Appendices

[These appendices are under development]

List of Appendices

Appendix 1.0

Agenda Consultation and Development Process

Some steps in development of the Research Agenda (note that there are Terms of Reference for the groups established to help develop the agenda)

Table 1: An iterative process of "co-development"

Milestone	
1	The need for new IRDR Science plan identified (mid 2019).
2	Decision taken to develop an agenda with a much broader reach (end Sept 2019); international collaboration – the doc needs to guide the future form of IRDR and other strategic objectives.
3	Discussion with **IRDR, ISC and UNDRR on what this means and how to proceed.**
4	Establishment of an ad hoc group to guide the process (which becomes the **Core Group** with 19 members consisting of representatives of the ISC, UNDRR, the IRDR SC and IRDR ED and other IRDR and external members), and a sub-group within this as a "**Leadership Group**" to deal with the more day-to-day tasks.
5	Initial Consultations with views and input solicited from the **IRDR community** (this occurred on a number of occasions through 2020). The IRDR community includes the IRDR SC, IRDR IPO, the ICoEs and NCs.
6	Drafting of an outline by Qunli Han of the IRDR IPO.
7	Drafting of a *Guidance document* setting out aims, scope and principles. (Endorsed by CG May 2020). This development of this document was an iterative process with the IRDR SC & IPO and CG.
8	**Survey of IRDR Community & CG for input to the analysis** of the current status of DRR research (June 2020).
9	***Draft report/literature review*** on the current status of DRR published research (July 2020).
10	Drafting and consultations – further discussion on agenda scope and emphasis – meetings with UNDRR, IRDR and ISC.
11	Draft report/literature review circulated to the IRDR and CG and revised in two major iterations.
12	Establishment of the **Expert Review Group (ERG)** (consisting of the IRDR SC, IRDR ICoE's and National Committees, representatives of the STAGs,

	as well as a wide range of people from diverse backgrounds (science/knowledge, advocacy, funder, private sector) outside the IRDR community) – on going (second half 2020). This group provides input and commentary from a wide range of perspectives.
13	Initial work on an **Indigenous group** to help with agenda development.
14	***Individual discussions with CG members*** **to** solicit views and inputs (Sept-Oct 2020).
15	*Two meetings with the* ***45 ERG members in two workshops*** to discuss key questions on scope etc (DATE?).
16	Initial work on a **Private Sector group** to support development of the agenda.
17	*Zero order draft* (Dec 2020).
18	CG meeting and feedback (Dec-Jan 2020/21).
19	Redrafting on the basis of feedback and comments
20	ZOD v2 sent for review to Core Group February 2021
21	ZOD v2 discussed with feedback at IRDR SC meeting 30 March 2021
22	Research Agenda v3 prepared and sent to Leadership Group (Friday 9 April 2021)
23	Research Agenda v3 sent for ERG comment (Monday 12 April 2021)
24	ISC Landing Page goes live with Agenda v3 and survey to stakeholders (12 April 2021)
25	International Indigenous Caucus Consultation Meeting (14 April 2021)
26	Pre-Conference draft for the 2021 IRDR International Conference posted on the conference website: 1 June 2021
27	Conference Draft for the 2021 IRDR International Conference posted on the conference website: 7 June 2021. This is for review by the conference.
28	IRDR Conference (June 9 – 10 2021)

Appendix 2.0

Members of the Leadership, Core and Expert Review Groups

Table 1: Members of the Agenda Development Leadership Group

Member Name	Member Affiliations	Location
Ben Payne (Lead Scientific Officer)	UNDRR JCDR, Massey University	Wellington, New Zealand
John Handmer (Co-Chair)	RMIT IRDR Science Committee	Canberra, Australia
Coleen Vogel (Co-Chair)	University of the Witwatersrand	Johannesburg, South Africa
Anne-Sophie Stevance	ISC	Paris, France
Jenty Kirsch-Wood	UNDRR	Geneva, Switzerland
Qunli Han	IRDR IPO	Beijing, China
Fang Lian	IRDR IPO	Beijing, China
Michael Boyland	SEI TDDR	Bangkok, Thailand

Table 2: Members of the Agenda Development Core Group

Member Name	Member Affiliations	Location
Ben Payne	UNDRR Massey University	New Zealand
John Handmer	RMIT IRDR Science Committee	Australia
Coleen Vogel	University of the Witwatersrand	South Africa
Anne-Sophie Stevance	ISC	France
Jenty Kirsch-Wood	UNDRR	Switzerland
Qunli Han	IRDR IPO	China
Fang Lian	IRDR IPO	China
Michael Boyland	SEI TDDR	Thailand
Marc Gordon	UNDRR	Switzerland
Irina Zodrow	UNDRR	Switzerland
Wei-sen Li	IRDR Science Committee	China
Jana Sillmann	CICERO IRDR Science Committee	Norway
Alonso Brenes Torres	FLACSO IRDR Science Committee	Costa Rica
Riyanti Djalante	UNU-IAS IRDR Science Committee	Indonesia
Juanle Wang	UNESCO-IKCEST, WDS	China
Mahefasoa Randrianalijaona	Periperi U IRDR Science Committee	Madagascar
Mark Stafford Smith	CSIRO Land & Water	Australia
Joyce Coffee	ARISE network	USA
Chloe Demrovsky	ARISE and DRI International networks	USA
Huadong Guo	AIR-CAS	China

