Community Risk Assessment

Connecting Technical Knowledge with Local and Indigenous Knowledge

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We acknowledge the traditional custodians across all the lands on which we live and work, and we pay our respects to Elders both past, present and emerging. We recognise that these lands and waters have always been places of teaching, research and learning.

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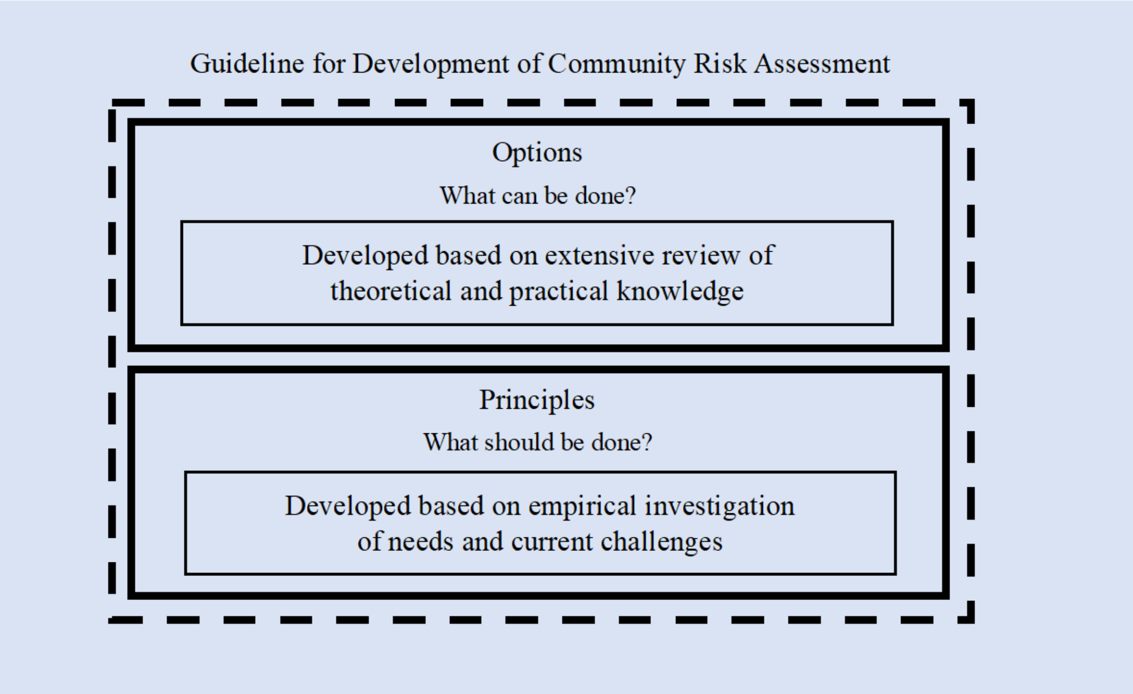
Executive summary

Two general approaches have been observed in community risk assessment. Top-down community risk assessments are often driven by agencies on macro scales. Meanwhile, bottom-up approaches are often driven by communities at local scales, placing the people at risk at the centre of the risk assessment process. Top-down approaches typically rely on technical, scientific and data-driven methods, while bottom-up approaches are rich in contextual, local and Indigenous knowledge. It is very common to see more quantitative and technical assessments in the top-down approaches in contrast to more qualitative and contextually rich assessments in the bottom-up approaches. Although the individual use of both approaches is extensively observed in different community risk assessment frameworks, there is a research gap concerning the benefits of their potential integration.

Box 1 – Guideline for the development of community risk assessment.



Organisations can use the guideline to develop community risk assessment approaches or revise their existing practices. The guideline provides guiding principles that can be considered in community risk assessment as well as alternatives that can be tailored based on the contextual needs.

In this report, we investigate the prospects of integrating top-down and bottom-up approaches in community risk assessment. For this purpose, we first conduct an extensive systematic literature review of community risk assessment models to provide a synthesis of common definitions and measurements. The systematic review of literature is complemented by the synthesis of practical examples. Through this synthesis, a range of alternatives is provided to conceptualise, define, and measure risks. These alternatives can be used in the development or revision of potential community risk assessment models based on contextual needs (i.e., the options in Box 1).

Our results are further informed by semi-structured interviews with risk management professionals as well as relevant documents published by a range of agencies and interest groups. Based on the opportunities and challenges arising from combining top-down and bottom-up approaches, we propose a set of principles as guidelines for the development of integrated community risk assessment models to capitalise on their complementary capabilities (i.e., the principles in Box 1). These principles can direct a range of communities and agencies in collectively developing their community risk assessment approaches using a range of alternative methods that are presented through the synthesis of literature and practice. The output of this research is only the first step in this direction because our informants mostly represent the agencies and organisations that are primarily developing top-down approaches. The extension of this project will further explore the input of broader stakeholders, especially communities, to elaborate on the nuances of integrating the two approaches.

Project partner statement

Sara Morgan, NSW State Emergency Service

New South Wales (NSW) State Emergency Service (SES) set out to investigate components of a comprehensive, multi-dimensional risk assessment approach to define risk levels and the impact of key natural hazards on social, economic, built and natural environments across NSW. A strengthened understanding of the risks and impacts of flood, storm and tsunami at a community level can directly shift strategic decision-making of resource allocation and activity prioritisation to support our communities' needs.

The work undertaken with Natural Hazards Research Australia (the Centre) and the University of Sydney was an initial step in understanding the context and potential, as well as seeking out opportunities to learn from, connect and align with others across the country working on similar challenges. Working closely with the research team was an integral part of this project, as we were able to undertake an iterative approach together, incorporating learnings from each interview and discussion into the next.

The outcomes of this work effectively provide strong support for working further to integrate top-down and bottom-up risk assessment approaches to provide more comprehensive and accurate understanding and predictions while also acknowledging the high level of complexity and nuance associated with data collection, consistency and the human element. There is still much work to be done in natural hazard predictive risk assessment, and this work has further reinforced the understanding that the end-use purpose remains the critical factor, as it defines the inputs and analysis required to best understand our communities and their needs.

Introduction

Recent extreme events have passed long-standing records by large margins, leaving significant impacts on society (Fischer et al., 2021). As the frequency and severity of these events rise, the imperative for informed decision-making and disaster risk management grows. The high benefit-to-cost ratio of disaster risk reduction efforts, ranging from 3 to 15 across different hazard types and geographical contexts, indicates the importance of preparedness. However, disaster risk mitigation strategies are only as good as the accuracy of the assessments behind them. In this context, community risk assessments have emerged as key tools to evaluate hazards, vulnerabilities and capacities, providing essential support for community-based disaster risk reduction (Van Aalst et al., 2008).

At the core of disaster risk assessments, communities stand as the ultimate beneficiaries of the process. This concept goes beyond mere justification for assessment endeavours; instead, it guides the risk assessment procedure, making the outcomes directly relevant and practical for community members through their contextual knowledge. During the past two decades, there has been growing interest in actualising the potential benefits of local perception in community disaster risk assessment (Cronin et al., 2004; File & Derbile, 2020; Granderson, 2018). However, despite being widely praised in academic and policy environments, local and traditional knowledge has remained underutilised in practice (Hadlos et al., 2022).

In this report, we investigate the context of community risk assessment and the extent of associated practices. We draw upon the academic literature on disaster risk assessment, current national and international practices and primary data collected through a set of semi-structured interviews with local and international risk management professionals. We present the results of our investigation as a set of recommendations that can inform the practice of agencies involved in community risk assessment when it comes to incorporating local and traditional knowledge within the processes associated with community risk assessment. At the core of these recommendations, we develop a generic synthesis of knowledge that can provide a blueprint for the advancement of bidirectional (top-down and bottom-up) community risk assessment models that connect community-driven and agency-driven inputs. The proposed guideline can be tailored to be used in different contexts as a framework to assess the risks associated with various hazards.

Background

Disaster risk

Disaster risk is defined as the potential losses of lives, health status, livelihoods, assets and services due to the occurrence of a disaster in a community or a society over a specified future period (United Nations International Strategy for Disaster Reduction [UNISDR], 2009). More recently, applications of this definition reflect the shift, both in research and practice, from a hazard management perspective to a risk management perspective, where hazards are considered as one of the elements contributing to the risk (Ward et al., 2022). According to this evolved perspective, the risk is viewed not only as a function of the hazard, based on its frequency and intensity, but also as a function of the characteristics of the hazard-bearing environment (Jin et al., 2022; Wang et al., 2016). Within this context, the Sendai Framework for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction [UNDRR], 2015) conceptualises disaster risk as a function of hazard, exposure and vulnerability. The hazard refers to a naturally occurring environmental phenomenon, for example an earthquake, and is framed by the probability of occurrence and its intensity. Exposure reflects the potential of impacts on people or assets. For example, the occurrence of a natural hazard in a remote area where people and assets are not present does not incur an immediate loss to a community and therefore, is not considered an immediate risk. Vulnerability reflects the susceptibility of a community and its assets to loss due to the occurrence of a hazard, for example as a result of unsafe housing conditions or a lack of early warning procedures (Ward et al., 2020).

(United Nations Office for Disaster Risk Reduction [UNDRR], 2015)

Risk elements

The majority of disaster risk assessment studies take on a risk conceptualisation closely related to that of the Sendai Framework (UNDRR, 2015), with hazard, exposure and vulnerability as the main elements of risk. These similar conceptualisations however, have manifested in a variety of different formulations. For example, Taubenböck et al. (2009) define risk as a function of hazard and vulnerability, where vulnerability itself is a function of exposure, susceptibility and coping capacity, that is, the degree to which a system is able to cope with the adverse effects of a hazardous impact. Meanwhile, Chiou et al. (2015) define risk as a function of hazard, exposure, mitigation and resistance. They define mitigation as the proactive measures to prevent or reduce the impact of a hazard on communities (e.g., through land-use regulations) and resistance as the ability to protect individuals during the occurrence of the hazard (e.g., through evacuation routes). From a theoretical point of view, the hazard-exposure-vulnerability trio, as advocated by the Sendai Framework, seems to be sufficiently comprehensive to capture all the involved factors to evaluate risk as the potential loss imposed on a society or community. Variables such as coping capacity, mitigation and resistance can be captured as the factors contributing to vulnerability. This common definition of risk (R) is presented as a function of hazard (H), exposure (E) and vulnerability (V):

$$R = f(H, E, V) \qquad (1)$$

For community risk assessment, the aim is to evaluate these three elements of hazard, exposure and vulnerability and combine their framing to assess risks. These approaches can generally be categorised as top-down and bottom-up. Top-down approaches, rooted in the knowledge officially developed and verified within the scientific community, have traditionally dominated the disaster risk assessment discourse (Gaillard & Mercer, 2013; Van Aalst et al., 2008). On the other hand, the relevance of bottom-up approaches, which are generally based on local and Indigenous knowledge developed by communities through their interactions with their immediate environment, to disaster risk assessment has also been recognised (Agrawal, 1995; Hadlos et al., 2022; Pelling, 2007). Examples include the observed capacities of local communities in major disasters such as the 2004 Indian Ocean tsunami (Arunotai, 2008; Baumwoll, 2008; Gaillard et al., 2008). These two risk assessment approaches use a variety of methods that are, in most cases, fundamentally different from each other to frame a community risk assessment.

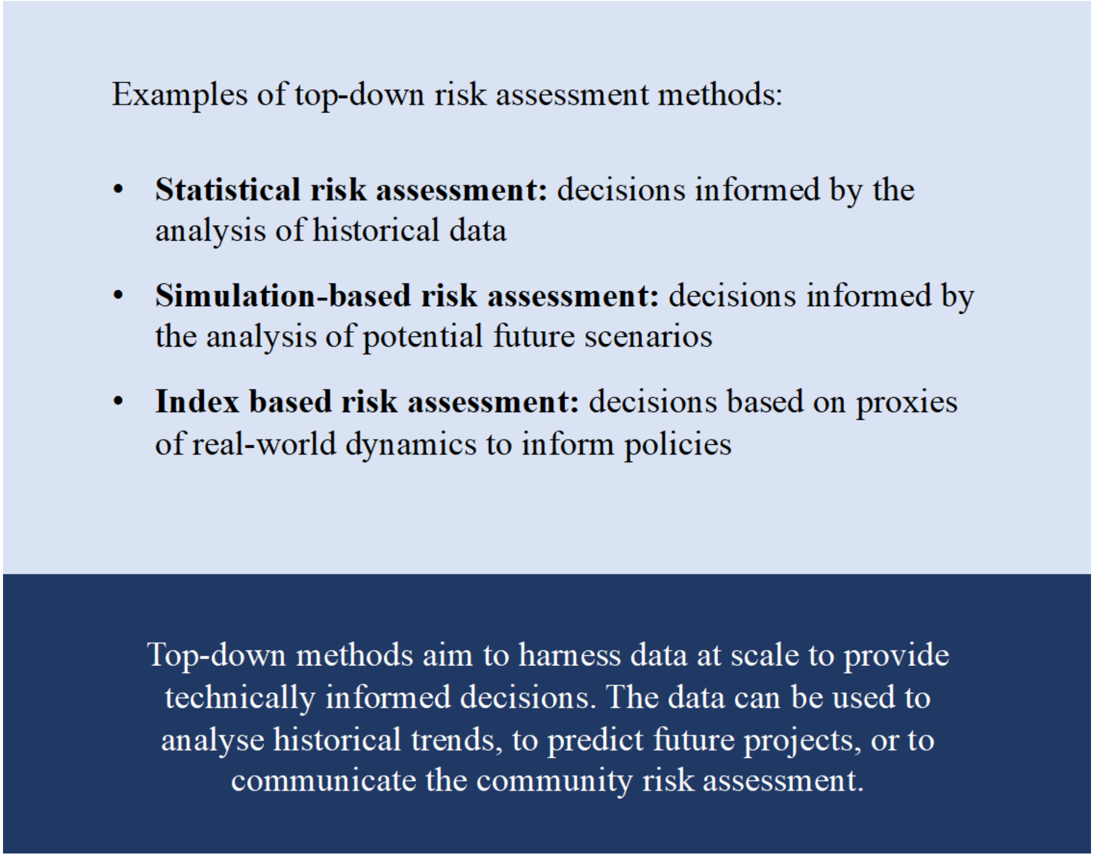
Top-down risk assessment

Different methods of top-down disaster risk assessment documented in the literature can be grouped into three general categories (Wang et al., 2016): (i) statistical methods where future disaster risk is presented through probabilities based on historical data, (ii) simulation-based methods that present different future risk scenarios using numerical models and (iii) index-based methods that aim to present risks through a series of proxies that measure latent variables (see Box 2).

Statistical risk assessment

Statistical methods generally attempt to estimate the probability of occurrence of a hazard and the potential of subsequent losses in the future derived from the probability of past hazard occurrence (Brink & Davidson, 2015; Liu et al., 2015; Wang et al., 2016). However, the adequacy of statistical risk assessment methods depends on the availability of meaningful, validated and calibrated historical data (Sun et al., 2015). This is particularly problematic for smaller-scale analysis, where granular historical data may not be available, for example, to carry out community risk assessment (Wang et al., 2016). Statistical methods do not fully capture less frequent but high-consequence events (Sherrill et al., 2022). Moreover, disaster risk cannot be readily decomposed and the contributions of different elements of risk, that is, hazard, exposure and vulnerability, may not be easy to obtain (Wang et al., 2016). Finally, statistical methods may not fully reflect the effects of different behaviours, such as changes in socio-economic and managerial factors, on the estimation of future risk (Sun et al., 2014). Still, statistical methods are useful to inform community risk assessments and these considerations of their limitations will make their impact more relevant to communities.

Box 2 – Examples of top-down risk assessment methods.



