant. This interaction lessens risk so their relationship is represented by a green line. There were multiple observations from several reports to support this, hence the high confidence.	High	A	50
2B	A driver within the vulnerability determinant has a secondary impact on another driver that is not typically captured within the hazard, vulnerability, or exposure of a quantitative model. This interaction was only observed once, so it is represented by dotted lines i.e. low confidence.	Low	B	10
3F	A driver in the vulnerability determinant has an impact on a driver in the exposure determinant. There were multiple observations from several reports to support this, hence the high confidence.	High	F	10

Figure 2.4 – Qualitative risk assessment results interpretation diagram (example only)



3 Results of qualitative assessment

In this section we describe the key results and conclusions from the qualitative risk assessment. We have structured the section as follows:

- *3.1 Interactions within the hazard risk determinant* – the interactions and patterns we found here applies to all domains, including key learnings, table of interactions, and results mapped in a diagram.
- *3.2 Interactions between determinants of built risk* – qualitative assessments for the built domain, including key learnings, table of interactions, and results mapped in a diagram.
- *3.3 Interactions between determinants of social risk* – qualitative assessments for the social domain, including key learnings, table of interactions, and results mapped in a diagram. We provide an additional table of interactions and diagram specifically for the vulnerability determinant of the social domain due to multiple feedback loops we found.
- *3.4 Interactions between determinants of economic risk* – qualitative assessments for the economic domain, including key learnings, table of interactions, and results mapped in a diagram.
- *3.5 Interactions between determinants of natural risk* – qualitative assessments for the natural domain, including key learnings, table of interactions, and results mapped in a diagram.

3.1 Interactions within the hazard risk determinant

Table 3.1 and Figure 3.1 show the identified interactions for the hazard determinant for all four domains (built, social, economic, and natural). Our qualitative assessment highlights the following:

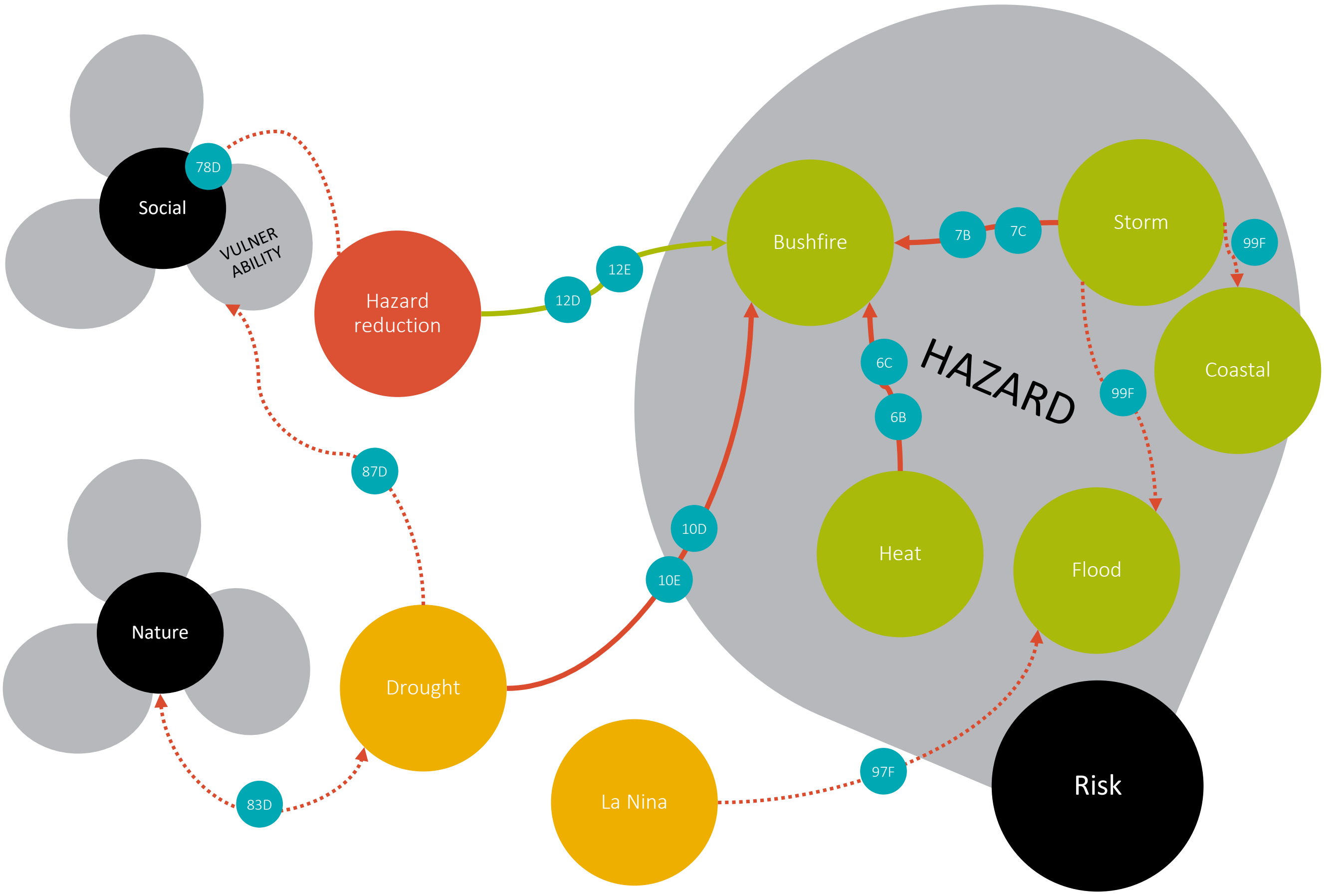
- *Hazards interact with each other* – e.g. storms can influence the occurrence of coastal inundation and erosion, floods and bushfires (through lightning); heat stress is associated with bushfires. Quantitative assessment models typically do not explicitly allow for such interactions.
- *Antecedent conditions and climate cycles can have significant impacts on hazards* – e.g. La Niña cycles are associated with increased floods in Australia. Quantitative assessment models, which are based on considering long-term timeframes, do not allow for such cycles. An example of this is in quantitative catastrophe models used by insurers to price disaster risk in Australia. These typically try to price through such climate cycles in order to avoid large fluctuations in insurance premiums from year to year.
- *Hazard reduction may affect antecedent conditions* – e.g. the deliberate introduction of fire to reduce fuel loads for future fires is another factor that is not explicitly allowed for within the typical quantitative models. These factors need to be considered within short term risk assessment and response planning, whereas this assessment is long-term.
- *Hazard reduction may lead to detrimental effects on social vulnerability* – e.g. smoke from hazard reduction fires can further exacerbate air quality issues.