Table 3: Members of the Agenda Development Expert Review Group

Member Name	Member Affiliation	Location

Anne Bardsley	OECD-DRR group	
Jose Machare	WFEO-CDRM	
Jing Peng	WFEO-CEIT	
Rajib Shaw	STAG	
Xu Tang	INMHEWS, Fudan University	
JC Gaillard	University of Auckland	
Victor Galaz	SRC	
Markus Reichstein	Risk KAN	
Coleen Vogel	University of the Witwatersrand, Johannesburg	
Nathanial Matthews	Global Resilience Partnership	
Franziska Gaupp	IIASA	
Franz Gatzweiler	UHWB	
Virginia Jiménez Díaz	IRDR SC	
Virginia Murray	IRDR SC, PHE	
Mark Pelling	IRDR ICoE, King's College London	
Donna Mitzi Lagdameo	RCRC climate centre	
Zinta Zommers	IFRC Climate Center	
Gretchen Kalonji	Dean of Institute of Disaster Management and Reconstruction (IDMR), Sichuan University- Hongkong Polytechnic University	
Soichiro Yasukawa	Chef of DRR Unit, UNESCO Division of Ecological and Earth Science	
Giuseppe Arduino	Chef of Section on Section on Ecohydrology, Water Quality and Water Education (EQE), Division of Water Sciences, UNESCO	
Saini Yang	BNU, APSTAG	
Chadi Abdallah	Arab STAG	
Rita Der Sarkissian	Arab STAG	
James Terry	Former Chair of ISC Asia Pacific Committee	
Irasema Alcántara Ayala	DRR Committee Member in ISC office in Latin America	
Barbara CARBY	DRR Committee Member in ISC office in Latin America	
Jose Rubiera	DRR Committee Member in ISC office in Latin America	
Shuaib Lwasa	IRDR former SC chair	
Djillali Benouar	PeriPeri U and University of Sciences and Technologies Houari Boumediene (USTHB)	
Clarissa Rios	Research Associate Centre for the Study of Existential Risk, University of Cambridge	
Marteen van Aalst	Director Climate Centre, IFRC	
Roger Pulwarty	NOAA	
Scott Williams	UNDP	

Peng Cui	IRDR SC	
Jörn BIRKMANN	IRDR SC	
Bapon (Shm) Fakhruddin	IRDR SC	
Haruo Hayashi	IRDR SC	
Nisreen D. AL-Hmoud	IRDR SC	
Julius Kabubi	UNDRR Regional Office for Africa	
Animesh Kumar	Deputy Chief, UNDRR Regional Office for Asia and the Pacific	
Ortwin Renn	IASS	
Dilanthi Amaratunga	Head, Global Disaster Resilience Centre	
Alex Altshuler	UNDRR E-STAG	
Richard Thornton	Bushfire and Natural Hazards CRC	
Ranit Chatterjee	IRDR Young Scientist	
Sufyan Aslam	ISC in Malaysia	
David Johnston	Massey University	
Lauren Rickards	RMIT	

Appendix 3.0

Towards a disaster risk reduction research agenda: A literature review

Version: Draft for inclusion as appendix to the Research Agenda (pre-IRDR Conference draft)

Date: 31 May 2021

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1. Abstract

In light of an evolving global risk landscape that demands new knowledge, action and ways of doing things, a research agenda development process has been initiated under the Integrated Research on Disaster Risk (IRDR) programme. Building on existing science, policy and implementation, the new research agenda aims to provide an inclusive and collaborative platform for innovation and partnerships towards more transformative approaches to conceptualizing, understanding and addressing risk – rooted in disaster risk science. Formulated as part of the research agenda development process, this working paper presents and discusses a state of knowledge around disaster risk science, based on scientific literature review and inputs from the IRDR community, and framed by the emerging priorities of the research agenda. Specifically, this paper i) traces the development and evolution of relevant concepts and frameworks, ii) discusses the application of relevant methods, tools and approaches, and iii) highlights important knowledge gaps.

We highlight how definitions and framings of key risk concepts from diverse and inter-related disciplines are constantly evolving and often contested, and how our understanding of risk has broadly evolved from 'natural' to 'systemic'. Yet, while there is a plethora of quantitative and qualitative approaches to assess risk, a holistic understanding and operationalization of risk is lacking, there is also limited integration of approaches that account for diverse, place-based ontologies and epistemologies across spatial and temporal scales, and knowledge production suffers from significant imbalances and disparities. Further, the relationship between progress in disaster risk science and advances in policy and implementation suggests a growing disconnect between knowledge, decision-making and action. A future research agenda needs to be conscious of power relations informing and informed by disaster risk science, and make space for subalterns studies and locally-produced knowledge to shape governance and drive progress. More than ever before, the confluence of these trends and progress calls for meaningful and inclusive collaboration across scales, geographies, and disciplines, and more progressive governance approaches to risk reduction.

***Keywords**: Risk; disaster risk science; disaster risk governance; disaster risk reduction; research agenda*

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1 Introduction

Disasters have been studied for centuries, but 'modern' disasters studies have arguably developed over the past half-century or so. The journal *Disasters* began publication in 1977, for instance. During this period, disaster knowledge and practices have evolved from an emergency management framing to a broader perspective encapsulated by 'disaster risk reduction (DRR)' (Davis, 2019). It has seen a shift in priority and focus from responding to disaster events (i.e. an *ex-post* approach) to proactively managing and reducing risks (i.e. an *ex-ante* focus). Risk, it has become widely accepted, is a function of hazards, exposure and vulnerability (Cardona et al., 2012; Wisner, 2004). Social sciences in particular inform our understanding of the vulnerability dimension of risk, with various frameworks emerging in the context of socio-ecological (or human-environment) systems (e.g. Cutter, 2003; Turner et al., 2003). Such framings have become foundational to how risk processes are conceptualised, particularly in Western scholarship.

Global policy developments in disasters (inc. management, reduction) can be traced from the 1990s UN International Decade for Natural Disaster Reduction (IDNDR), to the Yokohama Strategy for a Safer World adopted at the first World Conference on Natural Disasters in 1994, to the Hyogo Framework for Action (2005-2015) adopted at the second World Conference on Disaster Reduction in 2005, and currently to the Sendai Framework for Disaster Risk Reduction (2015-2030), adopted at the third World Conference on Disaster Risk Reduction in 2015. The names of these events and processes alone suggest a gradual shift in thinking of disasters as natural events (or 'acts of God') to broad acceptance that the risk- and development-related decisions and actions that humans take determine the disaster impact. This shift has enabled the imperative to reduce risk to grow in priority on global policy fronts – not least in relation to climate change (Kelman, 2015). These policy transitions are discussed in Aitsi-Selmi et al. (2016) and Tiernan et al. (2019), and summarized in Figure 1 below.