Examples of top-down risk assessment methods:

- **Statistical risk assessment:** decisions informed by the analysis of historical data
- **Simulation-based risk assessment:** decisions informed by the analysis of potential future scenarios
- **Index based risk assessment:** decisions based on proxies of real-world dynamics to inform policies

Top-down methods aim to harness data at scale to provide technically informed decisions. The data can be used to analyse historical trends, to predict future projects, or to communicate the community risk assessment.

Simulation-based risk assessment

Simulation-based risk assessment methods use numerical models to predict potential disaster-induced risk and loss scenarios. These methods are generally centred around numerical models that can simulate the trajectories of a hazard (or of multiple hazards) under various scenarios. For example, a finite element-based computer numerical model may be used to simulate the inundation range and water depth distribution of storm surge disasters under various scenarios (Xianwu et al., 2020), or a model that solves ground motion prediction equations may be used to estimate the spatial distribution of ground motion and shaking intensity for real and scenario earthquakes (Sherrill et al., 2022). The majority of simulation models aim to estimate the temporal and spatial distribution of hazard-related factors (e.g., ground motion and water depth). Therefore, the results of the physical model need to be combined with estimations of exposure and vulnerability obtained through methods corresponding to probabilistic or index-based approaches (Ming et al., 2022; Sun et al., 2015) and other simulation tools (Taubenböck et al., 2009). In addition, simulation-based methods are increasingly being developed to evaluate the performance of social and physical systems (Choi et al., 2017). Ideally, numerical simulations produce quantitative results that are verified and validated. However, such simulation results are constrained by limited data availability for model calibration and validation, the number of scenarios considered, and the need to simplify assumptions for computational feasibility (Ming et al., 2022).

Due to their reliance on numerical models that represent the physical phenomenon, simulation-based risk assessment methods are highly hazard specific. Often in cases where more than a single hazard is considered within a simulation model, the hazards share the same underlying physical phenomenon, for example, heavy rainfall, extreme river flow and storm surge all leading to flooding (Ming et al., 2022). However, more recently, multi-hazard approaches have been introduced that use more than one numerical simulation model, with each modelling a different physical phenomenon. The development of a comprehensive multi-hazard risk assessment approach using this approach, though, is conceivably restrained by the availability of reliable and compatible numerical simulation tools.

Index-based risk assessment

In index-based methods, different elements of risk such as hazard, exposure and vulnerability and associated contributing factors are represented as a series of normalised weighted indices that are proxies to indicate disaster risks. Factors contributing to risk elements can potentially be estimated using statistical- and simulation-based approaches (Brink & Davidson, 2015; Khallaf et al., 2018; X. Liu et al., 2021). Therefore, index-based methods can benefit from the advantages of these approaches to improve their accuracy. However, when applying statistical and simulation methods is not an option, for example, due to a lack of reliable historical data or numerical simulation models, indices can function as proxies through a variety of other methods, including satellite image analysis (Ebert et al., 2009; Hizbaron et al., 2018), field surveys (Brink & Davidson, 2015; Sorg et al., 2018) and interviews (Zhao et al., 2022). Flexibility in allowing qualitative data collection and analysis can help to capture the perceptions of people and facilitate engagement with communities (Maikhuri et al., 2017; Sorg et al., 2018). The weights of the indices and their contributing factors can be determined using subjective methods such as the analytical hierarchy process and expert scoring (Li et al., 2012; Wang et al., 2020; Wu et al., 2015), objective methods such as the entropy weight coefficient method (Luo et al., 2020) and the grey correlation method (Li et al., 2018) or combinations of objective and subjective methods (Guo et al., 2014; Jin et al., 2022; Yang et al., 2021).

Due to their modular structure, index-based methods are quite flexible and can be easily modified. For example, the hazard-exposure-vulnerability trio may be sufficient to capture all the contributing factors to risk for a community. But more dimensions can be added if needed, while the index can be also decomposed further. Some studies, for instance, have included resilience and recovery capabilities in risk assessments to capture longer-term effects (Marin et al., 2021; Sun et al., 2022). On the other hand, vulnerability-related concepts can be further segregated, for example, to distinguish mitigation and resistance, as suggested by Chiou et al. (2015). This makes it possible to capture the nuances of risk response and policy development. Moreover, the flexibility of index-based methods allows for relatively straightforward consideration of multiple hazards associated with fundamentally different physical phenomena, for example, floods and landslides (Marin et al., 2021). Index-based methods are commonly used for a range of national and international risk and resilience indices. The underlying assumption supporting the use of index-based methods is that they are acceptable proxies of a real-world phenomenon and their combination is arbitrary (Field et al., 2022). However, they are effective in communicating needs to decision-makers.

Bottom-up risk assessment

The disaster risk assessment body of knowledge is dominated by scientific top-down approaches. These approaches are rooted in scientifically developed and verified technical knowledge that is commonly used by government officials and academics to perform disaster risk assessment. While these approaches have proven effective and useful, especially on larger scales and in relation to infrequent and unprecedented events (Mercer et al., 2007), there is a growing argument for the missing role of local and traditional knowledge within these approaches.

Bottom-up approaches address such gaps because they aim for context-specific risk assessment, usually on smaller scales, for example, at a community level, by capturing local knowledge accumulated through the lived experiences of local residents. By placing people at the focal point of the investigation, these participatory risk assessment approaches (Granderson, 2018; Van Aalst et al., 2008) capture dimensions of the community risk that are arguably difficult, if not impossible, to obtain through technical top-down approaches. These aspects may include the perceptions, values and priorities of communities with respect to risk, which are subjective and therefore may be inherently outside the scope of technical risk assessment approaches. Furthermore, they can fill the gaps in technical top-down knowledge by impacting the granularity, thresholds, and updating frequency of the available data.

A variety of methods have been developed for participatory grassroots-level, bottom-up community risk assessment. It should be noted that the purpose of these methods is not to merely extract data from communities, rather it is to engage communities in the risk assessment process with the ultimate goal of community empowerment (Granderson, 2018; Zweig, 2017). Four types of common bottom-up community risk assessment methods are discussed in this report (see Box 3).

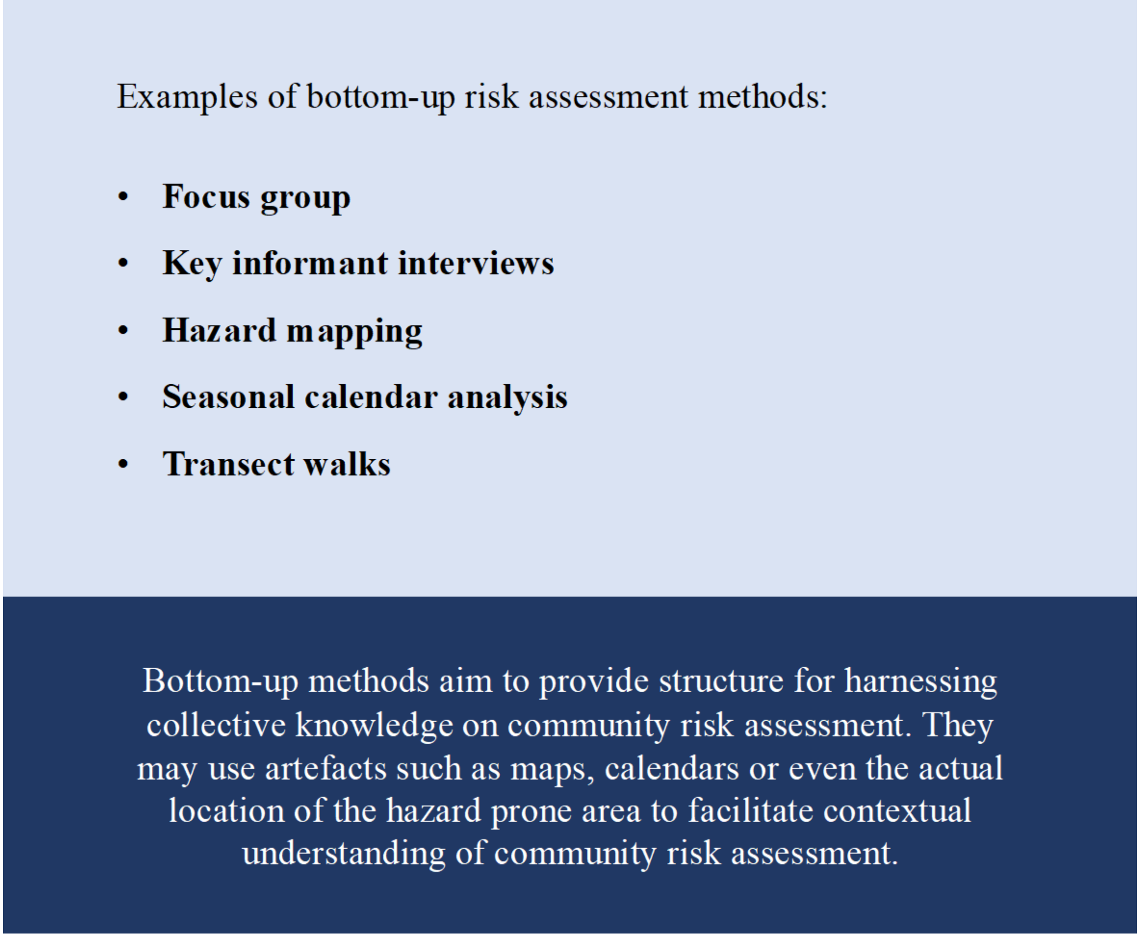
Focus group discussions and key informant interviews

Focus group discussions and interviews are the most general tool used to engage community members in disaster risk assessment and have been implemented in a range of different contexts (File & Derbile, 2020; Tyler & Fairbrother, 2013). Focus group discussions and interviews are useful for qualitative data collection, verification of relevant secondary data and validation of top-down risk assessment results.

Hazard mapping

Hazard mapping is a participatory tool used to explore significant hazards in a community as perceived by community members (Osti et al., 2008). Hazard mapping activities can be carried out in the form of focus groups or in a workshop setting. Such mapping can reveal differences between external investigators and local residents when it comes to priorities concerning and perceptions of hazards and risks (Van Aalst et al., 2008).

Box 3 – Examples of bottom-up risk assessment methods.



Examples of bottom-up risk assessment methods:

- **Focus group**
- **Key informant interviews**
- **Hazard mapping**
- **Seasonal calendar analysis**
- **Transect walks**

Bottom-up methods aim to provide structure for harnessing collective knowledge on community risk assessment. They may use artefacts such as maps, calendars or even the actual location of the hazard prone area to facilitate contextual understanding of community risk assessment.

Seasonal calendar analysis

Seasonal calendar analysis is a tool used to understand local knowledge associated with the systems of seasons and how community activities and hazards are affected by seasonal changes (File & Derbile, 2020). The focus of seasonal calendar analysis may be on seasonal hazards or seasonal livelihood, which is relevant to vulnerability analysis (Anik & Khan, 2012). Seasonal calendar analysis can be performed using a focus group setting or through interviews with multiple key informants. Such analysis can be extended to historical calendar analysis, where the investigators encourage participants to recall significant past events (Van Aalst et al., 2008).

Transect walks

Transect walks involve members of a risk assessment team walking through an area together with local community members to record the relevant physical and social characteristics of the community and its environment (Grove, 2014; Van Aalst et al., 2008). This approach is very helpful in capturing contextual information about the hazard, exposure and vulnerability, and in building rapport and a mutual sense of trust and understanding between external risk assessment teams and communities.

Top-down and bottom-up risk assessment integration

The Sendai Framework, the current global agreement to orchestrate protection of development gains from disasters, advocates the central role of technical knowledge while recognising the complementary potentials of traditional, Indigenous and local knowledge (UNDRR, 2015). While this recognition hints at an integrated approach towards community risk assessment, particularly in terms of the sources of knowledge, the discrepancies between the two knowledge bases along ideological, methodological and procedural continuum (Pelling, 2007) have challenged the development of truly integrated approaches (Gall et al., 2015). This has effectively led to the emergence of a dichotomy where the two approaches, coexisting in the landscape of disaster risk management, have evolved almost independently, each developing their own processes from data collection to the analysis and implementation of results. The forthcoming section delves into the challenges and potential solutions in bridging technical and local knowledge for community risk assessment.

Research approach

This report communicates the results of exploratory research to investigate the challenges involved in linking scientific and local knowledge bases for community risk assessment. Data was collected in two phases: first through a systematic literature review, including grey literature and common practices and then through semi-structured interviews.

The first phase of the study was a systematic literature review to understand the state-of-the-art methods of community risk assessment as reflected in the extant academic literature. Scopus and Web of Science databases were searched for disaster risk assessment, returning a total of 950 initial documents. After a series of automatic and manual filtering steps and the application of a set of inclusion criteria (e.g., language, quality of publication and relevance to community risk assessment), 45 final documents were selected for detailed analysis. Additionally, grey literature and current risk assessment frameworks and policy documents that are being implemented across Australia and internationally were reviewed to inform the synthesis.

The desktop search phase was followed by an empirical study that included a set of semi-structured interviews with risk management professionals. The data collection followed the ethics standards set by the Human Research Ethics Committee of the University of Sydney, ethics protocol number 2023/012. The details of the interviews with 29 individuals from a range of organisations and the backgrounds of the interviewees are presented in Table 1.

Table 1 – Interview details.

No.	No. of Individuals	Organisation	Interview duration (Minutes)	Interview transcripts' number of pages (words)
1	One	State Government Agency	93	20 (11911)
2	One	State Government Agency	72	19 (11685)
3	Two	National Agency	53	16 (7586)
4	Two	State Government Agency	76	20 (11332)
5	Two	State Government Agency	74	19 (11509)
6	Two	Disaster Management Consultant	78	20 (10461)
7	Two	Disaster Management Consultant	47	13 (6980)
8	Four	State Government Agency	53	14 (7992)
9	One	State Government Agency	55	16 (9070)
10	One	State Government Agency	61	16 (9344)
11	Two	State Government Agency	59	17 (9490)
12	Three	State Government Agency	57	18 (9873)
13	One	State Government Agency	27	7 (4008)
14	Two	Local Government	41	10 (5108)
15	One	State Government Agency	58	15 (8666)
16	One	Private Business	52	15 (8243)
17	One	State Government Agency	32	9 (4743)
Total	29 Individuals		988 Minutes	264 (238001)

Thematic analysis was used to study the collected data and explore any emerging themes associated with the main challenges of and potential solutions to incorporating local and traditional knowledge in disaster risk assessment.

Utilisation outputs

Why? - The need to connect the two types of knowledge

The empirical results suggest that current risk assessment processes are relatively satisfactory when it comes to taking advantage of technical and scientific knowledge. However, engaging communities in disaster risk assessment is believed to be one of the major missing parts in the process.

"I certainly feel from the discussions that I've had that we'd done relatively well in the past at finding the data and – in terms of that very hazard specific and impact specific stuff…. the two big things that we haven't done particularly well is bringing in any of the community bits and pieces, whatever that may look like and the speed at which we've done things."

Getting communities involved in disaster risk assessment is believed to be beneficial in a variety of ways, including the examples shared below.

Filling gaps in data

Collecting and processing the data required for risk assessment is time-consuming and resource intensive. This complexity limits the frequency of updates and the completeness of corresponding databases. Moreover, in most cases the collected data is not granular enough for risk assessment at the community level and any analysis of the technical models relies on assumptions about each scenario and context. The gaps in data collection for scientific and technical methods can be filled by community knowledge that can further develop assumptions so that they are closer to reality or that can serve as actual input data:

"…some decisions made more on assumptions and gut and we'd quite like to move a little bit more to ensuring that those areas of knowledge that we don't have pure data for are still accounted for [by] those people who know that there's specific things that happen in this particular community."

"…the more that we can involve community knowledge and information in that space the less likely we're going to get something to bite us on the bum that we had overlooked because we didn't have information and intelligence about that location or that particular hazard… it's a real gap for us because we acknowledge we can't be everywhere and know everything, we acknowledge we don't have data for the whole state but we should be tapping into the sources that do exist better."