Our qualitative assessment included reports that predominantly looked at bushfires, floods, storm and coastal hazards, and so excludes any interactions with and between cyclone and earthquake. The reports did not cover hazard reduction through structural intervention, such as flood levees and coastal protection structures, which have potential impacts on vulnerability. This type of hazard reduction is not possible in all coastal locations and existing levees may not offer the same protection to all types of buildings.

Table 3.1 – Interactions within the hazard determinant, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page Number*
10E	Dry conditions as an indicator to bushfire	High	E	5
10D	Severity of bushfires affected by climate change and prolonged drought	High	D	8
12D	Hazard reduction burning within 2-3 linear meters from houses and towns is most effective in managing risk	High	D	165
12E	Hazard reduction works	High	E	8
6C	Heatwaves increase bushfire risk	High	C	19
6B	Increase in heat will impact fire weather	High	B	42
7C	Storm increases bushfire risk	High	C	19
7B	Storm increases bushfire risk through lightning	High	B	21
78D	Hazard reduction increases risk to public health from smoke	Low	D	166
83D	Single water supply source is more vulnerable to pollution during drought conditions	Low	D	206
87D	Drought conditions prior to bushfire affected availability of volunteers	Low	D	250
97F	Antecedent conditions are amplified by La Nina	Low	F	2
99F	Heavy rainfall increases flash flooding and also coastal inundation	Low	F	10

Figure 3.1 – Interactions within the hazard determinant



3.2 Interactions between determinants of built risk

There are strong interactions between social vulnerability and vulnerability of the built environment in the context of our climate-related risk assessment:

- Low economic capital results in vulnerable populations residing in housing that is vulnerable in quality and location, with limited opportunity for investment in resilience.
- Conversely, disasters can result in strain on economic capital for households, leading to greater social vulnerability.
- Increased urbanisation may also lead to reduced access to the natural environment, thereby reducing health benefits to populations. These effects of increased urbanisation can also be exacerbated by heat island effects, caused by man-made hard structures that absorb or retain heat, which can increase heat hazards.

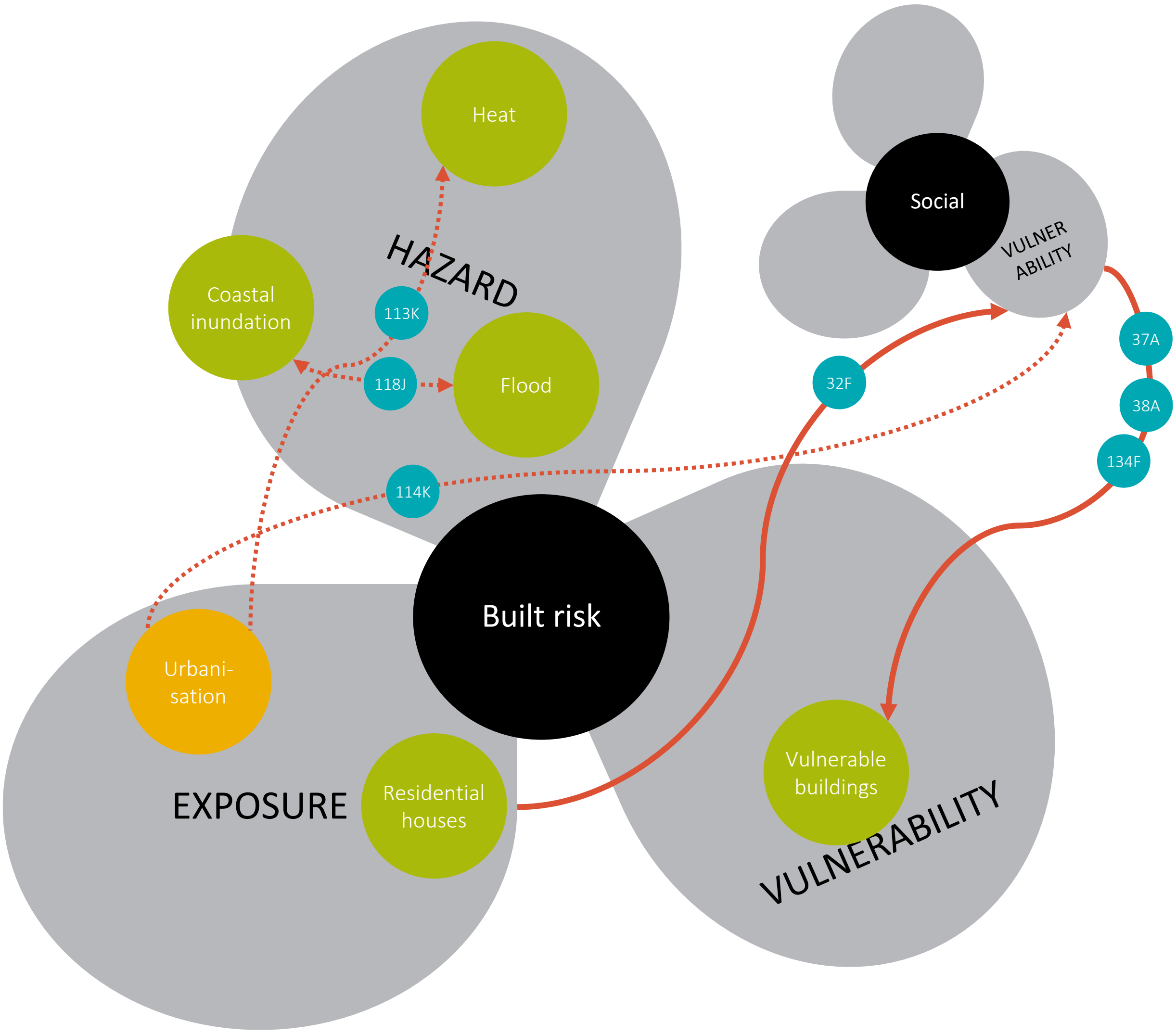
Table 3.2 below show the interactions between determinants of the built domains with other domains and Figure 3.2 shows the results mapped onto a diagram.