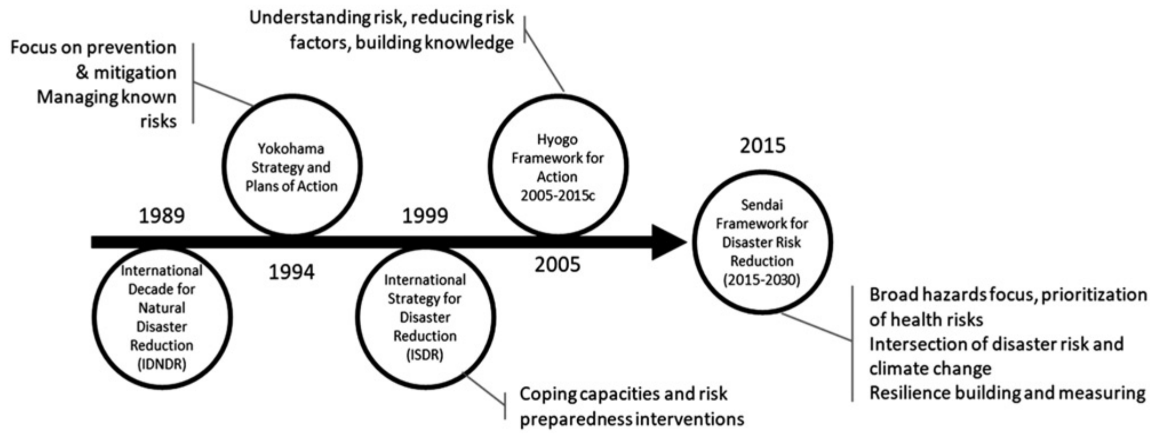


Figure 1. Disaster risk reduction global policy developments (Aitsi-Selmi et al., 2015; Tiernan et al., 2019)

Crucial to progress in understanding and managing disaster risk is 'disaster science', which spans both natural and social sciences, and cuts across various disciplines, including environmental, earth, economics, geography, engineering, sustainability, ecology, sociology, political science, law, education, health, anthropology and other sciences, as well as their specific branches. As science and research in these areas continue to grow at an almost exponential rate, multiple agendas, coalitions and processes have emerged at all levels, from global to local, for disaster scientists and researchers to coalesce around in the hope of informing DRR policy and practice.

Recognizing the knowledge and impact of existing networks and programmes, the Integrated Research on Disaster Risk (IRDR) programme seeks to establish a new research agenda to guide the development of disaster science in the coming decade. In the face of growing risks, the agenda will facilitate high quality inter- and trans-disciplinary knowledge production, and contribute to the transition to a peaceful, safe, equitable and sustainable world within the context of DRR.

As part of the development process for this new research agenda, this paper serves to provide context, baseline information and a 'state of knowledge' on disaster risk science and related disciplines. Specifically, this paper aims to i) trace the development and evolution of relevant concepts and frameworks, ii) understand the application of relevant methods, tools and approaches, and iii) highlight key gaps in data, information, and knowledge.

This paper is structured by the evolving research priorities of the new research agenda, and provides a literature-based discussion of concepts, methods and knowledge gaps of each priority, before a broader discussion of the implications of the current state of knowledge around these priorities for science, policy and implementation. The following sections present the methodology (section 2), analysis (section 3) and discussion and conclusions (section 4).

2 Methodology

The methodology for this paper is two-fold. Firstly, an online survey was designed and disseminated across IRDR networks (i.e. Science Committee members, ICoEs, NCs) and members of the Research Agenda Core Group to gather recommended literature for review. The survey received 15 responses with a total of approximately 200 (including duplicates) journal papers, edited books and grey literature reports recommended for inclusion in this review.

Secondly, literature was gathered and reviewed from online sources, specifically using the Scopus database accessed through Chulalongkorn University, Thailand. The following 'Title-Abstract-Keyword' search string was used to search for relevant literature in the advanced search function of Scopus:

> *TITLE-ABS-KEY ((disaster* OR emergency OR emergencies OR crisis OR crises OR hazard*) AND (resilien* OR vulnerab* OR adapt* OR mitigat* OR prevent* OR prepar* OR recover* OR reduction OR respond OR response* OR sustainability OR sustainable))*

Limiting the results to publications from the past 50 years, i.e. 1970-2020 (inclusive), the search returned over 542,632 results. The search was further narrowed down by excluding publications from the subject area of 'Medicine', which reduced the number of results to 301,333. By way of comparison, an earlier review of disaster science literature found over 27,000 papers published between 2012 and 2016 (Elsevier, 2017). Figure 2 below shows how the number of academic publications has accelerated in recent years. For instance there are 30,579 results for 2020 alone – more than the results for 1970-1997 combined (29,362 results in 28 years).