Community-specific response

Communities respond differently to similar risks. Therefore, it is important to ensure that communities are engaged in the risk assessment process. Community engagement makes it possible to capture nuanced differences that may not be readily represented by hard data:

"… while there may be two places where the same type of flood will impact the same number of homes or something like that, the response required might be quite different and the factors that will determine why that response is different is the community characteristics and about whether they've got their own boats, their own chainsaws, their own evacuation plan, they're in multi-story buildings and they'll just climb up to the second floor and clear it all out and they'll be fine."

Box 4 – Importance of contextual knowledge in community risk assessment

"… they had done all the numbers and looked at all the risk issues, and they decided that clearly these were the particular structures … that needed to be looked after and they would try very hard to save all the houses, and when they went to the community the community actually said, 'Don't worry about the houses, we'll live in a tent if we have to, but you must save the mill because that's the centre of our town and if that goes everything falls apart."

Moreover, there is a need to investigate the social and cultural contexts that impact the response of a particular community to risks. These may include, but are not limited to, local and traditional governance structures:

"…there are some Indigenous communities where they have a rule that if anyone's evacuating everyone has to evacuate and the order has to come from the leader of that particular town and that's kind of been the way we've done business with them is we've made that person aware well, you're all going to need to go because it's going to get this big or whatever…"

Socio-economic variables may also result in the emergence of a community-specific decision factor. For example, the residents of some communities may be more hesitant to evacuate their properties due to concerns over potential looting:

"If we're trying to drive something it's going to be difficult – if you lose the detail as you go larger scale but even at a zone level it's still a very large scale to be looking at those very small factors and those factors will only be an issue in certain areas of certain towns for example as looting in other places you wouldn't dream of it and it would never even cross anybody's mind."

Validation and verification using community input

Incorporating local knowledge in disaster risk assessment is also essential when validating and verifying the results of risk assessment models. Potentially incomplete, inaccurate and out-of-date input data; oversimplified assumptions; and granularity limitations make technical risk assessment models prone to errors. Input from community members can help to capture and rectify these errors by updating the models and their input or the resulting action plans that are further aligned and validated with the contexts of a community:

"…they get some modelling done of what might happen if a fire comes through here and they take that to a particular group and the group goes, "Oh well, hang on, this map doesn't even have the new caravan park on it. You need to make sure" – you know, so it's that sort of verifications which I think is probably the hardest thing to do..."

Challenges

Incorporating local and traditional knowledge in currently existing disaster risk assessment frameworks necessitates overcoming a wide variety of technical, organisational, sociopolitical and financial challenges ranging from data-related and methodological issues to organisational conflicts and misaligned interests.

Data-related issues

Availability, accessibility and interoperability of data

Sourcing data from communities is often more difficult than obtaining technical data such as climate change data, the time series of hazards and geospatial data. This can mainly be attributed to the existence of established technical databases that are supported by organisations. Defining and measuring variables to represent the behaviours of communities, especially in a way that can be incorporated in risk assessment models, is challenging. Collecting and updating data using large-scale surveys and interviews is costly, time-consuming and limited by the communities' willingness to participate.

Data is usually obtained and maintained by different organisations and therefore, even existing data is not necessarily accessible to other organisations. This may be due to data ownership dynamics and sharing policies or the absence of effective mechanisms to locate available data across organisations. Moreover, the lack of consistent data collection and maintenance protocols limits the interoperability of available and accessible data at other organisations' disposal.

"It's going to be difficult because you're going to have data gaps in some locations. Because the big thing for us is we're often not a data owner… say for floods, we don't actually go and obtain the data ourselves. It comes from councils and so we're reliant – I mean, they're meant to give it to us, but they don't always do that."

Granularity and privacy

The ideal level of data granularity that is required to carry out risk assessments at a community level and develop operational strategies for actions such as evacuation, rescue and resupply may raise some privacy concerns. These limitations, while necessary, may require a balance between the benefits of sharing and maintaining privacy:

> *"It's quite hard to do that precisely, one because no one agency has all the data and also privacy issues like should an agency actually know the status of every single person in all these circumstances and then classify them as various degrees of vulnerability. I think there are some issues about – we'd like to have more information, but I think we've got to watch how intrusively we come into people's lives."*

Assessment models and methods

Assumptions

Risk assessment models as partial representations of reality are inevitably based on a range of assumptions. The relevance and accuracy of these assumptions may be open to question, especially when human behaviour is involved. Examples of these uncertainties relate to how people in a community respond to a risk before, during and after a natural hazard under various circumstances:

> *"If I've been through three floods already this year and right now I'm sick with COVID and you ring me – you issue a warning for my area, I'm just going to evacuate because you know what, I don't have the energy, I don't have the stamina, I've been flooded three times, I haven't got it in me and so where that line is between me right now and [Organization X] is going to be quite different to where it would be if I hadn't had a flood, if I wasn't sick with COVID, if I didn't have all those other things."*

Quantification challenges

Many of the salient variables that affect the results of risk assessment models are not easily quantifiable, especially when it comes to social and human aspects. Still, some variables can be quantified by applying statistical methods based on survey data:

> *"… there's been a lot of research in that area to try and quantify that which we called the evacuation compliance rate in modelling it. A key thing in evacuation modelling is the departure curve for the area which you're doing in it. They did it in the context of dam break scenarios. Trying to quantify that departure period by survey questions. If you can imagine, with this approach they haven't gotten fully developed, but you can always say, "Here's a series of questions you can ask and we can fit it against one of those types of distributions and adjust the parameters to get an estimate of how they're likely to depart."*

However, there are arguments about how representative the results of such statistical methods may be:

> *"… it's the nature of statistics… the more factors you put in the more people you exclude. So you start off with a whole community and then you average it to a socio-economic status which knocks out whatever 20, 30, 40% sometimes of the population because you're just shoving that average into a box and then you say, 'Okay, well there's that' and then you add another layer of something else, whether it's multi person housing or something and that again knocks another proportion."*

Limited understanding of the natural phenomena

The accuracy of the predictions of risk assessment models is significantly affected by how well the physics of different natural phenomena such as floods, tsunamis and storms and their interactions with landforms are understood. Our limited understanding of these natural phenomena coupled with the uncertainties associated with the behaviours of individuals under various circumstances adds another level of complexity to effective community risk assessment.

Multi-hazard risk assessment

Risk assessment becomes even more complicated when considering multiple hazards such as concurrent events or the cascading effects of rainstorms and floods. Not only is the accuracy of risk predictions adversely affected by the limitations of current models in handling the interplay of multiple hazards, but also communities may respond differently to the compounding and cascading impacts of hazards. As a result of the complexities and methodological challenges involved in aggregating the risks of multiple hazards, there is the danger of oversimplification through the overlay of results from single-hazard models based on the input of various communities:

“I think there are still a lot of work per hazard to delve in, because that work will really inform all these ones. The various aggregated risk assessments, cross hazard ones, I think they need to take them into account as more a 2D, 3D spatial view, rather than just a matrix and a number and ranking.”

Model complexity and communication of results

The results of risk assessment models are often complex and trying to model a real phenomenon more accurately based on community input adds to the level of complexity. On the other hand, the target audience of these models, including the decision-makers and community members, is not necessarily comfortable with interpreting the results and may not fully comprehend them. So, a major challenge is maintaining the required level of complexity while at the same time ensuring the usability of a model for its audience.

“It’s a two-dimensional view. It’s showing you a spectrum, but sometimes people will say, “Give me a number so I can rank it. A single number.”

Risk assessment scale

Aggregating small-scale analysis

Top-down risk assessment is often carried out on large scales through state- or nationwide analyses. The results of such risk assessments will likely be used to develop policies and strategic plans. On the other hand, in order to engage communities effectively, bottom-up risk assessments need to be carried out on smaller scales. One major methodological challenge is to aggregate the results of smaller-scale analyses and incorporate them in larger-scale risk assessments.

“Where is the various risk concentrated, depending on which risk measures you’re using and I think that’s more important. Rather than saying, “For the state, flood is X and fire is Y.” Because that doesn’t tell you much.

The risk distribution across the state is not uniform. There could be big ones that are going to be averaged out to look like small ones."

Discrepancy of small-scale analysis

The discrepancy and disconnectedness of current small-scale risk assessments adds to the complexity of the aggregation problem. Moreover, the absence of clearly defined and shared risk assessment methods makes it difficult to combine, validate and interpret the results.

"All of the zone commanders say that they do a risk assessment when they are setting their zone priority for each year, but as to what that process is I don't know whether they are using the same process as each other… I don't know what inputs are being considered when they do that."

Governance/organisation

Organisational structure, responsibilities and ownership

Risk assessment and planning occurs within a complex organisational and inter-organisational structure where responsibilities for and ownership of resources and data are distributed. There is currently no established systemic perspective on coordinating risk assessment efforts even when they are being carried out within a seemingly hierarchical organisational structure. A systems approach to risk assessment that considers a range of stakeholders, including communities, requires more coordinated organisational processes with clear lines of responsibilities.

"They should be working with the zone planners, who don't report to me, to work out priorities and then they should be working with some of our own internal systems and documents and guidance things to tell them what their priorities are. But again, it's not – we don't have a systematic way of doing that other than our new [X] framework which we should be using to do that…I don't have a lot to do with influencing their decisions around identifying priorities…"

Box 5 – Organising community risk assessment data for effective use.

> *“ “I think if you can keep the information at the zones and keep them responsible for collecting it and maintaining it, if they’ve got ownership of it then they’re going to want to invest in maintaining those contacts. And if they can see how it can be used to make their job better and make them more effective, then I think they’ll have buy in to keeping that information up to date.”*

Centralisation versus flexibility

From a governance perspective, there seems to be a tension between the centralisation of risk assessment efforts and the existence of a level of flexibility that would allow certain amounts of autonomy for the actors at different levels of the organisational hierarchy. While centralisation is vital to ensure effective aggregation of risk assessment results, autonomy is required to facilitate the incorporation of context-specific variables that represent particular communities.

“We [need to] have a more consistent approach so that the way those planning and risk decisions are made in the northern zone are the same as the way the planning and risk decisions are made in the southern zone. Yeah, they’re not entirely independent and able to do whatever they like with those resources, but the intent is that we provide the structure and the governance I suppose from the headquarters perspective and the zones then apply that as to how that suits.”

Disjointed and uncoordinated risk assessment efforts

The complexities of balancing flexibility and autonomy requirements result in disjointed and uncoordinated risk assessment efforts at both the inter- and intra-organisation levels.

"Each agency is doing its own efforts in New South Wales, not just the emergency services, across a range of agencies there are lots of different things."

"…as most organisations once they get to a certain size everything becomes a little bit separate and what has happened is that each of those areas has built up their own way and a new leader will come into that particular area and change the way that they're getting that background information or which information they're utilising to make some of those planning decisions. We don't want to remove all of the autonomy from those areas, but we want to provide the consistent cupboard where they go to say, 'This is all the information that we need to utilise.'"

Social, political and financial influences on decision-making

The effectiveness and applicability of the results of disaster risk assessments on different scales are influenced by a variety of social, political and financial factors originating from misaligned perceptions and conflicts of interest. Strategic plans, including those associated with land use and development, are not only necessarily aligned with the results of disaster risk assessments but also shaped via the interactions of the various and often conflicting, decision-making criteria adopted by the different organisations, for example, state governments, local governments and agencies, responsible for risk assessment and planning.

"…local government makes the decision around where to build in terms of flood. So, whilst we would want to – whilst we try and work closely with local governments there's definitely a friction point, I think between us and them because they're the ones that ultimately making decisions about where land can be built on and where it's zoned for development, where it's zoned and no development can happen. They're not meant to approve development that increases the response burden to the [Organisation X], but they obviously do, for their own reasons and a lot of it's probably financial but we need to work closely with them because they're going to have a lot of this community information and the community connections that we would want to work through…"

Communities

Values and priorities

The responses of communities to the outputs of risk assessments and eventuated risks are driven by their values and priorities. As a result, these responses will likely vary by community or even for the same community at different times. For example, while the highest priority of the agencies responsible for risk management is saving homes, some individuals may instead prioritise saving other social or economic infrastructure within their communities. The decision to stay or leave is also affected by people's evaluation of the level of risk and its potential consequences, which may not necessarily be accurate.

"If an area is going to flood and your home is going to be isolated, we're going to tell you to evacuate because there's a risk that you're unsafe and your life will be at risk. But I think people often have a view that they're probably going to be okay and their priority is actually saving their property or staying with their property."

Perceptions

The perceptions of community members towards risks are not necessarily aligned with the views held by the responsible agencies and what the technical risk assessment results suggest. These perceptions may be affected by misconceptions regarding the nature and extent of damage and the capabilities of the communities to cope with them. Some of these misconceptions are driven by similar yet smaller-scale eventuated risk events.

"Last time we evacuated nothing happened, so I might as well stay this time."

The perceptions of individuals may also vary drastically towards different types of hazards. For example, people are likely to take bush fire hazards more seriously than flood hazards.

"…had some really interesting comments around people's view on the dangers and the risks around water as opposed to fire that really struck home with me and that, 'Oh, it's only a bit of water… everything gets wet it's okay.'"

Due to these misconceptions and unrealistic perceptions, community members may not be cooperative in the risk assessment and planning stages and may not trust and act in accordance with the recommendations of the responsible agencies based on the technical risk assessments. Consequently, when a high-consequence disaster risk is eventuated, rescue operations may not be carried out effectively.

"I think that was a huge frustration with the [X] area floods was that there were evacuation orders and people said, "No, no, no, we'll be fine. We'll stay here", but once it hit them they then expected that somebody would be there to rescue them within half an hour of calling the emergency services or whatever and there was a huge uproar when nobody came to get them because it was deemed that it wasn't safe for people to be in boats on the water because there were massive hazards et cetera that were putting their lives at risk. I think they're some of the clashes that I can see also coming up along the way."

Dynamic nature of communities

The dynamic nature of communities and their changing characteristics imposes additional challenges to natural risk assessment since time-dependent variations of exposure and vulnerability should be considered in different time frames. The perceptions of community members towards disaster risks evolve as a result of a range of factors including education, socio-economic status and past experiences. The demographic characteristics of communities also change in different time frames due to various factors such as migration, tourism and seasonal job opportunities.

"I think with the seasonal changes, even from a tourist perspective, the summer holiday destinations et cetera and the way the population can change massively from that."

Heterogeneity of communities

Communities are not homogeneous in terms of their perceptions of risk, their readiness to respond to a risk and even their willingness to participate in a community-driven risk assessment. Therefore, it is challenging to develop community risk assessment processes and risk response plans that capture the voice and suit the needs of the entire community.

"So, say in flood impacted communities, everyone's recovery is going to be at a different rate and it would be – it's going to be hard to push communities together or to participate in something when a large bunch of them will be ready and a large bunch won't be and may never be and knowing that whilst you know it's better practice to get everyone's voices or get the majority of voices, you're going to have to know that you won't get some people's – and that's their own choice, even though they might have something really valuable to add."

Low uptake of community engagement campaigns

A challenge is also observed with the lower-than-expected uptake of community engagement campaigns run by the agencies responsible for risk assessment and planning. This challenge can be partly associated with the above-mentioned unrealistic perceptions and lack of resources to balance the complexities. Therefore, opportunities to get input from communities and for community empowerment against risks are limited.

"… we ran a targeted campaign in the [Area X] in December and January – so December last year and January of this year. It had a really really low uptake and then February and April [Area X] flooded massively."

The low uptake of community engagement initiatives may also be affected by a lack of awareness within the communities about their responsibilities in planning for and coping with the consequences of risks. This is sometimes further reinforced by the results of the post-disaster interventions of government agencies:

"… every time the government offers people grants after a disaster, for me that just goes against what we're trying to get communities to… share that responsibility for risk reduction and risk management… needs to be a collaboration of efforts and the more government give out money at the end of every flood, every fire, every whatever, it's creating that reliance on someone else to help me fix my problem."