Table 3.2 – Interactions between determinants of built domain risk and with other domains, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
37A	There are limited resources to fix what is already vulnerable	High	A	7

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
38A	There is a lack of maintenance increases impacts on buildings in future	High	A	8
32F	Development for housing and safety decisions affect the vulnerable Caravan parks developed are not ideal for permanent residency and increases risk to older people	High	F	35, 40
134F	Disasters and the housing crisis magnify existing vulnerabilities in society	High	F	32
113K	Urbanisation can further increase urban temperatures	Low	K	2
114K	Urban vegetation improves human health	Low	K	12
118J	Coastal risk can cause loss of livestock, nutrient runoff and sedimentation in rivers and drainage systems	Low	J	12

Figure 3.2 – Interactions between determinants of built domain risk and with other domains[1]



[1] Interactions within hazard shown separately in Figure 3.1

3.3 Interactions between determinants of social risk

Multiple reports in the qualitive assessment found that hazards can increase social vulnerability, thereby providing a feedback loop that can increase the risk over time.

Illustrating how the social domain interacts with hazards drivers and exposure to risk, the reports noted the impacts on women, and specifically First Nations women. For example, women experience higher rates of domestic violence during and after disasters, while also facing barriers to accessing assistance from support organisations during times of disaster – this is compounded for women of colour and First Nations women. Further, women's opinions are often undervalued in disaster preparedness and reactivity, and First Nations women are often marginalised in areas of land and natural hazard management.

Repeating events or hazards, which are not explicitly accounted for in the typical linear quantitative model, have an impact on social vulnerability, as communities that are still recovering from one disaster are more vulnerable to another disaster. Such communities can also be more vulnerable to crime.

Hazards also impact cultural heritage, which is an important part of the social domain.

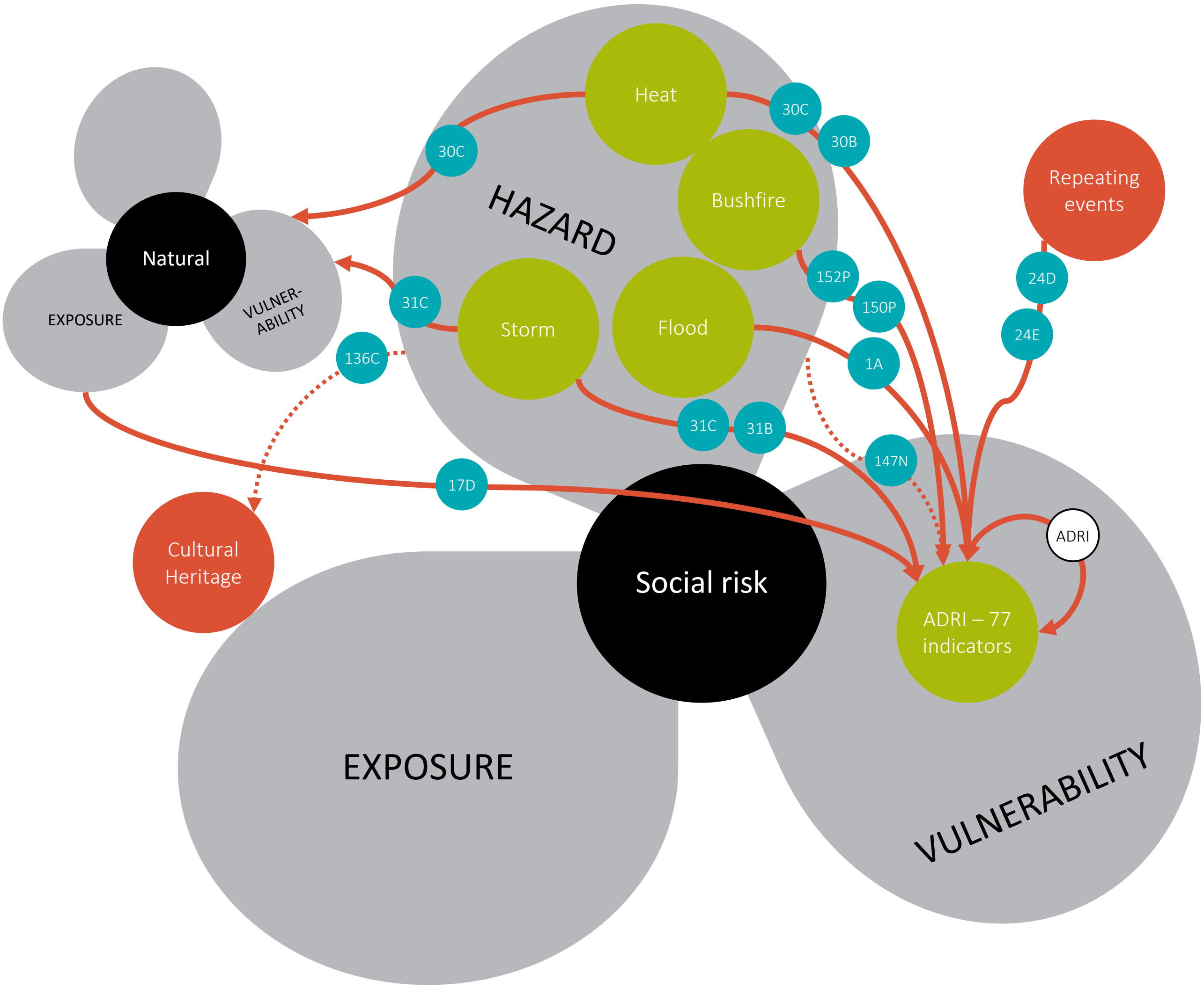
Table 3.3 below shows the interactions between determinants of social risk and the natural domain and Figure 3.3 shows the results mapped onto a diagram.