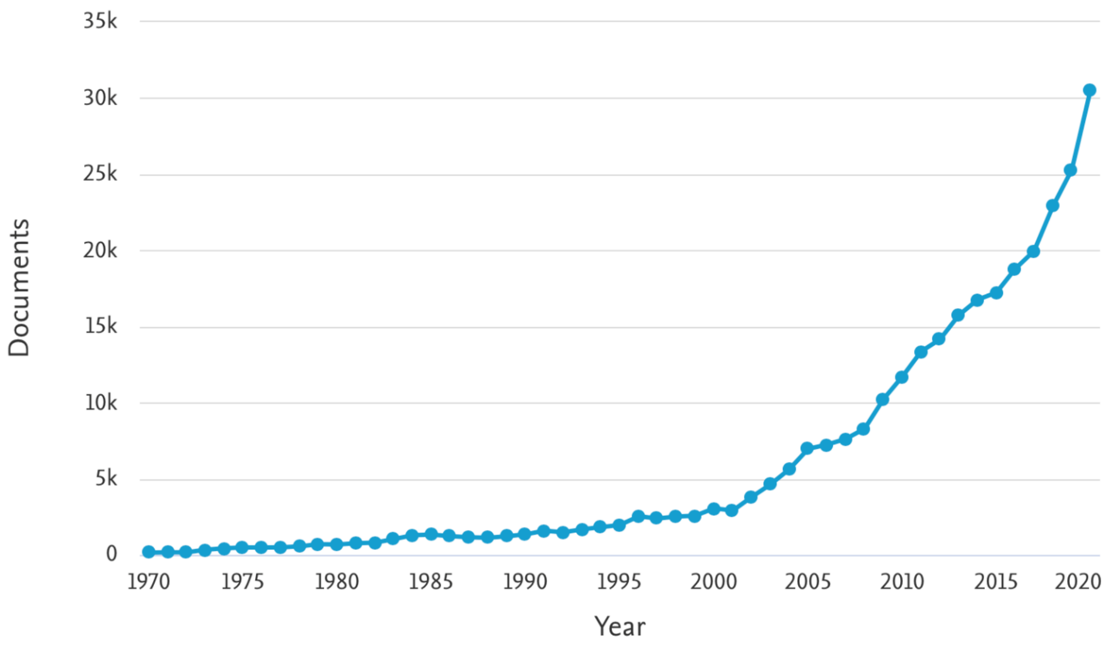
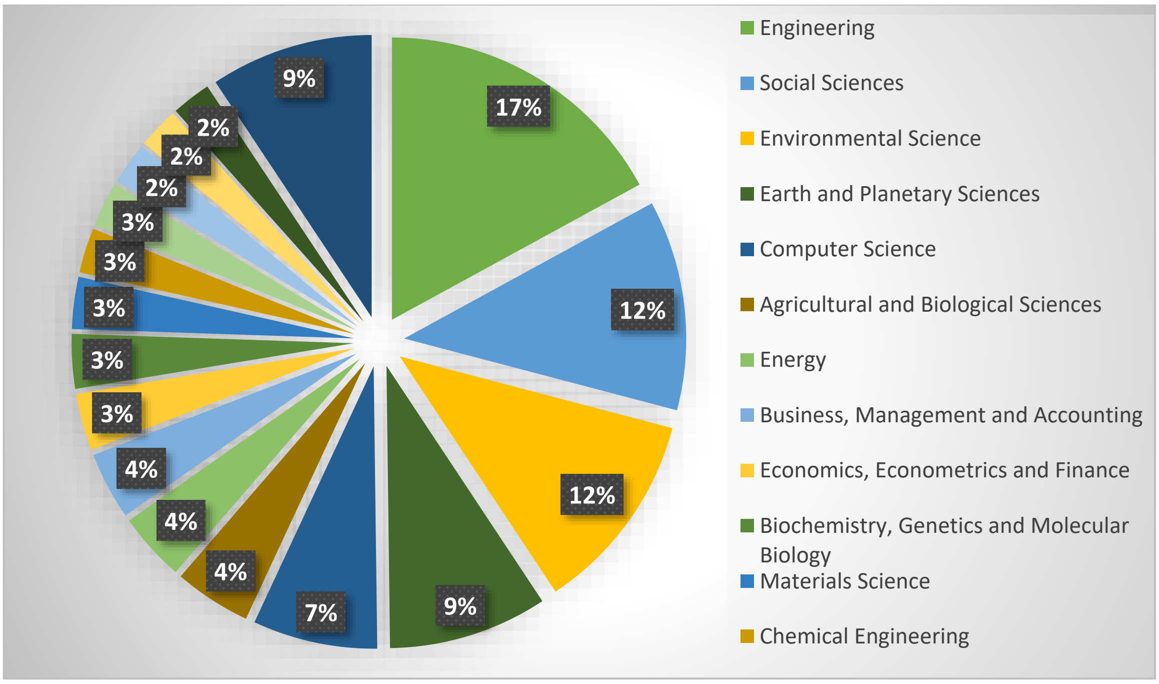


Figure 2. Literature search results per year (1970-2020).

Given the large number of results and non-specificity of the search string, it's also interesting to note the scientific disciplines from which the results are derived. Figure 3 shows the top three to be Engineering (17%), Social Sciences (12%), and Environmental Science (12%).[1]



[1] Scientific discipline assignment is done automatically by Scopus.

Figure 3. Literature search results by scientific discipline (1970-2020, excluding 'Medicine').

Results by region, as shown in Figure 4 below, given an indication of where scientific publications are coming from. The headline finding is that there is a relatively even split between Asia-Pacific (31%), Europe (31%) and the Americas (28%), but only 3% of results are from Africa. Three countries dominate the publication of literature – United States (21.8%), China (9.8%) and United Kingdom (6.4%).

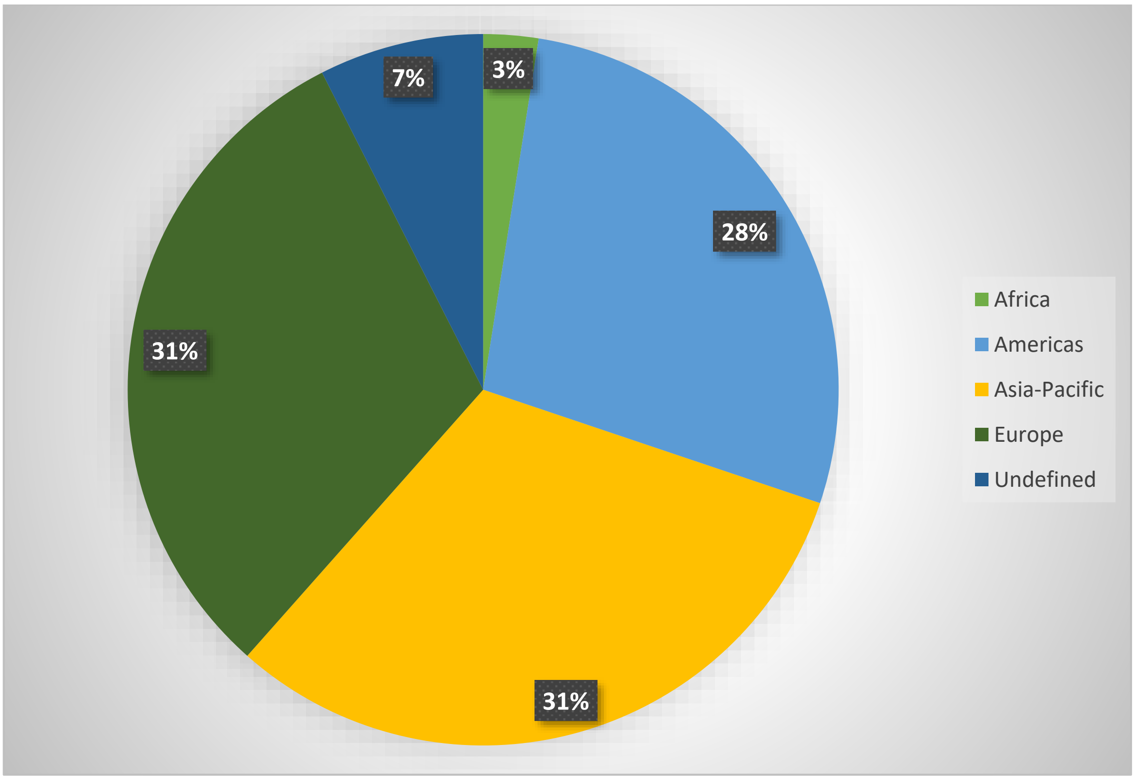


Figure 4. Literature search results by region of origin (1970-2020, excluding 'Medicine').