Resources

Human resources

Risk assessment is a resource intensive and time-consuming process, especially since engaging communities necessitates carrying out multiple smaller-scale events and establishing additional complex organisational support. Therefore, the agencies responsible for community risk assessments are under constant pressure in terms of the availability of skilled human resources and the frameworks within which community risk assessments are expected to be completed. People with relevant skill sets may not be allocated to the appropriate roles or may be misplaced due to organisational restructuring.

"… there is also the restructures that created just a misalignment of skillsets between people responsible for this kind of work and what they were actually good at. There were a lot of people put into a planning role who – (a) didn't want to do planning, (b) didn't know how to do planning and there was no mentoring of staff put into

those new roles, there was no – and the lack of I guess a centralised way of doing things from the state has really hampered that as well."

"And not just in terms of people but time. It's going to take time to do that properly. But a big challenge is going to really be getting the executive to really believe in it. Quite often we hear good words come out of the [Leaderships'] mouths around the importance of the work, say, our team does and the importance of working locally through our communities but it's often not, it's often overlooked and so it's going to be cultural change in the organisation which is incredibly difficult to achieve, it's going to be patience and allowing time to do it properly and not expecting – and having buy in from communities."

Physical resources

The physical resources at a community's disposal are essential parts of first response and emergency planning against disaster risks. The effectiveness of strategies to incorporate these resources in risk management plans can alleviate resource availability and logistics issues. However, the availability of physical resources and logistics also necessitates additional resources from communities. Specifically, the resilience of communities in response to eventuated risks is necessary from a collaborative emergency response point of view for communities and agencies. Such a collaborative view requires access to up-to-date information about available resources, their conditions and locations and points of contact.

"It's almost like that spontaneous volunteering, what have they got to deal with for their own – in their own community rather than us then going well, we need 25 boats. Well, we need a bloody big shed if we're going to put 25 boats in that we might use once every 10 years… It's going to be hard because that information is going to change over time and we need to not expect that a flood plan we wrote 10 years ago old Joe is still the right contact person."

Recommendations

In this section, we propose and discuss a set of guidelines to overcome the challenges involved in incorporating local and traditional knowledge in disaster risk assessment frameworks. Attempts to incorporate local community knowledge in technical approaches to disaster risk have been mostly focused on case studies at different stages of disasters, including at the assessment stage (Klimeš et al., 2019; Pauli et al., 2021; Peters-Guarin et al., 2012) and the post-disaster reconstruction stage (Masinde, 2015; Schilderman, 2004). While these instances have demonstrated the value of local and context-specific input, derived from the grassroots level to broader disaster risk reduction efforts, there are several methodological and procedural challenges that need to be addressed to strengthen the link between the bottom-up and top-down approaches (Van Aalst et al., 2008).

To strengthen the link between the two approaches towards integrated community risk assessment, our recommendations delineate actions that aim to respond to the following two questions: (i) *What should be done?* (ii) *What can be done?* The response to the first question includes a range of principles that are meant to guide communities and agencies in developing or revising their integrated community risk assessment strategies (see Figure 1). These principles can support integrated and collective approaches through a range of contextually defined practices. The response to the second question encompasses the range of common options that can be used by communities and agencies to develop or revise their community risk assessment practices (see Box 1). The guideline directs agencies and communities to consider the importance of the principles and then choose from a range of options to facilitate the integration of local knowledge in technical community risk assessment models.

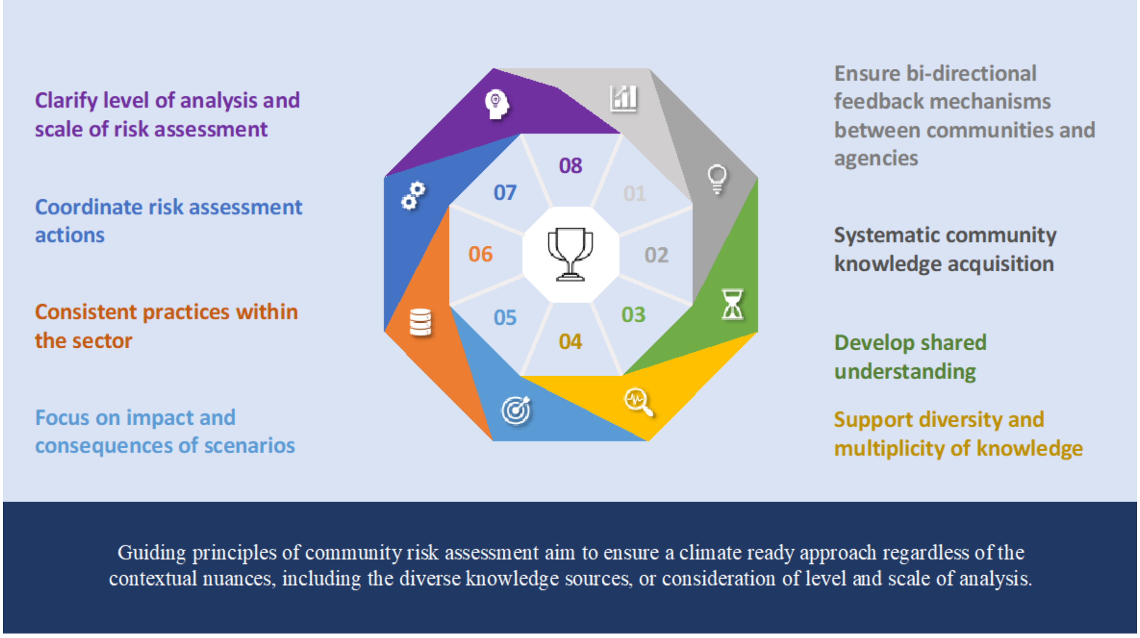
Principles: What should be done?

Clarify the level of analysis and scale of risk assessment

Some of the most fundamental challenges involved in connecting top-down and bottom-up risk assessment approaches can be addressed through a multi-scale risk assessment framework. Top-down risk assessment methods can be used to investigate general trends to identify desired areas of focus on larger scales, for example, the national and state levels. Bottom-up community risk assessments can then be used to provide more details and fill the gaps of top-down risk assessments in the identified risk zones.

Performing top-down risk assessments at larger scales helps to avoid problems with data granularity because they require less detail at lower levels. Additionally, maintaining consistency across local risk assessment studies at the national and state levels may be less critical since there would be no need to incorporate small-scale studies in a single large-scale risk assessment framework. The resulting multi-scale risk assessment framework could have varying levels of detail in different locations depending on the levels of risk identified using a top-down approach. The limited available time and resources could then be allocated to areas corresponding to higher detail.

Figure 1 – Guiding principles of community risk assessment.



Guiding principles of community risk assessment aim to ensure a climate ready approach regardless of the contextual nuances, including the diverse knowledge sources, or consideration of level and scale of analysis.

Coordinate risk assessment actions

Numerous independent risk assessment projects are carried out every year, both by academics and relevant agencies, investigating different aspects of community risk. These efforts vary across several dimensions, including the conceptualisation of risk based on risk components, such as hazard, exposure, vulnerability and resilience (see Table A1); the types of hazards investigated, such as floods, bush fires and rainstorms; the indicators used to quantify risks, such as precipitation, populations and GDP (see Tables B1–4); the approaches and methodologies used for risk assessment; and the scales encompassed by risk assessments. Although these efforts might not necessarily be integrated due to the above-mentioned differences, they can potentially be coordinated, especially for assessments that are funded by government agencies. This may include managing overlaps and interfaces, coordinating data collection and data sharing and cross-validation.

Consistent practices within the sector

A multi-level risk assessment framework eliminates the need to orchestrate community-level risk assessment efforts down to the smallest details. Instead, a set of established practices could be put forward by the responsible agencies at the national or state level to ensure that community-level assessments are sound, consistent and compatible with top-down assessments. Such practices would reduce unnecessary constraints on community-level assessments and support tailored assessments according to the needs and available resources of particular communities.

Focus on the impacts and consequences of scenarios

The development of a risk assessment framework should be guided by the goal of predicting the impacts and consequences of risks with suitable accuracy from a practical point of view. This principle defines the requirements regarding the data, the level of detail and even the methodologies used. For example, in multi-hazard scenarios, sufficient data may be available to investigate the compounded and cascading impacts of potential damage. The analysis of these impacts may eliminate the need for complex analysis of the compounded physical interaction of multiple hazards. As another example, data requirements and data granularity levels should be driven by their effects on the ability to accurately predict the evacuation behaviour of the residents of a community under different risk scenarios. An impact- and consequence-driven risk assessment framework helps to avoid spending time and resources on collecting and processing unnecessary data, limits the potential for privacy concerns associated with overly granular data and helps to address complex risk scenarios on a macro level without unnecessarily delving into the micro-level details of physical and social phenomena.

Develop a shared understanding

There is a need for a shared language that facilitates communication among the wide range of stakeholders, such as politicians, funding agencies, businesses, academics and the general public, involved in various stages of the risk assessment life cycle. Moreover, there is a need to develop appropriate tools to communicate the results of risk assessments to community members. This may include alternative mediums such as videos, podcasts, games and simulations. The corresponding content may need to be created in languages other than English to reach diverse community members depending on the demographic distributions of the target areas or the potential for temporary visitors such as tourists.

Support diversity of risk knowledge

While maintaining the shared understanding, there is a need to support and integrate diverse knowledge into the community risk assessment. The extent of the diversity of experiences and knowledge can reduce the biases, increase the effectiveness of the actions that are planned based on risk assessment and respond to diverse needs within the communities. Diversity of knowledge for community risk assessment starts with the integration of top-down and bottom-up knowledge and can extend to integration of knowledge from a range of stakeholders, agencies and diverse members of the communities. Specifically, there is a need to actively engage the voices that are naturally pushed aside and are not heard through existing channels.

Systematically capture and integrate local knowledge

Currently, technical knowledge is more likely to be accumulated and used consistently compared to local and traditional knowledge in the context of risk assessment. Current organisational structures do not provide an established process for local knowledge that is often anecdotal, unverified and undocumented. In many cases, local knowledge possessed by people who are currently working for an organisation is not properly internalised on an organisational level and therefore may be lost.

"… you're sitting in the room and somebody will go, 'Oh yeah,… that little town – there's a town of 300 people, they'll be fine because they get isolated every six months and they can sit there for two weeks, no problem' and we know that. But… if you get three people who know that and they all happen to leave the agency at the same time, then we can be in real trouble."

Effective mechanisms should be defined to systematically capture, internalise, use and update local knowledge. This may require maintaining a trade-off between robustness and flexibility since local knowledge comes in many different forms and with varying degrees of reliability.

Ensure bidirectional feedback mechanisms between communities and agencies

Getting input from communities in risk assessment should not be limited to obtaining data, rather it should be expanded to the entire life cycle of risk assessment. Following an impact- and consequence-driven approach to risk assessment, the results of the assessments should be presented to communities for feedback. This helps account for the problems associated with incomplete, faulty and incompatible input data and the inaccuracies and uncertainties involved in the risk assessment processes. The final outputs of community risk assessment, for example, resource allocation plans, evacuation plans and home emergency plans, can potentially be less technical than the intermediate steps involved in risk assessment and therefore, it may be easier to involve the general public and get their feedback at this stage.

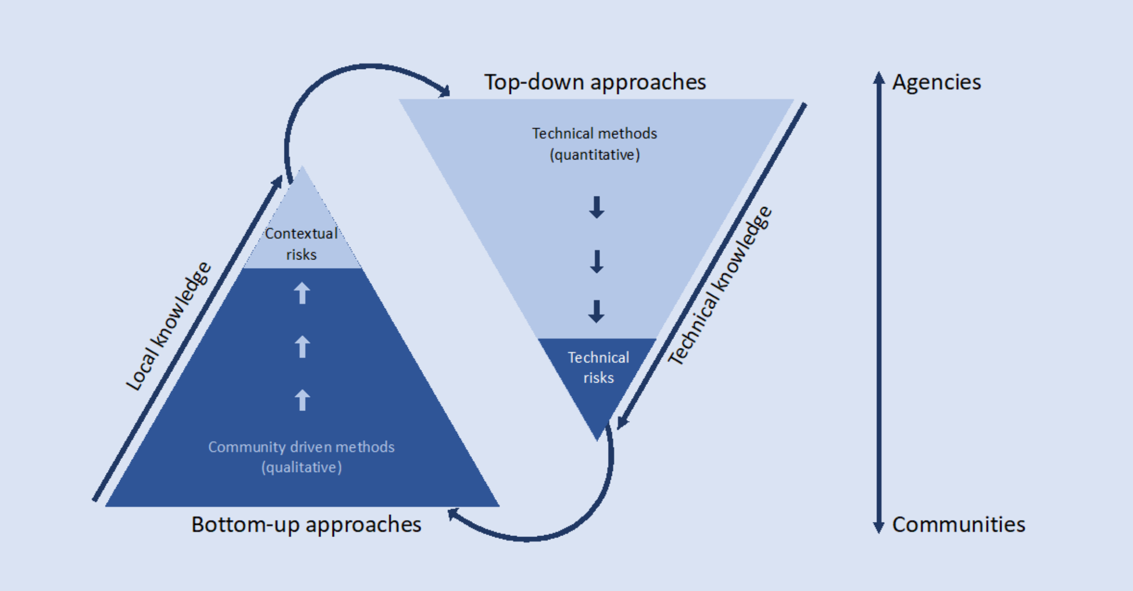
> *"… they get some modelling done of what might happen if a fire comes through here and they take that to a particular group and the group goes, 'Oh well, hang on, this map doesn't even have the new caravan park on it.'"*

Capturing community feedback should also be extended to the impacts of community engagement programs to ensure that the outputs of risk assessment are effectively communicated to the general public and result in meaningful community empowerment. To ensure successful empowerment, there is a need to share knowledge, information and objectives of strategies across all the involved stakeholders (Pearson et al., 2023). These eight principles can be considered in revisions or the development of community risk assessments by agencies and communities (see Figure 1).

Options: What can be done?

Considering these principles, community risk assessment can be developed through a range of alternative risk conceptualisations, definitions and quantifications based on a range of data sources (as presented in Appendices A–C). In this section, we propose a generic framework for community risk assessment by linking bottom-up and top-down community risk assessment approaches. The structure of the framework is shown in Figure 2.

Figure 2 – Schematic framework to connect bottom-up and top-down approaches.



The cycle shown for integrating bottom-up and top-down approaches will transform to a spiral in time. Continuous integration of technical and contextual knowledge ensures a bi-directional approach to reduce biases, address limitations, and tailor generalisations that result from a siloed approach.

The risk assessment process can benefit from the integration of top-down and bottom-up risk assessment approaches. In line with a multi-scale risk assessment approach as suggested above, technical risk assessment can be used on a larger scale, for example, at the national or state level, to identify higher-risk areas. These areas can then be investigated in more detail using bottom-up approaches. A list of potential options to define such top-down risk assessment approaches is provided in Appendix A. Users can adapt a combination of these alternative conceptualisations, definitions and quantification approaches to best suit their contextual needs and available resources. A list of indicators of risk elements for hazard, vulnerability, exposure is also provided in Appendix B, together with potential sources of data that agencies and communities can consider in their community risk assessments. Different combinations of indicators may be needed for risk assessment in different contexts and in the face of different hazards, especially with regard to the availability of data.

Upon identification and prioritisation of high-risk areas for community risk assessment, bottom-up approaches can be then used for a more contextual assessment by engaging community members. A list of relevant Australian and international resources that may be helpful to scope out, prepare for and implement a community-based, bottom-up risk assessment is provided in Appendix C. The resources include guidelines on how to engage communities, assessment tools and methods, recommendations regarding communication and implementation of the results and case studies.