Table 3.3 – Interactions between determinants of social risk and the natural domain, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
1A	Flood-impacted residents are at risk of disaster opportunism and financial exploitation	High	A	8
30B	Heatwaves decrease agricultural productivity, which leads to decline in community capital wealth and increases value of water	High	B	21, 23
30C	Heatwaves decrease agricultural productivity, which reduces quality of life and decreases natural resource	High	C	19, 21
31B	Storm decreases agricultural productivity, which leads to decline in community capital wealth and increases value of water	High	B	21, 23
31C	Storm decreases agricultural productivity, which reduces quality of life and decreases natural resource	High	C	19, 21
17D	Aboriginal and Torres Strait Islander communities have higher rates of chronic conditions and are more affected by poor air quality. Elderly and young children are at greater risk from poor air quality.	High	D	231, 232
24D	Drought, bushfires, COVID in quick succession resulted in a mental health toll	High	D	417
24E	COVID compounded the impacts of bushfires on people and hindered their recovery. COVID lockdowns prevented community support and engagement for recovery	High	E	9, 10
150P	Educational outcomes were poorer following bushfires, and these had lasting impacts on academic outcomes	High	P	17

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
152P	Long-term mental health impacts for bushfire victims, with the chance of having one or more mental health conditions ten years after the bushfires being double those not affected	High	P	11
136C	Storm damages cultural heritage	Low	C	19
147N	Natural disasters can affect reproductive outcomes, including early pregnancy loss, stillbirth, and premature delivery, leading to greater mortality rates for women compared with men	Low	N	2

Figure 3.3 – Interactions between determinants of social risk and the natural domain[2]



While social vulnerability can be measured quantitatively using the Australia Disaster Resilience Index (ADRI), the standard linear quantitative models do not account for the interactions between these indicators within the vulnerability determinant. This feedback loop within the vulnerability determinant for the social domain is labelled as 'ADRI' in the white circle in Figure 3.3 above, and then is expanded in Table 3.4 and mapped into Figure 3.4 below. The ADRI report discusses these interactions and implications in detail (Parsons, 2021).

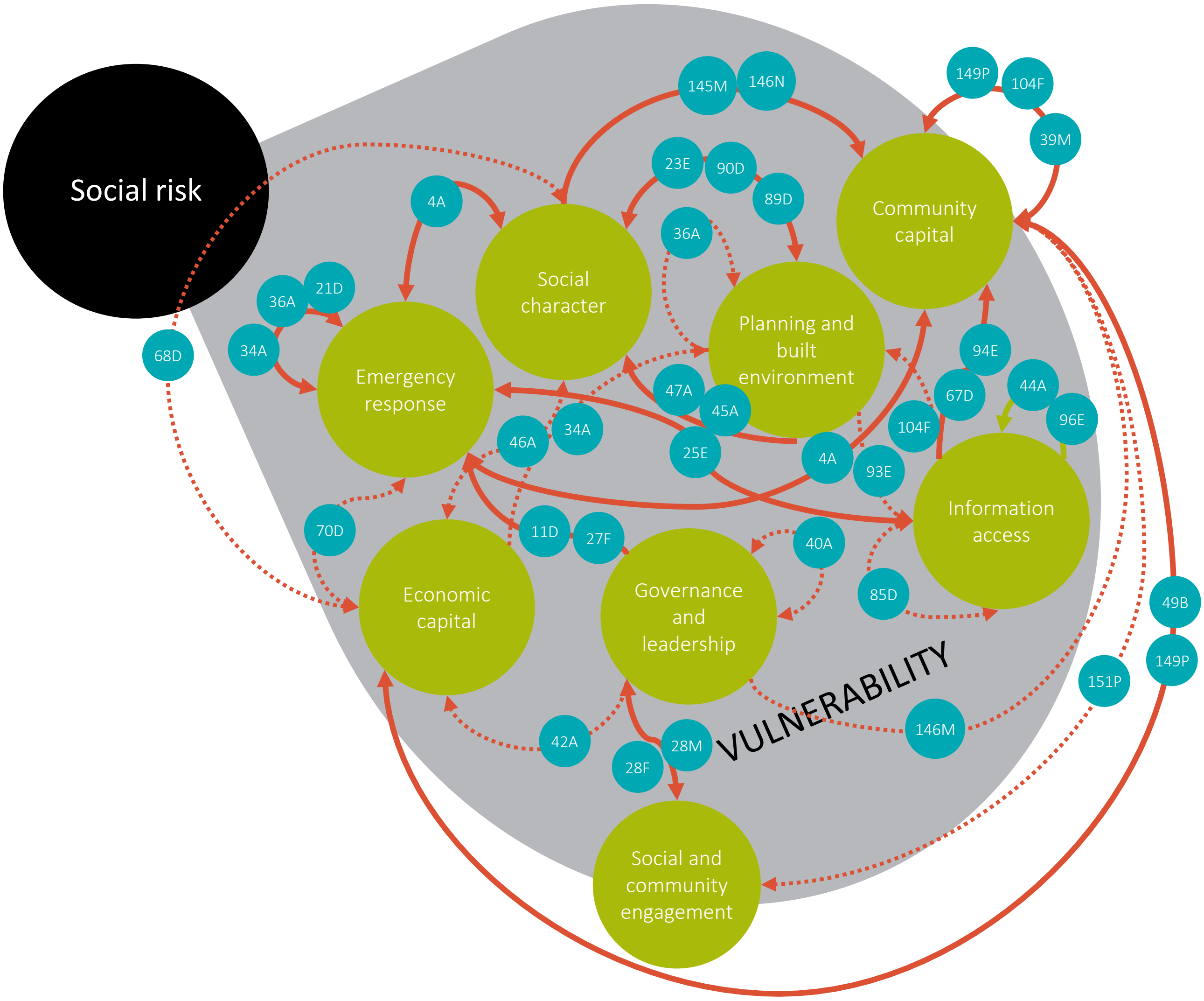
[2] Interactions within hazard shown separately in Figure 3.1