As demonstrated by the large number of results and also the disciplinary origins of some results (e.g. biochemistry, chemistry), it is clear that not all results are relevant for the aims of the paper, and the wider Research Agenda. Therefore, results were further restricted to the period 2010-2020 because IRDR was established in 2010, which produced a total of 206,515 results.

Results were then sorted by 'most cited' in order to prioritize, and the title and abstracts of the results were screened, with irrelevant results ignored, to produce the top 150 relevant results, which were the basis for this review. In addition, Google Scholar and Google searches were used to find literature which systematically or holistically review the literature to provide a synthesis of the state of knowledge on DRR and related themes. Survey results were cross-referenced with Scopus search results and select publications were included for review. Zotero is used as the reference management software.

Papers were reviewed to analyze i) the development and evolution of relevant concepts and frameworks, ii) the development and use of relevant methods, tools and approaches, iii) key gaps in data, information and knowledge, iv) key gaps in science-to-policy engagement, science communications, and research capacity, and v) science for key global policy missions (i.e. Sendai Framework, SDGs and Paris Agreement). The analysis is presented in the paper according to the emerging research priorities *(subject to change and finalization)* of the new Research Agenda, as follows:

1. Understand risk creation and perpetuation: systemic, cascading and complex risks;
2. Address inequalities, injustices and marginalisation;
3. Enable transformative governance and action to reduce risk;
4. Measurement to help drive progress;
5. Understand the implications of new thinking on hazards;
6. Harness technologies, innovations, data and knowledge for risk reduction;
7. Foster multi-stakeholder collaboration for solutions to risk challenges; and
8. Support regional and national science and knowledge for policy and action.

This paper is not without methodological limitiations. The scope is English-language publications only, therefore the paper is based on predominantly Western scholarship. It was also not in the scope of this paper to systematically review all bodies of literature relevant to disaster risk science. Rather, the paper synthesizes and assesses the current state of knowledge around key themes and concepts related to disaster risk science (and DRR more broadly), as well as adaptation, resilience and sustainability. Findings from the review will be used to develop recommendations for future research, policy and implementation.

3 Analysis

In this section we present key insights from the scientific literature for each of the research agenda priority areas by discussing concepts and frameworks, methods and approaches, and knowledge gaps for each.

3.1 Understand risk creation and perpetuation: systemic, cascading and complex risks

The science and knowledge behind understanding (disaster) risk proves increasingly complex. Studies underscore the need to address underlying causes of risks as well as the ways in which risks interact among themselves and with other systems. This calls for new and updated approaches to know, assess, measure and manage risks – trending away from discrete framings of 'disaster' 'climate' or 'environmental' risks, for instance. Further, there is more scrutiny on context-specific socio-economic and political processes within broader systems that create and perpetuate risk accumulation and distribution across geographical and temporal scales. Increased recognition and connectivity between physical/natural and social/political sciences is needed to understand and tackle risks holistically.

3.1.1 Concepts and frameworks

Disaster risk

The consideration of the word 'risk' in disaster studies encourages enquiry into broader risk contexts (i.e. risk without disaster) and underlying causes of disaster events. There is now greater emphasis on 'process' rather than event or outcome (Davis, 2019). The formulation of risk as the function of hazard, exposure and vulnerability is a foundational framework in disasters studies, as it encourages interdisciplinary analysis of the natural (i.e. hazards, environment) and the social (i.e. vulnerability, exposure, capacity) dimensions of risk (e.g. Cutter, 2003; Turner et al., 2003; Wisner, 2004). It should be acknowledge and discussed, however, that this and many other dominant risk framings are derived from Western scholarship and ontologies, and in a global sense there is no single view of what risk is and how it is formulated. Thus, there is a need for more diverse epistemologies and ontologies in understanding risk (see Gaillard, 2019).

Understanding risk requires taking into account the social, political and cultural construction of risk, or 'root causes' of risk, such as connections with global environmental change, economic development, urbanisation, and demographic shifts (UK Government Office for Science, 2012; UNDRR, 2019). Worldviews and values, informed by socio-cultural contexts, shape behavior and practice in response to hazards, consequently affecting risks (Thomalla et al., 2015). Yet, risk may also be framed as processes where people deal with uncertainty (Eiser et al., 2012), such as in the context of climate change, extremes and variability (Cardona et al., 2012). Responses to risk depend on how people interpret uncertainties. This interpretation is mediated by cognitive heuristics, experience, learning, and trust (Eiser et al., 2012). Thus any disaster response has an inherent or underlying level of risk associated with it.

A systems approach to understanding risk reflects the increasingly connected and complex social-ecological systems within which risks manifest – something which has also been recently recognized outside of academia, such as in Global Assessment Reports on DRR (UNDRR, 2019). However, dominant conventional framings of risk still often overlook temporal and spatial collisions of different hazards, or the collision of extreme events with slow onset events or protracted crises (Keys et al., 2019; Phillips et al., 2020). Anthropogenic changes and globalization processes further compound risks. Concepts such as compound risk, interacting risk, interconnected risk, systemic risk, cascading risk, 'NaTech' risk, and Anthropocene risk have emerged as alternative framings attempting to capture the dynamic nature of risks in 'modern' systems.

Interdependent systems and risks

The notions of systemic risk and Anthropocene risk center on interdependency as a driver of risks. The former focuses on networked elements while the latter calls attention to the context of linkages. Adopted from the financial management field, systemic risk refers to risks rooted in interconnected components of a whole. Poor understanding of their interactions may result in the collapse of the whole system. Systemic risks tend to be global, non-linear, inter-connected and stochastic in nature (Lucas et al., 2018; Renn, 2020). There are increasing calls for disaster risk thinking and DRR approaches to better consider and account for other risks (e.g. technological, geopolitical) and promote a system risk approach to disasters (Shaw, 2020; UNDRR, 2019).

Anthropocene risk is a complementary concept that captures the human-environment interactions that inform systemic risks. Anthropocene risk accounts for how anthropogenic changes, cross-scale linkages and global tele-coupling processes interact with traditional risks (Keys et al., 2019). As a conceptual tool, it highlights the need for a new governance architecture that better addresses challenges that are unique to the Anthropocene (ibid).