Conclusion

There is a growing call for a paradigm shift in community risk assessment in view of the increasing frequency and impact of disasters. Specifically, there is a need to better capture multi-hazard scenarios, multi-stakeholder decision-making practices and the dynamic interactions of community risk. Answering this call, our empirical study suggested a gap in the integration of bottom-up and top-down community risk assessment. Bottom-up community risk assessment is dominated by local, Indigenous and contextual knowledge, often qualitative and sometimes anecdotal. Top-down community risk assessment is dominated by technical knowledge, which is supported by scientific assessment and often quantitative.

Involving communities in the assessment of disaster risks provides advantages such as integrating community insights to enhance data quality, bridging data gaps, capturing community-specific responses to disaster risks and aligning strategies and resources for more effective responses. However, these efforts necessitate overcoming an array of technical, sociopolitical, organisational and financial challenges. More precisely, community risk assessments encounter challenges in comprehensively addressing various facets of risk, including community perceptions, values and priorities associated with risks, all while ensuring the technical and scientific rigour of the assessments.

Box 6 – Three main considerations for the future of community risk assessment.

Integration of bottom-up and top-down risk assessment should be resourced

Bi-directional integration requires system of systems approach

Appropriate level of integration is determined based on the context

Future initiatives to integrate bottom-up and top-down community risk assessment should address three critical reflections (see Box 6).

First, it should be noted that integration does not happen by itself and it needs to be resourced. Given the increasing resource limitations within both agencies and communities, such initiatives will be competing with other priorities. Specifically, these initiatives may compete with the growing interest in technological and digital initiatives. Therefore, to operationalise the integration of bottom-up and top-down approaches, their importance needs to be well understood within the sector. Such understanding and its consequent prioritisation will ensure that the required resources are provided to integrate community and agency knowledge in risk assessment.

Second, the integration needs to be bidirectional. That is, the discussion around the integration of community knowledge in agencies should run parallel to discussions about the integration of technical and agency-driven knowledge in communities. The latter is often facilitated through workshops, campaigns and different communication mediums. These educational opportunities provide an understanding of the logic behind and justification for top-down, often technical community risk assessment within the communities and can increase the effectiveness of coordinated actions in the face of disasters.

Third, the level of integration between the bottom-up and top-down approaches depends on the context. That is, higher integration is not always favourable. In this sense, the level of integration should be contextualised based on the needs of different involved actors and the nature of hazards. Agencies and communities can develop maturity levels to better understand what level and form of integration is appropriate for their specific cases.

To address the raised challenges, we proposed a guideline that was informed by an extensive review of literature and practice. The proposed guideline includes a set of *principles* that aim to address the question "What should be done by community risk assessment?" and *options* to address the question "What can be done in community risk assessment?" These principles can inform communities and agencies that are aiming to revise existing community risk assessments or develop new ones because they can use the range of options provided to conceptualise, define and measure risks within their community risk assessment frameworks. Understanding the range of options for defining and measuring community risk can assist the communities in better comprehending what fits their contexts and could inspire potential innovations based on the alternatives. Highlighting the need for further integration of bottom-up and top-down approaches, future research should explore the complexities of this integration in terms of resource requirements and participatory decision-making processes. Furthermore, there is a need to expand this research with empirical study of communities and their involvement in community risk assessment.

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Appendix A: Quantitative top-down risk assessment approaches

Table A1 - quantitative and semi-quantitative risk assessment methods.

Ref	Hazard types(s)	Definition of risk	Risk element assessment methods (output)					Risk assessment methodology	Notes
			Hazard (H)	Exposure (E)	Vulnerability (V)	Other	Risk		
(Brink & Davidson, 2015)	Earthquake	$R = f(H, V, RE)$	Monte Carlo simulation with importance sampling (probabilistic ground motion maps)		Fragility analysis (fragility curves for building types)	Resilience (RE): Weighted sum (household socio-economic resilience index)	Joint probability distribution (damage exceedance probability curves)	Hybrid: Statistical/index-based	
(Cai et al., 2019)	Flood	$R = f(H, V, E)$	Hydrodynamic simulation (inundation depth, inundation area, and inundation duration)	GIS analysis (ground elevation, ground slope and impermeability)	GIS analysis (building density and point of interest density maps)		Fuzzy comprehensive evaluation (risk level map)	Hybrid: Index-based/simulation-based	
(N. Chen et al., 2019)	Unspecified multi-hazard	$R = f(H, \mathrm{V})$	Machine learning/self-organising map (clustering and ranking of indicators)		Machine learning/self-organising map (clustering and ranking of indicators)		Technique for Order of Preference by Similarity to Ideal Solution (disaster risk ranking of regions)	Index-based	Vulnerability includes sensitivity, response ability, adaptability. The term danger of natural disasters is used for hazard
(Q. Chen et al., 2019)	Drought	$R = \mathrm{H} \times \mathrm{V}$	Weighted sum of historical and potential hazards (Hazard index map)		Weighted sum of indicators (vulnerability to drought index map)		Multiplication of indices (composite risk index map)		Exposure is considered as a contributing factor to vulnerability Weights of indices are calculated using analytical hierarchy process

(Chiou et al., 2015)	Debris flows	$R = (1 - \mathrm{M}) \times \mathrm{H} \times \mathrm{E} \times (1 - \mathrm{R})$	Weighted sum of indicators/ GIS spatial analysis (hazard indicator maps e.g., potential collapse area)	Weighted sum of indicators/ GIS spatial analysis (e.g., map of evacuation shelters, evacuation routes, and protected communities)		Mitigation (M) and Resistance (R) Weighted sum of indicators/ GIS spatial analysis (e.g., map of evacuation shelters, evacuation routes, and protected communities)	Weighted sum of indicators/ GIS overlay analysis (risk level map)	Index-based	
(Dwivedi et al., 2022)	Hydrometeorological disasters	$R = f(H, V)$	Normalized difference water index, remote sensing, GIS spatial analysis (Potentially dangerous lakes map)		Maximum entropy model, (Landslide susceptibility map)		Weighted overlay method (Glacier lake outburst flood risk map) (Rainfall-induced flash flood risk map)		
(Ebert et al., 2009)	Flood and landslide		Pre-existing (Hazard maps of floods and landslides)		Contextual analysis of image and GIS data (Social vulnerability map)			Index-based	The focus of this study is on social vulnerability assessment rather than risk assessment.
(Guo et al., 2014)	Flood	$R = f(H, \mathrm{E}, V, RES)$	Variable fuzzy set (VFS) theory set pair theory/GIS spatial analysis (Hazard level map)	Variable fuzzy set (VFS) theory/set pair theory/GIS spatial analysis (Exposure level map)	Variable fuzzy set (VFS) theory/set pair theory/GIS spatial analysis (Vulnerability level map)	Restorability: Variable fuzzy set (VFS) theory/set pair theory/GIS spatial analysis (Restorability level map)	Multiplication of exponentiated indicators (Risk level map)	Index-based	Weights are determined using combined weights of entropy
(Hizbaron et al., 2018)	Volcano		Pre-existing (volcano hazard maps)		Statistical and spatial analysis (Physical, social, economic, and			Index-based	The focus of this study is on vulnerability assessment rather

					total vulnerability maps)				than risk assessment.
(Jin et al., 2022)	Lightning	$R = f(H, \mathrm{S}, \mathrm{F})$	GIS spatial analysis (lightning hazard level map)	GIS spatial analysis (frangibility level map)	See note	Sensitivity of the hazard-bearing environment GIS spatial analysis (Sensitivity level map)	Weighted sum of indicators (risk level map)	Index-based	Exposure and vulnerability are combined as Frangibility of hazard-bearing body
(Li et al., 2020)	Rainstorm	$R = \mathrm{H} \times \mathrm{V} \times \mathrm{E}$	Copula joint function (probability of rainstorm under different return periods/rainstorm hazard maps)	Jenks natural breaks classification/GIS spatial analysis (exposure level map)	Jenks natural breaks classification/GIS spatial analysis (vulnerability level map)		Multiplication of risk elements (Risk level map)	Hybrid: Statistical/index-based	
(W. Liu et al., 2021)	Late frost of open-air grape	$R = f(H, \mathrm{E})$	Remote sensing, GIS spatial analysis	Image processing, GIS spatial analysis, machine learning e.g., random forest (distribution maps of exposed areas)			Remote sensing, GIS spatial analysis (risk level map)	Index-based	Risk is calculated using remote sensing and GIS spatial analysis on exposed areas. Hazard outputs are not presented separately.
(X. Liu et al., 2021)	Drought	$R = f(H, \mathrm{V}, \mathrm{E}, \mathrm{C})$	Kolmogorov–Smirnov test (drought distribution under different probabilities)	Weighted sum of indicators (-)	Weighted sum of indicators (-)	Disaster prevention and mitigation capability (C) (-)	Weighted sum of indices (risk level map)	Hybrid: Statistical/index-based	
(X. Liu et al., 2015)	Dust storm	$R = f(H)$	2-D and 3-D Frank Copula functions (joint probability distribution of dust storm hazard for different return periods)				Same as hazard.	Statistical	Risk is considered to be equivalent to hazard.

(Y. Liu et al., 2015)	Typhoon rainstorm-flood hazard	$R = f(H, V)$	GIS spatial analysis (flood submergence depth map)		GIS spatial analysis (flood loss distribution map)		Jenks Natural Breaks classification, GIS spatial analysis (loss value/risk of exceeding a 50-year Typhoon Morakot scenario flood)	Index-based	
(Y. Liu et al., 2021)	Strom flood	$R = f(H, V)$	Random forest, GIS spatial analysis (hazard factor distribution maps)		Random forest, GIS spatial analysis (vulnerability factor distribution maps)		Natural break-point method (risk level maps)	Index-based	Vulnerability is divided into natural and social factors Hazards are mentioned as disaster causing factors.
(Luo et al., 2020)	Agricultural drought disaster	$R = f(H, E, S, C)$	Grey incidence analysis methods, the maximum deviation and maximum entropy principle (indicator and time weights)	Grey incidence analysis methods, the maximum deviation and maximum entropy principle (indicator and time weights)	Grey incidence analysis methods, the maximum deviation and maximum entropy principle (indicator and time weights)	Drought resistance capacity (C) Grey incidence analysis methods, the maximum deviation and maximum entropy principle (indicator and time weights)	Grey cloud possibility function (drought disaster risk grade)		Weights of indicators are determined using the grey incidence analysis methods, the maximum deviation and maximum entropy principle Vulnerability is mentioned as damage sensitivity
(Marin et al., 2021)	Landslides, floods, earthquakes, and volcanic eruptions	$R = H \times E \times V \times (1 - RE)$	Estimates provided by institutional sources, weighted sum of indicators (indexed map of hazard)	Estimates indicators based on available statistics, weighted sum of indicators (indexed map of exposure)	Estimates indicators based on available statistics, weighted sum of indicators (indexed map of vulnerability)	Resilience (RE): Estimates indicators based on available statistics, weighted sum of indicators (indexed map of resilience)	According to risk definition formula (disaster risk assessment index map)	Index-based	Exposure is divided into direct and indirect exposure. Cluster analysis is performed to identify hot spots.

(Meng et al., 2016)	Heat injury for single-cropping rice	$R = f(H, E, V)$ $R = f(H, E, V, C)$	Correlation analysis (Hazard index maps in different time periods)	Ratio of indicators (Exposure index map)	Ratio of indicators (Vulnerability index map)	Disaster prevention/mitigation capacity (C) Weighted sum of indicators (Emergency response and recovery ability map)	Weighted multiplication of indices (risk level maps for three- and four-element risk assessment methods)	Hybrid: Statistical/index-based	Both three-element and four-element risk assessment methods are considered.
(Ming et al., 2022)	compound flooding: heavy rainfall, extreme river flow, and storm surge	$R = f(H, E, V)$	Copula functions (joint probability distribution of multi-hazards) 2-d hydrodynamic simulation (probabilistic inundation maps and frequency-inundation curves)	Captured within vulnerability assessment	Existing vulnerability analysis outcomes (Direct loss functions against inundation depth.)		Combination of hazard and vulnerability (Residential loss vs return period curves, risk map of average annual loss)	Hybrid: Statistical/simulation-based	
(Nepal et al., 2021)	Drought and erosion	$R = f(H, E, V)$	pair-wise ranking method (disaster prioritization) GIS spatial analysis (Drought severity map and erosion severity map)		Interviews and focus group discussions to understand vulnerability of drought and erosion (qualitative results)		Interviews and focus group discussions to understand the effects of drought and erosion (qualitative results)	Hybrid: Index-based/qualitative	
(Pan et al., 2020)	Flood and earthquake	$R = f(H, V)$	Information diffusion technology (Discrete joint probability distribution of flood and earthquake)		Information diffusion technology (Discrete vulnerability surface)		Information diffusion technology (Comprehensive risk loss due to flood and earthquake)	Statistical	
(Sarica et al., 2020)	Earthquake	$R = f(H, E)$	Classical probabilistic seismic hazard analysis (Peak ground acceleration maps with 10% and 2%	Image processing, simulation (build-up area maps)			Overlaying seismic hazard maps and build-up area maps)	Hybrid: Statistical/simulation-based	The focus of this study is on evolution of expose areas

			probabilities of exceedance in 50 years)						
(Sherrill et al., 2022)	Earthquake (secondary effects of liquefaction and landslide)	$R = f(H, V, E)$	Numerical simulation on five deterministic earthquake scenarios (spatial distribution of anticipated earthquake-induced landslides and liquefaction)	Pre-existing exposure analysis (internal to the simulation model)	Pre-existing vulnerability analysis (internal to the simulation model)		Numerical simulation (total economic losses, number of buildings damaged, and casualties)	Simulation-based	
(Sun et al., 2022)	Flood	$R = f(H, V, E, EC)$	Collection and collation of existing empirical data (sub-indicators)	Collection and collation of existing empirical data (sub-indicators)	Collection and collation of existing empirical data (sub-indicators)	Emergency and recovery capabilities (EC) Collection and collation of existing empirical data (sub-indicators)	The indicators are combined using Choquet integral method to consider the interactions of indicators and minimise information redundancy (Comprehensive risk zoning map on city level)	Index-based	
(Sun et al., 2015)	Drought	$R = f(H, V, E, R)$	Run theory (identification of drought events) Copula functions (Joint probability distribution of drought duration and intensity)	Internal to simulation model	Internal to simulation model	Drought resistance (R) Internal to simulation model	Numerical simulation (Drought loss as function of drought frequency)	Hybrid: Statistical/simulation-based	
(Sun et al., 2014)	Drought and waterlogging	$R = f(H, V, E, RES)$	GIS spatial analysis (-)	GIS spatial analysis (-)	GIS spatial analysis (-)	Restorability (RES) GIS spatial analysis (-)	GIS spatial analysis, fuzzy comprehensive evaluation, Kruger interpolation (Drought,		Weights of indicators are determined by combining AHP and entropy method

							waterlogging, and integrated risk zoning maps)		
(Taubenböck et al., 2009)	Tsunamis	$R = f(H,V)$	Tsunami inundation modelling and hydrodynamic inundation modelling (Inundation and hazard maps)	Within vulnerability	Remote sensing, spatial analysis, surveys, agent-based simulation (evacuation model)			Simulation-based	Vulnerability is defined as a function of exposed elements and their susceptibility and coping capacity. The focus of the study is on development of a tsunami early warning and an evacuation information system
(Wang et al., 2016)	Agricultural disaster (hazards not directly specified)						Probability density function algorithm (The trend yields of various crops, probability density function curves and distribution functions of the relative meteorological yields, the risk levels)	Statistical	Agricultural disaster risk is directly evaluated based on historical data and statistical methods.
(S. Wang et al., 2020)	Glacier lake outburst	$R = \frac{H \times V \times E}{A}$	Image processing, GIS spatial analysis (Spatial and temporal variation of glacial lakes and their potential risks)	Collection and collation of existing empirical data, spatial analysis (Exposure map)	Collection and collation of existing empirical data, spatial analysis (Vulnerability map)	Adaptability (A) Collection and collation of existing empirical data, spatial analysis (Adaptability map)	According to risk definition (Risk level map)	Index-based	Weights are determined using AHP
(W. Wang et al., 2020)	Four typical natural disasters including geology (such as landslides, debris flows, and so on.), earthquake, drought,	$R = f(H,V,E,C)$	Collection and collation of existing empirical data (sub-indicators)	Collection and collation of existing empirical data (sub-indicators)	Collection and collation of existing empirical data (sub-indicators)	Disaster prevention and mitigation capacity (C) Collection and collation of existing empirical data (sub-	Different single comprehensive risk assessment models (Risk indexes on city levels by various methods, risk	Index-based	Weights are determined using a combination of AHP and entropy method. The focus of the study is on combining the