Table 3.4 – Interactions within the vulnerability determinant for social domain, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
4A	Burden of recovery and volunteering shifts to a small group of people as time passes by Removal services or clean-up processes post-disaster cause residents to feel overwhelmed with decisions Re-telling and re-living disaster leads to negative mental health Temporary housing in inappropriate locations causes extra burden	High	A	18, 19, 20
11D	Community perceives hazard reduction burning difficult to obtain approval for and so do not pursue it, putting people at risk Early media reports on damaged properties caused distress People had to tell their story many times and relive the trauma People had to repeatedly provide personal information to different agencies post recovery	High	D	157, 378, 383
21D	Firefighters' mental health is impacted too and they need support	High	D	258
23E	Old and disabled people are not catered for in evacuation centres	High	E	9
25E	People were unfamiliar with official 'Neighbourhood Safer Places' People who seek shelter were not fully prepared Misconception among tourists that fires would not burn near the coastline More localised and detailed information about disaster risk can be a moral hazard for people has this information encourages people to delay evacuation information can be moral hazard for people as they delay evacuation	High	E	7, 8 ,10
27F	Poor leadership affected protection of lives and property in flood response Slowness in evacuation and response increased stress from disaster	High	F	12, 14
28F	Local councils and volunteers stepped in due to lack of leadership from government Approach to recovery centres was slow	High	F	15
28M	Women of Aboriginal or Torres Strait Islander background faced challenges in getting involved in community resilience programs because the management approach of the Government does not often recognise nor include Indigenous gender issues	High	M	75
34A	Back-to-back events impedes communities' clean-up from prior event	High	A	2
36A	Recovery fatigue reduces volunteering and increases vulnerability	High	A	8
39M	During and after disasters, women experience higher rates of domestic violence and intimate partner violence, while also facing barriers in accessing assistance from support organisations during times of disaster	High	M	70, 75

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
44A	Awareness created by past events motivates communities for future prep and mitigation	High	A	16
45A	Failures in telecommunications infrastructure/systems causes additional trauma	High	A	18
47A	Rebuilding impacts mental health	High	A	20
49B	Community capital health is declining, requiring more investment in line with changing climate	High	B	20
67D	Exhaustion during disaster is fuelled by constant threat of fire	High	D	9
89D	No appropriate evacuation plans were in place for aged care facilities	High	D	372
90D	Aboriginal communities were not well-supported during evacuation and led to people being at risk	High	D	379
94E	Length of disaster and repeated threats reduced preparedness	High	E	6
96E	Previous experience from bushfire helped with preparedness for future disasters	High	E	10
104F	People did not know if their property was in a flood prone area	High	F	26
149P	Women were more likely to experience domestic violence in high bushfire affected areas, which contributes to income loss and poorer mental health	High	P	13
145M	Because of gender bias, women’s roles are devalued during disasters – even during preparation phase – especially in male-dominated rural areas of Australia, potentially impacting evacuation	High	M	75
146N	Poverty and socially determined roles and responsibilities can make women more vulnerable during disasters	High	N	2
40A	Loss of trust in institutions	Low	A	14
42A	Bureaucracy makes it difficult to gain financial support	Low	A	2
46A	Financial pressures have mental health impacts	Low	A	20
68D	Many have no choice but to keep working outdoors in the smoke	Low	D	9
70D	Local resources drained so emergency response was insufficient	Low	D	9
85D	Frequent warnings to communities during extended periods lessen the impact of warnings	Low	D	237
93E	Mobile phone and power outages meant people could not access timely warnings	Low	E	5
146M	Male-dominated social structures create problems as violent incidents are overlooked or acceptable in response to a disaster	Low	M	76
151P	Neighbours moving away after the event resulted in a loss of community, making people more susceptible to depression	Low	P	19

Figure 3.4 – Interactions within the vulnerability determinant for social domain



3.4 Interactions between determinants of economic risk

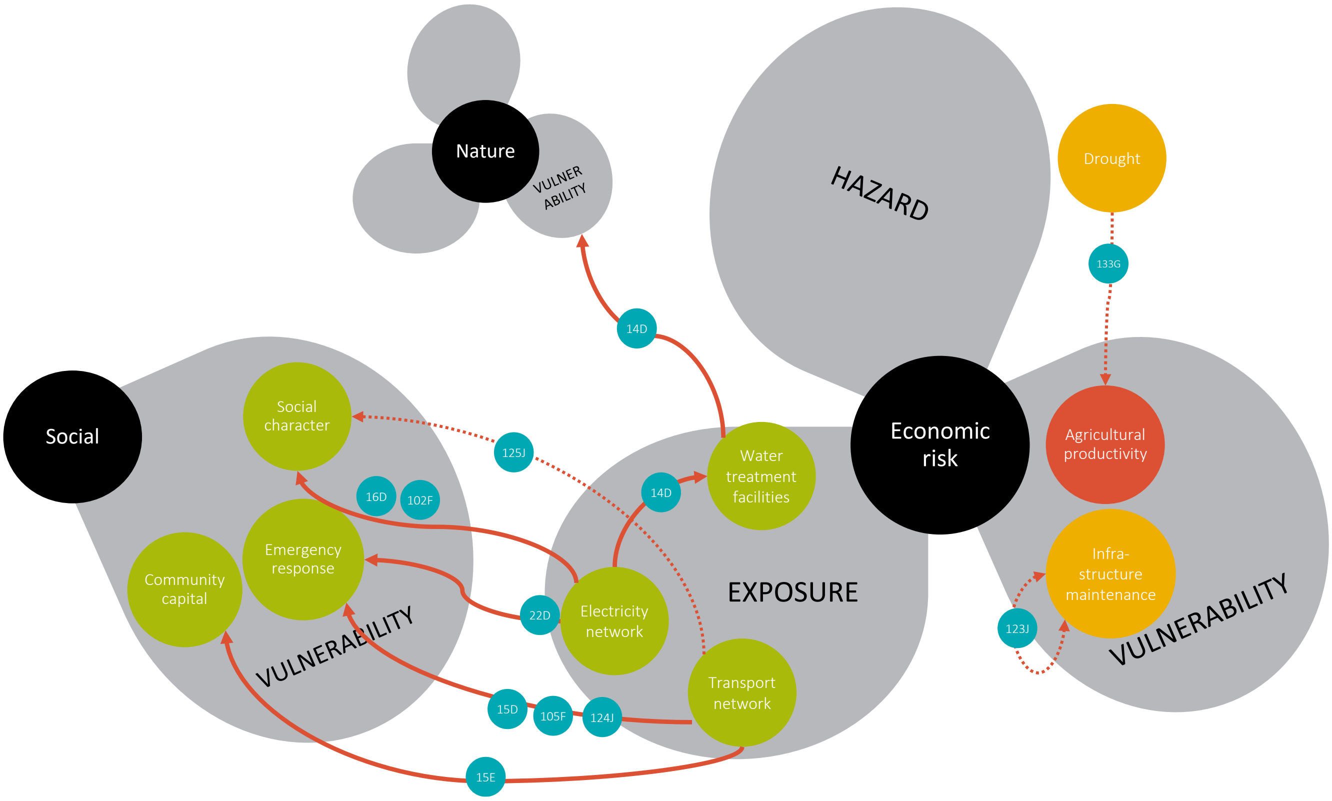
A standard linear quantitative assessment model is based on the consideration of critical infrastructure in each region. Our qualitative assessment found that this critical infrastructure directly influences social vulnerability as it provides essential services to communities. Consequently, there are strong interactions between the economic exposure and the social vulnerability determinants. We have mapped these interactions in Table 3.5 and Figure 3.5 below. Our conclusions are:

- Critical infrastructure plays a large role in disaster response and management. Many reports flagged the vulnerability and additional trauma caused by the loss of essential services and communications when critical infrastructure fails during a disaster.
- Emergency response also fails or is hindered when such critical infrastructure fails, which increases the harm to communities.
- Transportation and access to routes are also critical to emergency response.
- Where communities have low communication infrastructure, there is a compounding effect on access to emergency information, post-event societal connection, emergency response and early intervention. This has a direct impact on how people perceive the support they receive and their ability to cope with the loss resulting from disasters.

Table 3.5 – Interactions between determinants of economic risk and secondary impacts to social and natural domains, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
14D	Power failure to water treatment facilities causes water quality issues Property owners experienced very low to no water pressure in lead up to bushfires	High	D	207, 305
15D	Roads that are not resilient to bushfires have longer closures, which causes stress and impedes disaster management	High	D	207
15E	Power outages impede communication and the ability to acquire food, medication	High	E	9
16D	Electricity networks were affected by fires, leaving people without power	High	D	325
22D	Emergency alerts were hampered by power and telecommunication failures Power outages to water infrastructure impeded fire fighting	High	D	304, 360
105F	Road closures isolate communities from essential services	High	F	35
124J	Tidal inundation impacts roads and access to emergency services	High	J	13
102F	Loss of communications due to power outages causes distress	High	F	19
123J	Saline water increases road maintenance and affects drainage infrastructure leading to decline in coastal ecosystem	Low	J	13
125J	Decreased capacity to maintain roads means road closures and community isolation	Low	J	13
133G	Drought causes loss of groundcover, decreasing agricultural productivity	Low	G	22

Figure 3.5 – Interactions between determinants of economic risk and secondary impacts to social and natural domains[3]



3.5 Interactions between determinants of natural risk

Many of the reports assessed discussed interactions within the natural domain.

The most important interaction is that impacts on land, water and air quality within the natural domain have consequent health impacts, affecting social vulnerability. For example, air pollution can cause respiratory illnesses, particularly in children, aged and First Nations people.

While the value of water is not typically modelled within a linear quantitative model, our qualitative assessment found that the natural domain (water) has significant an impact on the social domain (through mental health and physical health). First Nations people value water as a whole entity without strict separation into individual resources (Indigenous Knowledge Institute, n.d.). The value of water is placed on cultural flows – the return and reconnection of water to First Nations people (Indigenous Knowledge Institute, n.d.).

Other conclusions from our assessment are as follows:

- The ecological environments of flora and fauna are interlinked – for example, damage to flora can impact fauna that depend on that flora for food or habitat. Grazing can also impact on ecological environment and soil erosion.
- Change in levels of vegetation (exposure) and bushfire threat level (vulnerability) are interlinked as increased vegetation can increase fuel loads.