Risk interaction

Not only are risks intertwined with larger systems, they also interact and collide. There are four types of risk based on the domain in which interactions take place: compound risk (concurrence of natural events in the environmental domain), interacting risk (sequential, triggered events in physical domain), interconnected risk (across physical and social networks) and cascading risk (social and infrastructural vulnerability in the anthropogenic domain) (Pescaroli and Alexander, 2018). Alternatively, when classifying by the nature of the interactions between hazards, four different typologies of compound events are identified, i.e. preconditioned events, multivariate events, temporally compounding events and spatially compounding events (Zscheischler et al., 2020). Such a systematic classification and mapping of risks and their interactions provides the tools for better analytical and modeling approaches that capture the increasing interconnectedness of global systems.

3.1.2 Methods

New and emerging framings that seek to address the complexity of interacting risks require a paradigm shift in analysis and new approaches to assessment and implementation (Shaw, 2020). For example, Zscheischler et al. (2018) call for risk assessment and attribution frameworks that explicitly address compound events using an impact-centric perspective and bottom-up methodology in order to identify underlying drivers and processes. Modeling compound events also requires a comprehensive approach, involving diverse stakeholders' perspectives, the nature and amount of physical variables, spatial and temporal scales as well as the strength of dependence (Leonard et al., 2014).

Traditional approaches, for instance in climate science, largely avoid the discussion of low likelihood events, which are by their very nature deeply uncertain, yet could bear the highest risks and impacts. Event-based storylines, which are physically self-consistent unfolding of past events, or of plausible future events, have been proposed as a way of articulating the risk perspective in such cases, with an emphasis on plausibility rather than probability (Hazeleger et al. 2015; Shepherd et al. 2018). This concept links directly to common practices in DRR using "stress-testing" for disaster preparedness based on events that are conditional on specific (plausible) assumptions.

3.1.3 Knowledge gaps

Further research is still needed to understand, articulate and analyze risk in all of its complexity and uncertainty. New knowledge and understanding of risks means transformation *of* disaster risk science is just as important as transformation in it. In particular, there is a need for more diverse voices from different geographical regions and scales as well as bottom-up (or 'local') knowledge to capture the diverse epistemologies and ontologies related to risk. Participatory, local-led research initiatives as well as indigenous, traditional, bottom-up knowledge and practices will be critical to ensure that science is grounded on lived experiences and tailored to actionable change (Fatorić and Seekamp, 2017; Gaillard, 2019; Kamara et al., 2018). Further effort is needed to unleash the power of local researchers, concepts and methodologies and challenge the hegemonic Western scholarship over disaster science and prevent the loss of local knowledge (Gaillard, 2019; Gaillard and Mercer, 2013). Recognising and contextualizing risks in everyday cultural, political and social experience should be a priority in future research endeavours.

3.2 Address inequalities, injustices and marginalisation

Understanding and addressing underlying causes of risks cannot be separated from interrogating historical and continuing social injustice, inequality and marginalisation. Existing social, economic and political structures make some communities more susceptible to the impacts of hazards than others. Ineffective DRR policy and practice risks reinforce such outcomes, deepening the divide along social, economic and political lines. However, there is great potential for risk reduction and resilience approaches to promote the values of disaster (and climate) justice, which will continue to play a critical role in the sustainability of DRR.

3.2.1 Concepts and frameworks

Disaster justice refers to fairness in policies addressing catastrophic hazards and disasters (Verchick 2012), and "a moral claim on governance" (Douglass and Miller 2018). While it overlaps with environmental, social and climate justice, disaster justice is distinctly shaped by a moral obligation in the context of the Anthropocene, the political nature of disaster governance, everyday inequality that inform vulnerability, and the role of recognition and empowerment in disaster governance (Lukasiewicz, 2020). Disaster justice foregrounds the importance of participatory and inclusive modes of disaster governance, collective agency and just distribution of resources that address underlying causes of vulnerability (Douglass and Miller, 2018).

Meanwhile, other disaster-related concepts and terminologies could also contribute to the reproduction of inequalities and marginalisation. Resilience, for example, has proved a popular concept and framework in disasters and related themes. However, critics argue resilience is now serving more as a 'policy buzzword' than a science or paradigm (Comfort et al., 2001; Reghezza-Zitt et al., 2012). It does not necessarily challenge the status quo and advance our understanding of issues related to risk, vulnerability, poverty and marginalization (Alexander, 2013), while the social-ecological systems approach to resilience has been critiqued for overlooking power asymmetries and assuming the existence of a desired resilient state (Brown, 2014; Gaillard, 2010). Among others, the 'equitable resilience' framing has emerged as a response to such critiques of resilience (Matin et al., 2018).

3.2.2 Methods

Justice research often adopts Amartya Sen's human capabilities approach. In the context of disaster, the framework highlights the link between natural hazards and socio-economic conditions, the importance of democratic values, and community's social, built and natural infrastructures (Verchick, 2012). Another approach frames disaster justice as a governance question, highlighting procedural justice and the roles of different actors in disaster decision making from a longitudinal and multi-scalar perspective (Douglass and Miller, 2018).

Drawing from research on procedural, distributive and interactional justice, Lukasiewicz and Baldwin (2020) propose future research on disaster justice to focus on i) understanding vulnerability and resilience of groups that might not be obviously or visibly vulnerable, ii) tackle rights, responsibilities, accountabilities, values and expectations around disaster management, iii) account for everyday injustices as well as justice issues across the different phases of DRR, and iv) interrogate the connections between procedural, distributive and interactional justice.

In terms of methodological design, there is a need to shift away from over-using the case study approach and instead to adopt evaluative and comparative methodologies in disaster justice research (Lukasiewicz and Baldwin, 2020). In the climate justice literature, quantative and mixed-method analysis remains an open opportunity for future research (Alves and Mariano, 2018).

3.2.3 Knowledge gaps

Social justice and equity remains an understudied area within the literature on disaster and climate change. 'Disaster justice' as a distinctive concept and framing for DRR stakeholders and audiences is only emerging. Research in this area must not be siloed away from critical thinking in other disciplines; multidisciplinary scholarship is needed in order to generate evidence and affect change (Douglass and Miller, 2018). On the climate change adaptation side, a recent review of climate justice literature emphasizes room for improvement in the definition of climate justice and expansion of the research theme (Alves and Mariano, 2018).

The literature also highlights several areas for future research within disaster and climate justice. For example, more work needs to be done on political freedoms and transparency guarantees, as well as on the relationship between gender equality, women's freedoms and adaptation (Alves and Mariano, 2018). There is also a need for research that analyses justice issues at the regional, national and more micro level as well as cross-scale analysis of justice (ibid). Regarding adaptation effectiveness, Owen (2020) finds a big gap in the literature addressing power relations in the distribution of benefits, adaptation process and knowledge production.