	and flood					indicators)	values based on combining various assessments)		results of single comprehensive evaluation methods.
(Wu et al., 2017)	Flood	$R = f(H, V)$	GIS spatial analysis, inverse distance weighted interpolation method, bias correction for future prediction (Flood hazard zonation map)		Collection and collation of existing empirical data, GIS spatial analysis (Vulnerability map)		Weighted sum of hazard and vulnerability, The Jenks optimization method, aka the natural break classification (risk level map)	Index-based	Weights are determined using a combination of AHP and entropy method.
(Wu et al., 2015)	Flood	$R = f(H, V)$	GIS spatial analysis, inverse distance weighted interpolation method, bias correction for future prediction (Flood hazard zonation map)		Collection and collation of existing empirical data, GIS spatial analysis (Vulnerability map)		Weighted sum of hazard and vulnerability, The Jenks optimization method, aka the natural break classification (risk level map)	Index-based	Weights are determined using a combination of AHP and entropy method.
(Xia et al., 2022)	Earthquake	$R = f(H, V, E)$	Probabilistic seismic risk assessment (probabilities of experiencing a certain value of the selected ground motion parameter/PGA distribution map)	Pre-existing grid data (Population grid distribution map)	Field survey, spatial analysis (Lethality level distribution map)		Multiplication of mortality rate of a certain grid at a certain intensity level, a certain lethal level, and population (earthquake lethal risk level map)	Hybrid: Statistical/index-based	
(Xianwu et al., 2020)	Strom surge	$R = f(H, V)$	Numerical simulation (inundation range and water depth distribution of storm surge disasters under various scenarios, hazard map)	Considered within vulnerability					

(Yang et al., 2021)	Aeolian disaster	$R = \mathrm{H} \times \mathrm{V} \times \mathrm{S} \times (1 - \mathrm{C})$	Temporal and spatial analysis of indicators (Hazard maps of disaster-causing factors)		Temporal and spatial analysis of indicators (Vulnerability of disaster-bearing bodies maps)	Disaster prevention and mitigation capacity (C) Temporal and spatial analysis of indicators (Disaster prevention and mitigation capacity maps) Sensitivity of disaster-forming environment (S) Temporal and spatial analysis of indicators (Sensitivity maps of the disaster-forming environment)	Fuzzy comprehensive, exponentiated multiplication of indices (Risk level maps)	Index-based	Weights are calculated using the optimal combination weighting method
(Ye et al., 2022)	livestock snow disaster	$R = \mathrm{H} \times \mathrm{V} \times \mathrm{E}$	Boosted regression tree model (time series of snow-disaster-day probabilities based on historical data) Numerical simulation (Projected time series of snow-disaster-day probabilities)	Existing exposure results (gridded herd density distribution data)	Existing vulnerability model based on sum of indicators (-)		Bias-corrected climate data (The baseline and future periods of snow disaster event set in the different scenarios) Multiplication of risk element indices (Annual total mortality)	Hybrid: Statistical/simulation-based	
(Yin et al., 2011)	Rainstorm waterlogging	$R = f(H, V, E)$	GIS spatial analysis, numerical hydrology simulation (inundation depth maps for different scenarios)	GIS spatial analysis (Exposure maps of building contents for different return periods)	Analysis of loss data/average replacement values of waterlogging from field surveys and interviews (Stage-damage curves for residential buildings and contents)		Overlaying risk elements (Exceedance probability curve, a risk curve and an average annual waterlogging loss)	Simulation-based	

(Zarghami & Dumrak, 2021)	Bushfire	$R = f(H, V)$	Pre-existing hazard analysis (Forest fire danger index)		Weighted sum of dynamically simulated vulnerability indicators (changes of indicators and total vulnerability over time)		Multiplication of hazard and vulnerability (Risk indexes for different danger categories in different points in time)	Hybrid: Simulation-based/index-based	The focus of the study is on social vulnerability assessment Weights for the social vulnerability are identified using AHP
(Zhang et al., 2021)	Earthquake	$R = f(H, V, E)$	China probabilistic seismic hazard assessment and deterministic seismic hazard analysis (Mapping of peak ground acceleration (PGA) and spectral acceleration (Sa)	Census data, remote sensing, GIS spatial analysis (Building inventory and typology)	Incremental dynamic analyses (Fragility curves for structures)		Overlaying hazard, exposure, and vulnerability (Probabilistic physical damage of an individual building, direct economic loss and casualties)	Hybrid: Statistical/simulation	

Appendix B: Indicators of risk elements and sources of data

Table B1 - Hazard indicators used in the selected studies and corresponding sources of data.

Hazard type	Factors/indicators	Study: Data source
Flood	Annual precipitation	(Sun et al., 2022): National Meteorological Administration [China] (Guo et al., 2014): China Meteorological Data Sharing Service Network during 1960–2009 (Luo et al., 2020): Henan Water Resource Bulletin [China]
	Frequency of rainstorm	(Sun et al., 2022): National Meteorological Administration [China]
	Vegetation coverage	(Sun et al., 2022): Bulletin of the first geographical survey of Shanghai and Jiangsu, Zhejiang, and Anhui (Guo et al., 2014): Cold and Arid Regions Science Data and Database of Global Change Parameters, Chinese Academy of Sciences
	Drainage density	(Sun et al., 2022): Bulletin of the first geographical survey of Shanghai and Jiangsu, Zhejiang, and Anhui [China] (Guo et al., 2014): STRM system of digital elevation model data; Cold and Arid Regions Science Data of Global Change Parameters, Chinese Academy of Sciences
	Inundation depth	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Inundation area	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Inundation duration	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Extreme precipitation event frequency	(Guo et al., 2014): China Meteorological Data Sharing Service Network during 1960–2009
	Altitude	(Guo et al., 2014): Shuttle Radar Topography Mission (STRM) system of digital elevation model data
	Elevation standard deviation	(Guo et al., 2014): Shuttle Radar Topography Mission (STRM) system of digital elevation model data
	Extreme rainfall in the main flood season	(Wu et al., 2017; Wu et al., 2015)
	Elevation	(Wu et al., 2017; Wu et al., 2015): Geospatial Data Cloud
	Slope	(Wu et al., 2017; Wu et al., 2015): Geospatial Data Cloud
	Terrain slope	(Wu et al., 2017; Wu et al., 2015): Geospatial Data Cloud
	Drainage density	(Wu et al., 2017; Wu et al., 2015): Geospatial Data Cloud
	Reservoir storage modules	(Wu et al., 2017; Wu et al., 2015): Geospatial Data Cloud
	Flood detention basin modulus	(Wu et al., 2017; Wu et al., 2015): Huaihe River Commission of the Ministry of Water Resources [China]
	Daily average flow discharge	(Ming et al., 2022): The UK National River Flow Archive
	Daily rainfall	(Ming et al., 2022): The Centre for Environmental Data Analysis
	Daily maximum surge	(Ming et al., 2022): The British Oceanographic Data Centre
	Flood submergence depth	(Y. Liu et al., 2015): Field investigation; Survey
	Average annual rainfall	(Pan et al., 2020): Santai County Chronicles, Santai County Statistical Yearbook, Santai County Statistical Bulletin, etc. [China]
Storm flood	Extreme values of daily	(Y. Liu et al., 2021): Flood event database Xinjiang [China]

	precipitation	
	Monthly average precipitation extremes,	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
	Days with daily precipitation ≥25 mm extremes	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
	Elevations and coefficients of variation	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
	Relative elevation	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
	Slope	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
	Runoff curves (curve number)	(Y. Liu et al., 2021): Flood event database Xinjiang [China]
Glacial lake outburst flood	Type of glacial lake	(Dwivedi et al., 2022): Field investigations, records of previous occasions, etc.; Previous work
	Lake volume and maximum possible discharge	(Dwivedi et al., 2022): Field investigations, records of previous occasions, etc.; Previous work
	Distance from mother glacier	(Dwivedi et al., 2022): Field investigations, records of previous occasions, etc.; Previous work
	Slope of the associated terrain	(Dwivedi et al., 2022): Field investigations, records of previous occasions, etc.; Previous work
	Number of potentially dangerous glacial lakes (PDGL)	(S. Wang et al., 2020): Landsat imagery, topographic maps, ASTER digital elevation map
	PDGLs area	(S. Wang et al., 2020): Landsat imagery, topographic maps, ASTER digital elevation map
	Area change of PDGLs	(S. Wang et al., 2020): Landsat imagery, topographic maps, ASTER digital elevation map
Rainfall induced flash flood	Rainfall	(Dwivedi et al., 2022): Central Groundwater Board [India]
	Slope	(Dwivedi et al., 2022): Remote sensing; Previous work
	Distance to river stream	(Dwivedi et al., 2022): Remote sensing; Previous work
	Landslide susceptibility	(Dwivedi et al., 2022): Remote sensing; Previous work
	Elevation	(Dwivedi et al., 2022): Remote sensing; Previous work
Rainfall induced flash flood	Rainfall	(Dwivedi et al., 2022): Central Groundwater Board [India]
	Slope	(Dwivedi et al., 2022): Remote sensing; Previous work
	Distance to river stream	(Dwivedi et al., 2022): Remote sensing; Previous work
	Landslide susceptibility	(Dwivedi et al., 2022): Remote sensing; Previous work
	Elevation	(Dwivedi et al., 2022): Remote sensing; Previous work
Earthquake	Earthquake ground motion intensity	(Brink & Davidson, 2015): Monte Carlo simulation with importance sampling on results of previous works
	Occurrence probability	(Brink & Davidson, 2015): Monte Carlo simulation with importance sampling on results of previous works (Sarica et al., 2020): U.S. Geological Survey Database
	Magnitude of Earthquake	(Pan et al., 2020): Santai County Statistical Yearbook; Santai County Statistical Bulletin; Random sampling to assess the local earthquake losses (Sherrill et al., 2022): Deterministic counterfactual scenario
	Peak ground acceleration	(Xia et al., 2022): China Earthquake Parameter Zoning Map (Sarica et al., 2020): U.S. Geological Survey Database (Zhang et al., 2021): Earthquake Catalog; Tectonics and Geology data
	Spectral acceleration	(Zhang et al., 2021): Bore-hole data; Digital Elevation Model
	Earthquake location	(Sherrill et al., 2022): Deterministic counterfactual scenario
	Earthquake source type	(Sherrill et al., 2022): Deterministic counterfactual scenario
	Depth of Earthquake	(Sherrill et al., 2022): Deterministic counterfactual scenario
	Wave propagation characteristics	(Sherrill et al., 2022): Deterministic counterfactual scenario
Drought	Historical drought frequency	(Q. Chen et al., 2019): China meteorological data service center; China's meteorological disaster books (Tibet Volume); Meteorological Bureau of Tibet Autonomous Region
	Historical drought intensity	(Q. Chen et al., 2019): China meteorological data service center; China's meteorological disaster books (Tibet Volume);

		Meteorological Bureau of Tibet Autonomous Region
	Annual mean precipitation	(Q. Chen et al., 2019): China meteorological data service center; China's meteorological disaster books (Tibet Volume); Meteorological Bureau of Tibet Autonomous Region
	Annual mean temperature	(Luo et al., 2020): Henan Water Resource Bulletin [China] (Q. Chen et al., 2019): China meteorological data service center; China's meteorological disaster books (Tibet Volume); Meteorological Bureau of Tibet Autonomous Region
	Average runoff depth	(Q. Chen et al., 2019): China meteorological data service center; China's meteorological disaster books (Tibet Volume); Meteorological Bureau of Tibet Autonomous Region
	Precipitation	(X. Liu et al., 2021): Hydrological stations Heilongjiang Province [China]; Heilongjiang Province Water Resources Bulletin; Field data (Sun et al., 2015): China Meteorological Data Sharing Service System (Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Soil moisture content	(X. Liu et al., 2021): Soil moisture stations Heilongjiang Province [China]
	Sunshine	(Sun et al., 2015): China Meteorological Data Sharing Service System
	Maximum temperature	(Sun et al., 2015): China Meteorological Data Sharing Service System
	Minimum temperature	(Sun et al., 2015): China Meteorological Data Sharing Service System
	Wind speed	(Sun et al., 2015): China Meteorological Data Sharing Service System (Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Relative humidity	(Sun et al., 2015): China Meteorological Data Sharing Service System (Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Temperature	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Groundwater resources	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Surface runoff	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Slope	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Drought severity	(Nepal et al., 2021): Remote sensing (Earth explorer and The United States Geological Survey)
	Total water resources	(Luo et al., 2020): Henan Water Resource Bulletin [China]
Waterlogging	Slope	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Elevation	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	River density	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Plant coverage	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Precipitation	(Sun et al., 2014): Unspecified – "statistical offices and remote sensing"
	Total rainfall	(Yin et al., 2011): Unspecified – Administrative boundary data of Shanghai, census data of Shanghai,
	Catchment characteristics	(Yin et al., 2011): National Engineering Handbook [China]; Previous studies
	Drainage	(Yin et al., 2011): Assumption
	Catchment area	(Yin et al., 2011): Unspecified – Land use and land cover maps of Shanghai, topographic contours of Shanghai

Erosion	Rainfall erosivity	(Nepal et al., 2021): Remote sensing (Earth explorer and The United States Geological Survey)
	Soil erodibility	(Nepal et al., 2021): Remote sensing (Earth explorer and The United States Geological Survey)
	Slope length	(Nepal et al., 2021): Remote sensing (Earth explorer and The United States Geological Survey)
	Slope steepness	(Nepal et al., 2021): Remote sensing (Earth explorer and The United States Geological Survey)
Rainstorm	The rainstorm volume	(Li et al., 2020): Chinese Meteorological Date Service Center
	Number of rainstorm days	(Li et al., 2020): Chinese Meteorological Date Service Center
	Rainstorm intensity	(Li et al., 2020): Chinese Meteorological Date Service Center
	Rainstorm contribution rate	(Li et al., 2020): Chinese Meteorological Date Service Center
Storm surge	Typhoon track	(Xianwu et al., 2020): Shanghai Typhoon Institute, China Meteorological Administration
	Typhoon intensity	(Xianwu et al., 2020): Shanghai Typhoon Institute, China Meteorological Administration
	Radius of maximum wind	(Xianwu et al., 2020): Shanghai Typhoon Institute, China Meteorological Administration
	Surge and water level	(Xianwu et al., 2020): East China Sea Marine Forecasting Center, Oceanic Administration of China
	Submarine topography	(Xianwu et al., 2020): Surveying and Mapping Bureau of Shanghai
Agricultural disaster		
	Precipitation	(Wang et al., 2016): China Meteorological Administration
	Temperature	(Wang et al., 2016): China Meteorological Administration
	Precipitation anomaly	(Wang et al., 2016): China Meteorological Administration
	Temperature anomaly	(Wang et al., 2016): China Meteorological Administration
Dust storm	500-hPa atmospheric longitudinal circulation index	(X. Liu et al., 2015): Geopotential Height Grid Data of China Meteorological Administration
	Maximum wind speed in the 10m high near ground	(X. Liu et al., 2015): China Meteorological Data Sharing Service System; National Meteorological Information Center [China]; Inner Mongolia Meteorological Bureau
	Surface soil moisture	(X. Liu et al., 2015): Xilingaole Meteorological Station [China]; Wushenzhao Meteorological Station [China]; Xianghuangqi Meteorological Station [China]
Debris flows	Types of rocks	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
	Ratios of potential collapse areas	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
	Accumulated rainfalls	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
	Areas of effective watersheds	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
	Average slopes of riverbeds	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
	Volumes of sediments of debris flows	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
	Areas of deposition regions	(Chiou et al., 2015): Not specified - Various governmental agencies and ArcGIS
Lightning	Cloud-to-ground lightning density	(Jin et al., 2022): The Jiangsu ADTD-II lightning positioning system [China]
	Cloud-to-ground lightning current density	(Jin et al., 2022): The Jiangsu ADTD-II lightning positioning system [China]
	Thunderstorm days	(Jin et al., 2022): The Jiangsu ADTD-II lightning positioning system [China]
Late frost of open-air grape	Temperature (Min, Max, Avg)	(W. Liu et al., 2021): China Meteorological Data Sharing Network
	Sunshine duration	(W. Liu et al., 2021): China Meteorological Data Sharing Network
	Wind speed	(W. Liu et al., 2021): China Meteorological Data Sharing