[3] Interactions within hazard shown separately in Figure 3.1

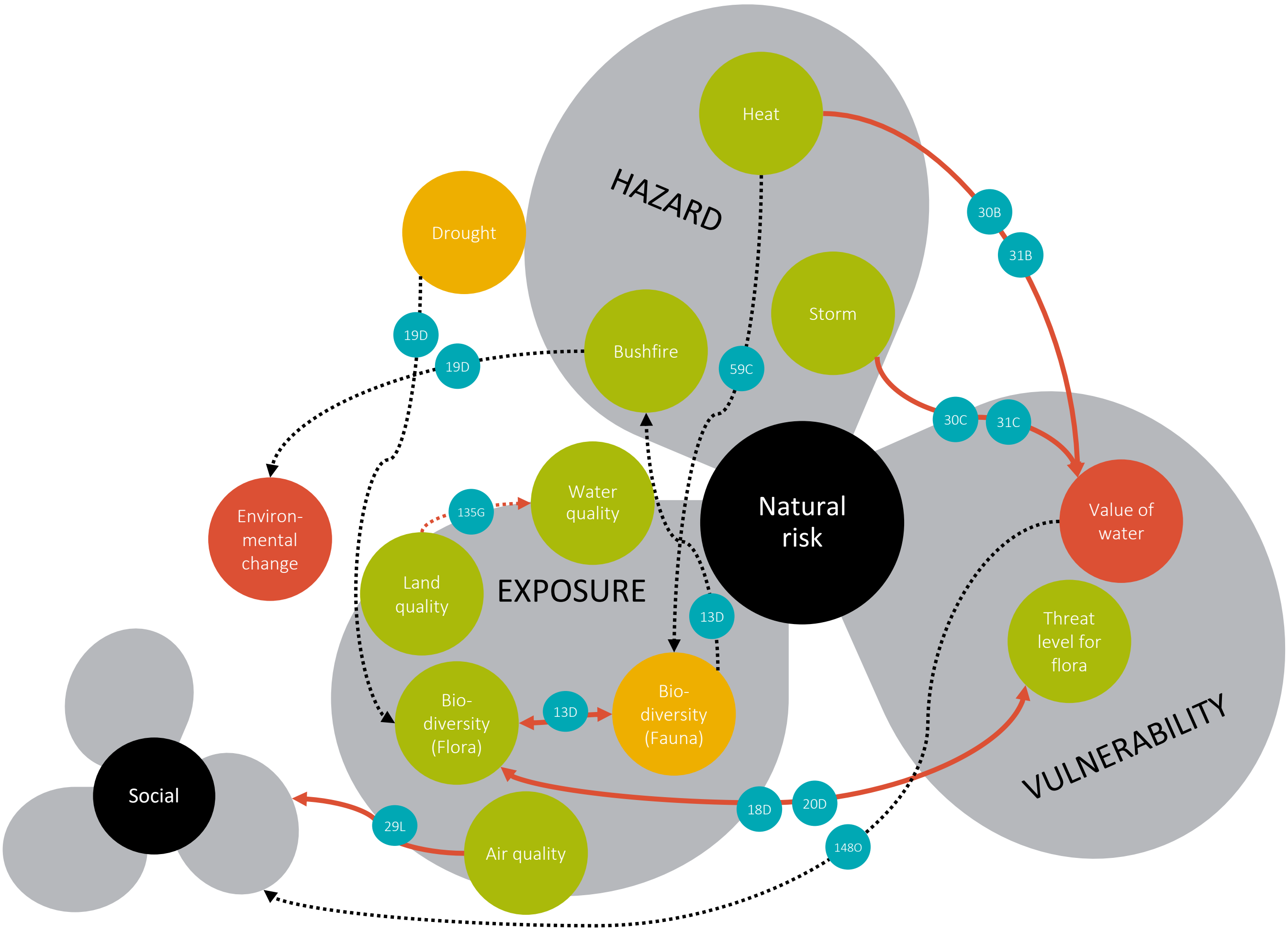
- The value of water is not captured within the typical linear quantitative model but has a secondary impact from the storm hazard.
- We noted that hazards interact with each other – e.g. heat stress is associated with bushfires, which is associated with droughts (Figure 3.1). Hence, any interaction with heat, for example heatwaves changing breeding behaviours for fauna, will also be interlinked with bushfires and drought.

Table 3.6 shows the interactions between determinants of natural risk and the social domain and Figure 3.6 shows these results mapped onto a diagram.

Table 3.6 – Interactions between determinants of natural risk and the secondary impacts to the social domain, sorted by high to low confidence

Label	*Interaction noted from report*	*Confidence*	*Report*	*Page*
13D	Animals can alter the amount, structure, or condition of fuel for bushfire Grazing can increase soil compaction and erosion, and accelerate weed invasions	High	D	172, 173
18D	Plant species are at high or medium risk of decline as a result of bushfires	High	D	239
19D	It is unclear how drought affects plant re-sprouting and recovery Interactions between fire and environmental change is not well understood	High	D	240
20D	Animal habitats are affected by bushfires Animals that survived the bushfires have nowhere to return to	High	D	243
29L	Air pollution causes heart and lung disease and puts the elderly and children at most risk	High	L	3
30B	Heatwaves decrease agricultural productivity, which decreases community capital wealth and increases the value of water	High	B	21, 23
30C	Heatwaves decrease agricultural productivity, which reduces quality of life leading to decline in natural resources	High	C	19, 21
31B	Storms decrease agricultural productivity, which decline community capital wealth and increases value of water	High	B	21, 23
31C	Storms decrease agricultural productivity, which reduces quality of life, leading to decline in natural resource	High	C	19, 21
59C	Heatwaves (and indirectly, drought) change breeding behaviours for fauna	Low	C	19
135G	Soil erosion has implications for water quality	Low	G	41
148O	First Nations people have a strong relationship with water, viewing water as a complex circulatory system that reflects physical health, and the health of the spirit	Low	O	4

Figure 3.6 – Interactions between determinants of natural risk and the secondary impacts to the social domain[4]



4 Key learnings

4.1 Overall findings

Our qualitative assessment has analysed risks that arise – through the three key determinants of hazard, exposure, and vulnerability – for the four domains of social, built, natural and economic. We looked at risks between domains, within domains, within determinants, and between determinants. Overall, we have five key learnings:

- *Climate risk is complex, and linear thinking can overlook the nuances of complexity* – Climate risk really is complex, and we are presented with a 'square peg in a round hole' dilemma. The nature of climate risk, and its complexities, is round, but we employ linear thinking; the square peg. As actuaries working in this space, our actuarial training and thinking can be linear and, in this framework, we lose nuances in solutions and their implementation.

- *Different time horizons give different treatments* – Timescales are important as the outcomes from a risk assessment change depending on whether risk is being viewed in the short-term or

[4] Interactions within hazard shown separately in Figure 3.1.

long-term. Short term risk may focus on emergency response and recent events, where long-term risk may not look at antecedent conditions and focuses more on resilience building. Different assessments and risk treatment options arise depending on the time horizon. Insurers typically ignore stage of the climate cycle, or how long it has been since the last disaster, but antecedent conditions and climate cycles can have significant impacts on hazards.

- *Climate risk exacerbates existing risks in the social domain* – When analysing the impacts of climate risk on the social domain, it is clear in the identification of problems that the problems are not necessarily caused by a natural disaster, but that natural disasters highlight the way we have set up societal structures, and exacerbate existing inequalities in those structures. This is clear for gendered impacts, First Nations viewpoints, people with disabilities and other identities. This makes risk treatment difficult, and is largely missed by quantitative models.

- *There are interactions between hazards* – Storms can influence the occurrence of coastal inundation and erosion, floods and bushfires (through lightning); heat stress is associated with bushfires. Current linear quantitative assessment models do not explicitly allow for such interactions.