3.3 Enable transformative governance and action to reduce risk

Effective and even transformative DRR action calls for governance models that enable unheard voices and collective actions from all actors and stakeholders. The disaster governance literature is an important pillar of DRR scholarship, and suggests several approaches to governance in the context of an increasingly complex riskscape. Yet, translation of knowledge on risk governance to changes in decision-making and action remains a significant challenge across scales.

3.3.1 Concepts and frameworks

Disaster governance is an alternative to the conventional approach to managing disasters through preparedness and response. When governments are unable to effectively and adequately manage risks, disaster governance focuses on collaboration and engagement with stakeholders, and strengthening the voices of local and marginalized actors, across different scales (Gall et al., 2014). Principles of accountability and transparency are central to governance (ibid), and bring in a strong rights-based perspective to disaster- and risk-related decision-making.

New thinking and understanding of risk and its interconnected nature has also prompted new approaches to governance. Adaptive governance, developed from socio-ecological systems thinking, is an approach enabled by multi-stakeholder platforms offers an alternative model for managing complex socio-environmental issues such as disasters, with a focus on collaboration, participation, learning and self-organisation (Djalante, 2012). The transformative potential of adaptive governance in the context of DRR has also been discussed (Munene et al., 2018).

The literature on systemic and compound risks has also explored alternative approaches to analyze and govern risks in the context of increasing interconnectedness. A multidisciplinary approach to globally networked environmental risks, also referred to as global systemic risk or nested vulnerability, identifies five major insights shaping global governance. They range from the influence of international institutions and international norms and legal mechanisms, to transboundary, cross-sectoral institutions, innovation as strategy and legitimacy issues (Galaz et al., 2017). In addition, scholars have increasingly advocated for integrating disaster governance with climate change adaptation and sustainable development (Gall et al., 2014).

3.3.2 Methods

The literature on disaster governance is abundant when it comes to conceptual studies, yet fewer works focus on operationalizing the transformation in existing risk management structures (Gall et al., 2014). For example, research on the linkages between DRR and climate change adaptation foregrounds the need for improved governance, collaboration, resource sharing, and community engagement, yet few research focuses on operationalization and case studies of context-based implementation (Islam et al., 2020). Applied and or comparative research to generate empirical evidence is needed to understand and facilitate transformative governance to reduce risks.

One potential method to evaluate the effectiveness of (risk) governance is through the use of resilience as an indicator. Yet, resilience itself is a complex concept with different definitions and uses, and noted above and by many authors, and a sound and standardized approach to measuring and documenting resilience is still missing (Gall et al., 2014). Other quantitative outcome measures for governance require specific data and longitudinal research, along with information that captures uncertainty is still missing (Gall et al., 2014).

3.3.3 Knowledge gaps

A knowledge gap exists between the conceptualization of governance at the abstract level and its translation to policy and action. To bridge the gap between theory and practice, Islam et al. (2020) suggest taking the political economy approach improve understanding of decision-making and policy processes with an emphasis on stakeholders and their power dynamics. More qualitative research using participatory, bottom-up and interndisciplinary approach to enrich existing knowledge on adaptation intervention and decision-making processes (Fatorić and Seekamp, 2017; Shaffril et al., 2018) as well as analysis of adaptation finance, implementation action and outcomes (Ford et al., 2011; Klöck and Nunn, 2019; Lwasa, 2015) is also needed. Finally, innovation in risk governance often occurs at the local level while upscaling is challenged by the dominant and powerful structures that maintain a status quo (Galaz et al., 2017). Further research is needed to understand and facilitate cross-scale shifts in governance systems for more transformative DRR.

3.4 Measurement to help drive progress

Disaster science can influence risk governance and drive action in multiple ways. One such channel is building operational understanding of key DRR concepts such as exposure, vulnerability and resilience. These are complex and highly debated concepts with multiple uses and meanings in different strands of literature. Tools to unpack and measure these concepts both qualitatively and quantitatively are needed to influence risk reduction.

3.4.1 Concepts and frameworks

Exposure

Exposure is a major driver of risk subject to influence from existing social institutions and skewed development processes (Cardona et al., 2012). Reflecting the role of climate change in DRR, the notion of 'multiple exposure' refers to susceptibility augmented by exposure to various ongoing challenges, such as climate change, globalization, poverty, epidemic, earthquakes, landslides and more. Climate change is one among many that communities and assets are exposed to, and efforts in response to multiple exposure should be coordinated towards the goal of sustainability (Kelman et al., 2015).

Resilience

While many resilience definitions exist and the word has a long history (see Alexander 2013; Manyena 2006; Zhou et al. 2010), Holling's (1973) definition of resilience as "a measure of the ability of ecological systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling 1973, p. 18) is often credited as one of the earliest and most influential for the study of disasters. Coming from the field of ecology, Holling's work first related resilience to a systems theory approach. One particular influence of the origins of the term in ecology has been a dominant emphasis on system stability characterizing resilience in other fields and domains (Alexander, 2013). In a review of disaster resilience themes, (Tiernan et al., 2019) summarize resilience to refer to system attributes: i) maintaining stability, ii) recovering, and iii) adapting. Resilience is also credited with acting as a bridging concept between DRR and adaptation.

Vulnerability

Multiple definitions of and strands of research on vulnerability, beyond UN glossaries, recognize the social processes that influence vulnerability via the capacities to cope or protect oneself, the situations of vulnerability that people move into and out of over time, and the social construction of vulnerability (Wisner, 2004). Approaches to understanding vulnerability that frame it as a condition overlook relationships and temporal dimensions that influence vulnerability (Kelman, 2018). Adapted from the Pressure and Release model, Wisner et al. (2012) propose "the progression of vulnerability" as a framework explaining vulnerability in the context of disaster risk by relating root causes, dynamic pressures, fragile livelihoods, unsafe locations and hazards.

3.4.2 Methods

The studies reviewed in this research, which is only a snapshot of the vast literature, demonstrate a range of tools and modeling approaches to quantify exposure and impacts. Dottori et al. (2018) use a multi-model framework to estimate human losses, direct and indirect economic damages and welfare losses from river flooding under different temperature and socio-economic scenarios. A study on hurricane Harvey using an energy and moisture perspective to examine the link between ocean heat content and hurricanes finds evidence of a warming ocean supercharging and substantially intensifying the natural hurricane, thus highlighting the unnatural quality of disasters and the importance of adaptation (Trenberth et al., 2018).