		Network
Rice crop heat injury	Temperature (Min, Max, Avg)	(Meng et al., 2016): National Meteorological Information Center, China Meteorological Administration
Tsunamis	The hazard factors are not discussed directly	(Taubenböck et al., 2009): I suggest we remove such studies from this table.
Aeolian disaster	Drift potential	(Yang et al., 2021): European Centre for Medium-Range Weather Forecasts; Desert Meteorology, China Meteorological Administration, Urumqi; Geospatial Data Cloud; Cold and Arid Regions Sciences Data Center [China]
	Dust event index	(Yang et al., 2021): European Centre for Medium-Range Weather Forecasts; Desert Meteorology, China Meteorological Administration, Urumqi; Geospatial Data Cloud; Cold and Arid Regions Sciences Data Center [China]
	Distance from sand source	(Yang et al., 2021): European Centre for Medium-Range Weather Forecasts; Desert Meteorology, China Meteorological Administration, Urumqi; Geospatial Data Cloud; Cold and Arid Regions Sciences Data Center [China]
Livestock snow disaster	Daily precipitation	(Ye et al., 2022): NASA Earth Exchange/Global Downscaled Projections; Previous work
	Temperature	(Ye et al., 2022): NASA Earth Exchange/Global Downscaled Projections; Previous work
	Wind speed	(Ye et al., 2022): Coupled Model Intercomparison Project; Previous work
Unspecified multi-hazard	Frequency	(N. Chen et al., 2019): The national bureau of statistics database and official yearbook [China]
	Number of missing	(N. Chen et al., 2019): The national bureau of statistics database and official yearbook [China]
	Direct economic losses	(N. Chen et al., 2019): The national bureau of statistics database and official yearbook [China]
	Number of collapsed houses	(N. Chen et al., 2019): The national bureau of statistics database and official yearbook [China]
	Area of damaged crops	(N. Chen et al., 2019): The national bureau of statistics database and official yearbook [China]

Table B2 - Exposure indicators used in the selected studies and corresponding sources of data.

Disaster	Factors/indicators	Study: Data source
Flood	Urbanization rate	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
	Population density	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics) (Guo et al., 2014): Statistical Yearbook of Liaoning Province; Chinese macro data mining analysis system website
	Building density	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
	Economic density	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
	Ground elevation	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Ground slope	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Impermeability	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Assets density	(Guo et al., 2014): Statistical Yearbook of Liaoning Province; Chinese macro data mining analysis system website
	Economy density	(Guo et al., 2014): Statistical Yearbook of Liaoning Province; Chinese macro data mining analysis system website
	Number/value of exposed	(Ming et al., 2022): National property database; Digimap service

	properties	
Earthquake	Built-up area	(Sarica et al., 2020): Landsat TM images; digital elevation models (DEM); OpenStreetMap (OSM) data; land-use maps; local historical road network maps
	Population	(Xia et al., 2022): World pop project (Sherrill et al., 2022): Census data, employment data, proprietary insurance data, expert opinion, and tax records (Internal to Hazus model)
	Building inventory	(Zhang et al., 2021): Census data; statistical reports; field investigation (Sherrill et al., 2022): Census data, employment data, proprietary insurance data, expert opinion, and tax records (Internal to Hazus model)
Drought	Crop planting area	(X. Liu et al., 2021): Statistical yearbook; County (city) rural economic and social statistics summary [Heilongjiang Province, China] (Guo et al., 2021): Earth Stat; Literature (Sun et al., 2015): Digitized soil data (Jilin soil Chi)
	Yield per unit area	(X. Liu et al., 2021): Statistical yearbook; County (city) rural economic and social statistics summary [Heilongjiang Province, China] (Sun et al., 2015): Digitized soil data (Jilin soil Chi)
	Number of animals per unit area/cultivated area	(Q. Chen et al., 2019): Tibet statistical yearbooks [China]; Basic map database of China
	Population density	(Q. Chen et al., 2019): Tibet statistical yearbooks [China]; Basic map database of China (Luo et al., 2020): Henan Statistical Yearbook (Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Proportion of agricultural output/Proportion of animal husbandry output	(Q. Chen et al., 2019): Tibet statistical yearbooks [China]; Basic map database of China
	Per capita arable land area	(Luo et al., 2020): Henan Statistical Yearbook
	Agricultural GDP/GDP	(Luo et al., 2020): Henan Statistical Yearbook
	Normalized Difference Vegetation Index	(Nepal et al., 2021): LANDSAT 8 OLI/TIRS
	Plant coverage (%)	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Gross output value of agriculture	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Gross industrial output value	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
Waterlogging	Population density	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing” (Yin et al., 2011): Census data of Shanghai [China]
	Cultivated area	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Number of industrial enterprises	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	residential building footprint	(Yin et al., 2011): Manual visual interpreting from aerial photographs
Rainstorm	Population density	(Li et al., 2020): National Earth System Science Data Sharing Infrastructure (National Science and Technology Infrastructure of China)
Debris flow	Distances between communities and affected areas	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
	Distances between evacuation shelters and affected areas	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
	Ratios of evacuation route lengths in the affected areas	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
Rice crop heat injury	Ratio of planting area of single-cropping rice	(Meng et al., 2016): Provincial statistical yearbooks of various provinces [China]
	Agricultural acreage	(Meng et al., 2016): Provincial statistical yearbooks of various provinces [China]
Glacier lake outburst flood	Population density	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
	Livestock density	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
	Cultivated area	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
	Density of road network	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]

	Density of agricultural economy	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
Livestock snow disaster	Herd size exposed to snow disasters	(Ye et al., 2022): Previous work
Multi-hazard: Landslides, floods, earthquakes, and volcanic eruptions	Sales and capital stock of firms	(Marin et al., 2021): Italian Business Registry; national accounts; previous work
	Market values of residential buildings	(Marin et al., 2021): Osservatorio Mercato Immobiliare (OMI)

Table B3 - Vulnerability indicators used in the selected studies and corresponding sources of data.

Disaster	Factors/indicators	Study: Data source
Flood	Old and young population per unit area	(Sun et al., 2022): China Statistical Yearbook (China National Bureau of Statistics)
	Proportion of crop – sown area	(Sun et al., 2022): China Statistical Yearbook (China National Bureau of Statistics)
	Building density	(Cai et al., 2019): Not specified; Internal to DigitalWater Simulation hydrodynamic model
	Points of interest density	(Cai et al., 2019): Baidu map
	Proportion of male and female	(Guo et al., 2014): Statistical Yearbook of Liaoning Province [China] ; Chinese macro data mining analysis system website
	Education level	(Guo et al., 2014): Statistical Yearbook of Liaoning Province [China] ; Chinese macro data mining analysis system website
	Proportion of industrial electricity	(Guo et al., 2014): Statistical Yearbook of Liaoning Province [China] ; Chinese macro data mining analysis system website
	Waterlogged farmland	(Guo et al., 2014): Statistical Yearbook of Liaoning Province [China] ; Chinese macro data mining analysis system website
	Population	(Wu et al., 2017; Wu et al., 2015): Department of Comprehensive Statistics (National Bureau of Statistics [China])
	GDP	(Wu et al., 2017; Wu et al., 2015): Department of Comprehensive Statistics (National Bureau of Statistics [China])
	Sown area of farm crops	(Wu et al., 2017; Wu et al., 2015): Department of Comprehensive Statistics (National Bureau of Statistics [China])
	Socio-economic status	(Ebert et al., 2009): Maps and remote sensing data
	Commercial and industrial development	(Ebert et al., 2009): Maps and remote sensing data
	Distance to lifelines	(Ebert et al., 2009): Maps and remote sensing data
	Flood loss rate	(Y. Liu et al., 2015): Statistical data; field survey
	functions against inundation depth	(Ming et al., 2022): Previous work
Storm flood	Population per square kilometre	(Y. Liu et al., 2021): National Science and Technology Infrastructure (National Earth System Science Data Center [China])
	Cultivated land area	(Y. Liu et al., 2021): National Science and Technology Infrastructure (National Earth System Science Data Center [China])
	GDP	(Y. Liu et al., 2021): National Science and Technology Infrastructure (National Earth System Science Data Center [China])
	Distance from rivers	(Y. Liu et al., 2021): National Science and Technology Infrastructure (National Earth System Science Data Center [China])
	Road network density	(Y. Liu et al., 2021): National Science and Technology Infrastructure (National Earth System Science Data Center [China])
Glacial lake outburst flood	Proportion of rural population	(S. Wang et al., 2020): Statistical Yearbooks of various counties [China]
	Percentage of small livestock	(S. Wang et al., 2020): Statistical Yearbooks of various counties [China]
	Road level	(S. Wang et al., 2020): Statistical Yearbooks of various counties [China]
	Building level	(S. Wang et al., 2020): Statistical Yearbooks of various counties [China]
Earthquake	Building fragility	(Brink & Davidson, 2015): Institut Teknologi Bandung; Geoscience

		Australia; Previous work (Sherrill et al., 2022): Internal to Hazus model
	Mortality rate	(Xia et al., 2022): Previous work
Drought	Dry land proportion/Grassland proportion	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Grain yield/ Proportion of large domestic animals	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Per-capita net income of farmers and herdsmen	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Per cultivated area/Per grassland area	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Grain output per capita/Livestock per capita	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Average cultural level of farmers and herdsmen	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Topographic relief	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Government emergency management capability	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Meteorological station density	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Engineering disaster prevention ability	(Q. Chen et al., 2019): Tibet statistical yearbooks; Basic map database of China; Literature
	Total power of agricultural machinery	(X. Liu et al., 2021): Statistical yearbook; County (city) rural economic and social statistics summary; Local standard water quota [Heilongjiang Province, China]
	Amount of fertilizers affecting grain yield	(X. Liu et al., 2021): Statistical yearbook; County (city) rural economic and social statistics summary; Local standard water quota [Heilongjiang Province, China]
	Per capita water consumption	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Vulnerable population	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Proportion of easy-drought farmland	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Water consumption per unit of GDP	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Impacts of drought and erosion on livelihoods	(Nepal et al., 2021): Semi-structured questionnaire interviews; Focus group discussions
Rainstorm	GDP per land area	(Li et al., 2020): National Earth System Science Data Sharing Infrastructure (National Science and Technology Infrastructure of China)
	People’s vulnerability	(Yin et al., 2011): Based on mortality function (Literature)
	Stage-damage curves	(Yin et al., 2011): Field survey
Storm surge	Land use	(Xianwu et al., 2020): Land and Resources Bureau of Shanghai
	Important exposure (e.g., hospitals, schools)	(Xianwu et al., 2020): Land and Resources Bureau of Shanghai
Volcano	Number of buildings	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Building density	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Buffer affected area	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Availability of EWS	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Evacuation route	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Sabo DAM	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Altitude	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Affected area to lahar	(Hizbaron et al., 2018): Satellite images; Records from government

		institutions; Field observation; Questionnaire
	Total population	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Population density	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Disabled population	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Youth population (children under five)	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Elderly people	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Miners	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Poor Households	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Farmers or people working in the agricultural sector	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
	Agricultural land	(Hizbaron et al., 2018): Satellite images; Records from government institutions; Field observation; Questionnaire
Rice crop heat injury	Degree of sensitivity of single-cropping rice to disaster	(Meng et al., 2016): National Meteorological Information Center (China Meteorological Administration); Grand Collection of China Meteorological Disasters; Statistical yearbooks
	Adaptability of the single-cropping rice growth period to external changes	(Meng et al., 2016): National Meteorological Information Center (China Meteorological Administration); Grand Collection of China Meteorological Disasters; Statistical yearbooks
	Adaptability of the farmland ecosystem	(Meng et al., 2016): National Meteorological Information Center (China Meteorological Administration); Grand Collection of China Meteorological Disasters; Statistical yearbooks
Aeolian disaster	Population density	Resource and Environment Data Cloud Platform [China]
	GDP density	Resource and Environment Data Cloud Platform [China]
	Land-use types	Resource and Environment Data Cloud Platform [China]
	Livestock density	Chinese Academy of Sciences (Xinjiang Branch)
Livestock snow disaster	GDP	Statistical yearbooks of various counties [China]
Bushfire	Low-income family members	(Zarghami & Dumrak, 2021): Australian Bureau of Statistics; Official website of the Government of South Australia; Additional public data source
	Culturally and linguistically diverse backgrounds	(Zarghami & Dumrak, 2021): Australian Bureau of Statistics; Official website of the Government of South Australia; Additional public data source
	Elderly population (Age≥ 65)	(Zarghami & Dumrak, 2021): Australian Bureau of Statistics; Official website of the Government of South Australia; Additional public data source
	Children population (Age≤ 4)	(Zarghami & Dumrak, 2021): Australian Bureau of Statistics; Official website of the Government of South Australia; Additional public data source
	Disability population (4 < Age<65)	(Zarghami & Dumrak, 2021): Australian Bureau of Statistics; Official website of the Government of South Australia; Additional public data source
Unspecified multi-hazard	Regional population	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Rural population density	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Urban population density	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Cultivated land	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Building density	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Number of medical & technical personnel per ten thousand residence	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook

	Number of medical beds per ten thousand people	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Original property insurance revenue	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Number of medical institutions	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Number of fire officers and soldiers for public	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Security Rescue equipment	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Total number of seismic stations	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Total number of automatic meteorological station	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Water amount per capita	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Sex ratio (per 100 female)	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Elderly population ratio	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Illiterate population more than 15 years old	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Local finance general budget expenditure	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Budget expenditure for disasters	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	GDP per capita	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Disposable income per capita	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
	Forest coverage	(N. Chen et al., 2019): The national bureau of statistics database; Official yearbook
Landslides, floods, earthquakes, and volcanic eruptions	Extension of agriculture	(Marin et al., 2021): Agricultural Census [Italy]
	Dependency on agriculture	(Marin et al., 2021): Agricultural Census [Italy]
	Age	(Marin et al., 2021): Population Census [Italy]
	Wealth	(Marin et al., 2021): Ministry of Economy and Finance [Italy]
	Poverty	(Marin et al., 2021): Population Census [Italy]
	Inequality	(Marin et al., 2021): Atlante Prin-Postmetropoli
	Unemployment	(Marin et al., 2021): Population Census [Italy]
	Institutional capacity	(Marin et al., 2021): Atlante Prin-Postmetropoli
	Political rights	(Marin et al., 2021): Ministry of Interior [Italy]
	Population pressure	(Marin et al., 2021): Population Census [Italy]
	Urbanisation	(Marin et al., 2021): ISPRA
	Building characteristics	(Marin et al., 2021): Atlante Prin-Postmetropoli
	Ecosystem conversion	(Marin et al., 2021): Agricultural Census [Italy]
	Education	(Marin et al., 2021): Population Census [Italy]
	Family structure	(Marin et al., 2021): Population Census [Italy]
	Female condition	(Marin et al., 2021): Population Census 2011 [Italy]
	Health	(Marin et al., 2021): Ministry of Health [Italy]

Table B4 - Indicators of other risk elements used in the selected studies and corresponding sources of data.