- *Complex risks require coordinated solutions* – Climate risks have varying impacts across domains, with stakeholders being impacted and to differing degrees. Treatments for complex climate risk require conversation and coordination, making risk treatment very difficult due to competing priorities. Natural disaster events occurring in succession means more resources are spent on response rather than resilience-building.

The following sections go into more detail on the cascading risks, compounding risks, and feedback loops derived from our assessment between and within said determinants and domains.

4.2 Cascading risk

- Various cascading hazards were identified; storms can influence the occurrence of coastal inundation, erosion, floods and bushfires (through lightning); heat stress can increase the chance of bushfires.
- Hazard reduction was also found to have cascading effects on social vulnerability, e.g. hazard reduction can further exacerbate air quality issues.
- The social domain has a lot of cascading risks that flow from other domains, with strong impacts from critical infrastructure (economic domain), housing quality and location (built domain), and water, land, and air quality (natural domain). For example, storms decrease agricultural productivity, leading to decline community capital wealth and natural resources which reduces quality of life, and increases vulnerability to hazards.
- A cascading risk between exposure and vulnerability was found e.g. change in levels of vegetation (exposure) and bushfire threat level (vulnerability) are interlinked as increased vegetation can increase fuel loads.
- Hazard determinants were also found to have cascading impacts as antecedent conditions and climate cycles can have significant impacts on hazards – e.g. La Niña cycles are associated with increased floods. However, hazard determinants are also compounding in that pre-existing conditions are also amplified by La Niña.
- Built risks were also seen to have a large cascading influence as increased urbanisation may also lead to reduced access to the natural environment, thereby reducing health benefits to populations. These effects of increased urbanisation can also be exacerbated by heat island

effects, caused by man-made hard structures that absorb or retain heat, that can increase heat hazards.

4.3 Compounding risk

- Where communities have low communication infrastructure, there is a compounding effect on access to emergency information, post-event societal connection, emergency response and early intervention. This has a direct impact on how people perceive the support they receive and their ability to cope with the loss surrounding disasters.
- Compounding events, such as drought, bushfires, and COVID that happened in succession, increased the mental health toll of communities impacted, aggravated by COVID lockdowns preventing community support and engagement for recovery. Back-to-back climate events compound and set back communities' clean-up from prior events. Back-to-back events also have the cascading effect of recovery fatigue, reducing volunteering rates and increasing vulnerability to the next event.
- People with one or more existing social vulnerabilities had compounded risk when exposed to a hazard, in line with intersectional theory. The assessment found elderly and disabled people were not catered to in evacuation centres, and children, aged and First Nations people are more vulnerable to respiratory illnesses caused by air pollution.

4.4 Feedback loops

- Within the social domain there are multiple feedback loops between the drivers of vulnerability. Compounding and cascading social risks can create a feedback loop where people at the intersections of vulnerabilities are made more vulnerable to disasters.
- Hazards can increase social vulnerability, thereby providing a feedback loop that can increase the risk over time. For example, low economic capital results in at-risk populations residing in vulnerable housing, with limited opportunity for investment in resilience. Meanwhile disasters can result in strain on economic capital for households, leading to greater vulnerability and even lower economic capital.
- The ecological environments of flora and fauna are interlinked – for example, damage to flora can impact fauna that depend on that flora for food or habitat. Grazing can also impact on ecological environment and soil erosion.

4.5 Improvements

- This qualitative assessment looked at bushfires, floods, storm, and coastal hazards, excluding any interactions with and between cyclone and earthquake. A more comprehensive assessment would include these.
- Our qualitative assessment did not cover hazard reduction through structural intervention, such as flood levees and coastal protection structures, which may have potential impacts on vulnerability. This type of hazard reduction is not possible in all coastal locations and existing levees may not offer the same protection to all types of buildings.
- We acknowledge that the list of reports referenced for our analysis is not exhaustive of all possible sources of climate risk interactions. There is vast ongoing research, on top of many past inquiries, and a more comprehensive array of sources across Australia and over time would improve the results of our overall qualitative risk assessment.
- While we did discuss vulnerabilities in the social domain for a selection of identities, and intersections of identities, there is further work to be done to analyse the complexities of risk

for a broader range of communities, for example, the LGBTQIA+ community, people with disabilities, and people who have migrated to Australia.

4.6 Potential Solutions

- Applying a First Nations systems thinking lens to the parts of an ecosystem or set of knowledges in a risk assessment and how they are interrelated. Looking at how vulnerabilities, exposure and hazards overlap and interact, and having First Nations people drive this knowledge. Further, tools such as the Aboriginal Waterways Assessment can assist to consider Aboriginal cultural and spiritual values relating to water when modelling the interactions between social and natural domains in a qualitative risk assessment (Indigenous Knowledge Institute, n.d.).
- Employing an intersectional lens in risk assessments to those at the intersections of vulnerabilities to understand how feedback loops occur and how they can be broken. Intersectionality can be used to highlight the interactions between risk domains of social, natural, economic and built, that may be missed in a linear quantitative assessment. For example, a young woman that is Indigenous and has low economic capital may have compounding risks by being at the intersection of vulnerable social groups. Her low economic capital can result in her residing in vulnerable housing, which increases her exposure to risk of a disaster, an eventuality that would put further strain on economic capital due to the cost of repairing infrastructure and recovery. Additionally, during and after a disaster, she is more likely to experience domestic violence as a woman, and as a young First Nations person she is also at risk of respiratory illness from air pollution. The economic costs of healthcare from these cascading risks can place further strain on economic capital. We can see from this example that the structural inequality that affects certain population groups can make them more vulnerable in disasters. These social vulnerabilities can add barriers that further diminish economic capital, such that when one starts with lower economic capital, a feedback loop is initiated.
- Further work on the qualitative assessment and integration of systemic impacts, including cascading and compound events, within the typical linear quantitative assessment.
- Technology and innovation can play a role in mitigating and limiting cascading risks, compounding risks and feedback loops. Tools such as radar could be used to identify large fuel loads, this information could then serve to minimise cascading risk if fuel loads were reduced before exposed to heat stress. Similarly, innovations around soil erosion, such as geopolymers, seeds of herbaceous plants, and hydraulic engineering, could halt the feedback loop where grazing and the subsequent soil erosion impact flora.

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