Risk element	Disaster	Factors/indicators	Study: Data source
Emergency and recovery	Flood	Number of health technicians (per 10,000	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)

capabilities		people)	
		Number of beds in medical institutions (per 10,000 people)	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
		Number of medical and health institutions	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
		GDP per capita	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
		Unemployment rate	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
		Proportion of illiterate population aged 15 and over	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
		General budget expenditure of local financing	(Sun et al., 2022): Statistical Yearbook (China National Bureau of Statistics)
Restorability	Flood	Density of road network	(Guo et al., 2014): Cold and Arid Regions Science Data Center at Lanzhou; Database of Global Change Parameters (Chinese Academy of Sciences)
		The per capita medical person	(Guo et al., 2014): Statistical Yearbook of Liaoning Province; Chinese macro data mining analysis system website
		Per capita GDP	(Guo et al., 2014): Statistical Yearbook of Liaoning Province; Chinese macro data mining analysis system website
	Drought	Effective irrigated area	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
		Average income	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
		Proportion of students	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
	Waterlogging	Resource allocation	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
		Action capability	(Sun et al., 2014): Unspecified – “statistical offices and remote sensing”
Household resilience	Earthquake	Income	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
		Wealth	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
		Individual fragility	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
		Education	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
		Access to information	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
		Household size	(Brink & Davidson, 2015): Indonesian government statistics bureau household survey; damage survey data collected after the 2009 Padang earthquake
The disaster prevention and mitigation capability	Drought	Water resources allocation	(X. Liu et al., 2021): Heilongjiang Province Water Resources Bulletin; Field research data
	Aeolian disaster	Planting area	(Yang et al., 2021): Chinese Academy of Sciences (Xinjiang Branch)
		Agriculture, forestry, and water affairs expenditure	(Yang et al., 2021): Chinese Academy of Sciences (Xinjiang Branch)
Drought resistance	Drought	Irrigation water supply rate	(Sun et al., 2015): Jilin Statistical Yearbook [China]

(capacity)		Agricultural machinery power per unit area	(Luo et al., 2020): Henan Statistical Yearbook [China]
		Per capita GDP	(Luo et al., 2020): Henan Statistical Yearbook [China]
		Rural per capita disposable income	(Luo et al., 2020): Henan Statistical Yearbook [China]
		Effective irrigation index	(Luo et al., 2020): Henan Water Conservancy Yearbook [China]
		Proportion of water saving irrigation area	(Luo et al., 2020): Henan Statistical Yearbook [China]
Mitigation	Debris flows	Existence of prevention constructions	(Chiou et al., 2015): Primary data collection (details not specified)
		Types of prevention constructions	(Chiou et al., 2015): Primary data collection (details not specified)
		Quantities of prevention constructions	(Chiou et al., 2015): Primary data collection (details not specified)
Resistance	Debris flows	Architectural types	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Architectural materials	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Used time of architecture	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Evacuation route lengths for walking	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Evacuation route lengths for driving	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Numbers of bridges in evacuation route	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
		Ratios of road type lengths	(Chiou et al., 2015): Not specified – Various governmental agencies and ArcGIS
	Landslides, floods, earthquakes, and volcanic eruptions	Density of business	(Marin et al., 2021): DB
		Wealth	(Marin et al., 2021): Ministry of Economy and Finance [Italy]
		Debt	(Marin et al., 2021): AIDA - PA
		Poverty	(Marin et al., 2021): Population Census
		Homeownership	(Marin et al., 2021): OMI - Fiscal Agency
		Unemployment	(Marin et al., 2021): Population Census
		Productivity	(Marin et al., 2021): Asia – Istat
		Sectorial dependence	(Marin et al., 2021): DB
		Government effectiveness	(Marin et al., 2021): AIDA - PA
		Institutional capacity	(Marin et al., 2021): Atlante PrinPostmetropoli
		Education	(Marin et al., 2021): Population Census
		Health	(Marin et al., 2021): Ministry of Health [Italy]
		Social capital	(Marin et al., 2021): Nannicini et al. 2013
Sensitivity of hazard-pregnant environment/ Sensitivity of disaster-forming environment	Lightning	Altitude	(Jin et al., 2022): Shuttle Radar Topography Mission
		Topographic relief	(Jin et al., 2022): Shuttle Radar Topography Mission
		Drainage density	(Jin et al., 2022): National Basic Geographic Information Center [China]
		Soil electric conductivity	(Jin et al., 2022): Harmonized World Soil Database
	Aeolian disaster	Relief amplitude	(Yang et al., 2021): Geospatial Data Cloud
		Vegetation coverage index	(Yang et al., 2021): Geospatial Data Cloud
		Soil moisture	(Yang et al., 2021): Geospatial Data Cloud
		Soil erodibility	(Yang et al., 2021): Geospatial Data Cloud
Frangibility of hazard-bearing body	Lightning	GDP per land area	(Jin et al., 2022): Resource and Environment Science and Data Center [China]
		Population density	(Jin et al., 2022): Resource and Environment Science and Data Center [China]

		Soil utilization type	(Jin et al., 2022): Resource and Environment Science and Data Center [China]
Adaptability	Glacier lake outburst	Regional GDP	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
		Financial revenue share of GDP	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]
		Density of fixed assets investment	(S. Wang et al., 2020): Statistical yearbooks of various counties [China]

Appendix C: Australian and international resources for community risk assessment

Table C1 - Australian examples of community risk assessment.

Title	Organisation	Date	Specific Hazard(s)	Description
Hawkesbury-Nepean Valley Flood Research	Infrastructure NSW	2022	Flood	Quantitative telephone survey to investigate community sentiment towards flood based on recent events
Community Engagement for Disaster Resilience	Australian Institute for Disaster Resilience (AIDR)	2020		High-level guidance to support those who engage with communities in disaster prevention, preparedness, response and recovery; Principles, approaches and core elements of effective community engagement before, during or after an event
Practitioner's Guide: Understanding and addressing challenges in community engagement	Australian Institute for Disaster Resilience (AIDR)	2020		Practical advice to identify and address potential challenges in the process of community engagement (Companion to Community Engagement for Disaster Resilience)
National Emergency Risk Assessment Guidelines	Australian Institute for Disaster Resilience (AIDR)	2020		A method for undertaking emergency risk assessments, including their preparation, conduct and outputs; a guide for a nationally consistent approach to assessing emergency risks
Community Emergency Risk Assessment	Victoria State Emergency Service (VICSES)	2016-2017		A framework provided by VICSES to be used by Municipal Emergency Management Planning Committees (MEMPCs) for considering and improving the safety and resilience of their community before, during and after emergency events; The core process is based on two facilitated Community Emergency Risk Assessment (CERA) sessions. The outputs are heat maps and residual risk tables as well as a dashboard view of risk ratings for different hazards.
Developing Community Profiles for Community Engagement	Country Fire Authority	2022	Bushfire	Literature review of the existing theories, methods, and factors relevant to understanding the demographic composition, needs, strengths and vulnerabilities of communities against bushfire hazard

Mapping Approaches to Community Engagement for Preparedness in Australia	Bushfire and Natural Hazards CRC	2019		A mapping of the community engagement for preparedness approaches currently used by Australian agencies; A framework to guide and support community engagement activities by end-users and agencies ; Toolkits for grass root level implementation of the framework (Community Engagement Toolkit and Monitoring, Evaluation and Learning (MEL) Toolkit)
Emergency risks in Victoria	State Crisis and Resilience Council (SCRC)	2020		A risk register containing information about Victoria's significant emergency-related risks, including a comparison of their severity, and the institutional arrangements in place to manage these risks
Resilient Communities Framework	Minderoo Foundation	2022		A holistic framework to catalyse and influence disaster resilience strategy, policy, practice and evaluation across Australia and internationally; Sets out a series of principles for resilient communities (e.g., Community-Led Approaches and Inclusive Engagement) with respect to various environments (e.g., Social, Cultural, and Economic); Proposes qualitative tools to facilitate conversation and community engagement within the framework (Assessment and Prioritisation Tool and Initiative Enhancement Tool)
Risk Assessment Process Handbook	Queensland Fire and Emergency Services	2018		A probabilistic risk assessment methodology to be used within disaster management planning at all levels of Queensland's Disaster Management Arrangements (QDMA) – Local, District and State; Details risk identification (based on hazard, exposure, vulnerability) and risk overall risk level assignment (based on likelihood, vulnerability, consequence); The outputs are risk assessment tables, risk register, and decision log.
Systemic Disaster Risk	Australian Institute for Disaster Resilience (AIDR)	2021		A set of guidelines and principles to promote a shift from a hazard-by-hazard risk assessment to a systemic risk assessment approach to capture complex interdependencies of hazards, exposures, and vulnerabilities
People at Increased Risk in an Emergency	State Emergency Management Committee (Tasmanian Government)	2019		A guide to determine emergency risk profiles, develop strategies and discuss and apply emergency plans with a focus on people at increased risk; Divides clients into resilience categories based on the interaction of susceptibility and protective factors; Proposes a set of example questions for community service providers to initiate conversation about emergency planning and preparedness with clients.
Queensland State Disaster Management Plan	Queensland Disaster Management Committee	2023		Framework, arrangements and practices to enable disaster management in Queensland including guidance for disaster management stakeholders through the provision of commentary and directions to supporting documents such as plans, strategies or guidelines
Insights Report	Mental Health Commission of NSW, NSW Council of Social Service, and University of Canberra	2021	Drought, flood, bushfire, COVID-19	Insights report on case studies of community risk assessment in five local government areas across NSW; Data collected through a review of the available literature; semi-structured interviews with people across five local government areas; community workshops and co-design workshops
Bega Valley local government area (LGA) case study	Mental Health Commission of NSW, NSW Council of Social Service, and University	2021	Drought, flood, bushfire, COVID-19	Case study findings regarding available community assets, barriers to utilisation of community assets in recovery and resilience, enablers of utilisation of community assets in recovery and resilience, and community perceptions of good community recovery and resilience; Data collected via individual interviews and a subsequent workshop.

community findings	of Canberra			
Workbook for Community-based Organisations	Mental Health Commission of NSW, NSW Council of Social Service, and University of Canberra	2021		Worksheets designed for local organisations to help plan and prepare for their roles in disaster recovery
Tasmanian Disaster Risk Assessment	Tasmanian Government	2022		Explores the quick-onset disaster risks that might impact Tasmania, assesses the state's exposure to these disasters, analyses vulnerabilities and capabilities that increase or decrease the risks; Sets out definitions, explores example scenarios, and introduces methods and tools e.g., Cross-hazard likelihood and consequence matrix
Tasmanian Emergency Risk Assessment Guidelines	Department of Police, Fire and Emergency Management	2017		Guidelines for users to undertake consistent risk assessments and design strategies and programs to treat the priority risks that they own; Risk assessment through facilitated workshop environment attended by relevant stakeholders
Tasmanian Emergency Risk Assessment Guidelines – Tables and Templates	Department of Police, Fire and Emergency Management	2017		Criteria tables, Templates, etc. to assist with the activities in the Tasmanian Emergency Risk Assessment Guidelines
Community Disaster Resilience Scorecard Toolkit	Torrens Resilience Institute	2015		A toolkit for communities to self-assess their potential resilience and to develop a springboard for an action plan to strengthen resilience; Scorecards, mostly composed of multiple-choice questions, to be completed in group meetings by members of the community;

#	Title	Organisation	Context	Date	Description
1	A Facilitator's Guide to Community Risk Assessment and Risk Reduction Action Plan	Ministry of food and disaster management	Bangladesh		Outlines a general description of community risk assessment together with a detailed guide to activities to be employed in a community risk assessment process (Transect walks, social mapping, Hazard Venn, interviews, workshops, etc.)
2	Child-Centred Multi-Risk Assessment	Plan International	Myanmar (Pilot)	2018	Guidelines on planning and implementation of child-centred multi-risk assessment together with a set of tools to engage the children, youths, and adults in the risk assessment process (e.g., Risk and

	Guide				resource mapping (Risk and resource mapping, Action planning, Seasonal calendar, Transect walk, etc.)
3	UNICEF Guidance on Risk-Informed Programming	UNICEF		2018	Guidelines on risk-informed child-centred programming to strengthen resilience to shocks and stresses by identifying and addressing the root causes and drivers of risk, including vulnerabilities, lack of capacity, and exposure to various shocks and stresses; Introduces flexible, participatory-style GRIP workshops
5	Risk Assessment: Guidance for CDEM Group Planning	National Emergency Management Agency	New Zealand	2022	Guidelines to support civil defence emergency management (CDEM Group) to undertake an informed and robust risk assessment, using nationally consistent methods, as part of CDEM Group planning processes; Guidelines on how to prepare and run risk assessment workshops and using tools such as consequence table
5	A Guide to Local Climate Change Risk Assessments	Ministry for the Environment	New Zealand	2021	A guide for local government representatives to lead and implement local climate change risk assessment in partnership with local iwi/Māori on behalf of communities; Provides guidance on project team formation and governance, stakeholder engagement, and risk assessment using various tools (vulnerability and risk matrices, surveys, workshops, etc.)
6	WASH Climate Resilient Development	UNICEF			A guide to support national workshops in developing draft programmes, strategies and plans for climate resilient development of water supplies and sanitation facilities mostly focusing on rural settings; provides procedures to identify hazards, exposures, vulnerabilities, and capacities and assess risk and confidence scores;
7	All Hazards Risk Assessment Methodology Guidelines	Public Safety Canada	Canada	2012-2013	A process to produce a whole-of-government risk picture to support emergency management planning across federal government institutions in Canada; Sets out the objectives, required inputs, and expected tasks involved in risk identification, analysis, evaluation, and treatment; Suggest various tools such as SWOT and PESTLE analysis, risk event scenario description, and economic category assessment tool;
8	Framework on Community Based Disaster Risk Management in Vietnam	Centre for International Studies and Cooperation	Vietnam		A framework for orientation and reference of community-based disaster risk management practitioners at national and provincial level in Vietnam; Sets out the principles and proposes steps and tools (e.g., historical profile, hazard and seasonal calendar, transect walks, problem tree, vulnerability and risk assessment matrix)
9	National Disaster Risk Assessment	United Nations Office for Disaster Risk Reduction		2017	Provides guidelines for preparing and scoping, conducting, and utilising the results of national disaster risk assessment in support of the Sendai Framework for Disaster Risk Reduction 2015-2030;
10	Child Inclusive Community Risk Assessment	DIPECHO Partners in Bangladesh (DPB)	Bangladesh		A combination of approach, process, tools and method to address the risk at the local level with a focus on children; Introduces tools to be employed in a community risk assessment process (Transect walks, social mapping, Hazard Venn, interviews, workshops, etc.)
11	Community Risk Assessment	Pflugerville Fire Department	United States	2018	Reports the results of a community risk assessment for Travis County, Texas, US; Using a variety of data sources e.g., US Census data, call data, and data gathers from other stakeholders, different community profiles such as hazard and response profiles are generated;

12	City of Brantford Community Risk Assessment	Dillon Consulting	Canada	2019	Final report on the community risk assessment of City of Brantford, Ontario, Canada; Using various sources of data such as Statistics Canada, Municipal Property Assessment Corporation (M.P.A.C.) data, O.F.M.E.M. Standard Incident Reporting, data provided by the Brantford Fire Department (B.F.D.) and desktop research various community profiles are generated and analysed e.g., demographics profile, critical infrastructure profile, hazard profile; the outputs are presented as risk prioritisation and categorisation;