Scenario modeling of flood exposure and adaptation has also been used to quantify future flood losses in 136 major cities by 2050 and estimate the required defence standard to address increased risk (Hallegatte et al., 2013). Using 3D and GIS modeling and statistical regression at the global scale, Peduzzi et al. (2012) analyze the trend in mortality risk from tropical cyclones and identify cyclone intensity, exposure, poverty and governance to be important determining factors. These tools, as such, have greatly improved scientific knowledge on how society is contributing to and influenced by climate change and disasters.

Regarding measuring community-level resilience, various frameworks and tools have been developed. Two prominent and well-cited frameworks are Norris et al. (2008) model of four components of resilience – economic development, social capital, information and communication and community competence, and the Disaster Resilience of Place (DROP) model (Cutter et al., 2008). The DROP model, which integrates system attributes with inherent community resilience and vulnerability, enables the consideration of infrastructure, institutional and ecological components. The DROP model was later expanded with a series of indicators for assessing community resilience – social, infrastructure, institutional, economic, and community resilience (Cutter et al., 2010). The thinking behind this model has subsequently been built upon and expanded in several studies, such as one on the connection between wellbeing and resilience to drought in Southern African countries, which used a capacity approach with more weight on the social dimension of community resilience (Brown, 2014).

3.4.3 Knowledge gaps

For the most part, the focus in risk measurement and assessment has narrowly focused on physical hazards and economic impacts. More attention is needed to reflect the complex nature of hazards and risks as well as socia dimensions of vulnerability (Aitsi-Selmi et al., 2016; Rahman and Fang, 2019). Systematic, long-term data is needed to improve measurement. The reviewed literature includes research on both past and future impacts of disasters and climate change, and corresponding responses. Yet, a gap remains in data and knowledge on long-term resilience and vulnerability (Alves and Mariano, 2018; Fatorić and Seekamp, 2017; Klöck and Nunn, 2019; Owen, 2020). This is in sync with the gap of literature on the implementation and outcomes. More systematic, longitudinal data on implementation and monitoring and implementation, as well as research on the sustainability, longevity and suitability of risk management approaches in each context over the long term would enrich the literature.

3.5 Understand the implications of new thinking on hazards

Improvement in hazard knowledge and classification has revealed challenges and gaps in the measurement and assessment of risk and vulnerability. New, updated approaches, models and frameworks are needed to take into account new knowledge and also to expand understanding of the complexity of hazards in the Anthropocene.

3.5.1 Concepts and frameworks

Understanding of hazard has expanded beyond those with natural causes to encompass a broader scope. Early definitions describe hazards as events and phenomena that are well defined temporally and spatially, overlooking processes such as creeping environmental changes (Kelman, 2018). Yet, science has evolved over time to recognize the complex, dynamic nature and the social construction of hazards. In particular, human activities can either contribute to the production of hazards or how a hazard is experienced (Wisner, 2004). The UNDRR now defines hazard as processes, phenomena and human activities that have harmful impacts on health, life, property and social, economic and environmental conditions (UNDRR and ISC, 2020).

As an effort to advance knowledge on hazards, a recent study sought to clarify the scope of all hazards, identifying a total of 302 hazards classified into eight clusters: meteorological and hydrological hazards, extraterrestrial hazards, geohazards, environmental hazards, chemical hazards, biological hazards, technological hazards, and societal hazards (UNDRR and ISC, 2020). The study, however, excludes "complex human activities and processes where it was difficult to identify a single or limited set of hazards, compound and cascading hazards, and underlying disaster risk drivers (such as climate change)" (UNDRR and ISC, 2020, p. 9). This signifies that, despite a shift in the formal definition of hazard and increasing knowledge on interconnected risks, much emphasis remains on more quantifiable and less complex hazards. Chains and synergies among hazards are often subject to neglect in the "still widespread reductionist approach" to hazard analysis and risk assessment (Fakhruddin et al., 2020, p. 226).

3.5.2 Methods

Given recent shifts in the definition and framing of risk and hazard, as outlined above, scholars have called for new tools and approaches to assess and measure systemic or compound risk and hazard. Birkmann et al. (2015) call for the need and potential to link global and local scenario building for better vulnerability analysis. Qualitative scenario assessment using the global WorldRisk Index and local participatory scenario development at the community level demonstrate how vulnerability trends and patterns can be identified and analyzed at different scales and through different lenses for complementary outcomes (Birkmann et al., 2015).

Zscheischler et al. (2018) call for risk assessment and attribution frameworks that explicitly address compound events using an impact-centric perspective, bottom-up methodology that focus on impacts in order to identify underlying drivers and processes. The modeling of compound events is also complex, involving stakeholders' perspectives, the nature and amount of physical variables, spatial and temporal scales as well as the strength of dependence (Leonard et al., 2014).

3.5.3 Knowledge gaps

Appropriate indices and metrices are critical to capture the dynamic nature of and interactions among hazard and vulnerability elements (Fakhruddin et al., 2020; Gallina et al., 2016). There are existing tools to identify and aggregate multiple natural hazard types and assess the vulnerability of multiple targets to a specific natural hazard. However, they do not yet account for other climate change impacts, climate-induced hazards, or other types of hazards (Gallina et al., 2016). Similarly, Fakhruddin et al. (2020) highlight the need to shift towards dynamic vulnerability analysis that accounts for cascading impacts, the temporality of vulnerability, and the complex interplay between coping capacity and sensitivity. More research exploring the merging and combination of different scenario approaches at different spatial and temporal scales for vulnerability assessment is also needed (Birkmann et al., 2015).

3.6 Harness technologies, innovations, data and knowledge for risk reduction

Given the increasing complexity around risk, hazard and vulnerability, as well as depth of knowledge and understanding around risk reduction, science and technology will be essential to informed decision making and innovative solutions to critical challenges. While it is imperative to harness the power of science and technology in all forms, ensuring no one is left behind in the process will be crucial to long-term sustainability.

3.6.1 Concepts and frameworks

Science and technology play an important role in DRR. It has supported the development and implementation of major global frameworks and initiatives and will continue to do so, as recognized in the Sendai Framework for DRR 2015-2030 as well as the Science and Technology Conference on the Implementation for the Sendai Framework (Aitsi-Selmi et al., 2016). The science and technology community has expanded and shifted from operating as a closed group to playing a more collaborative, co-productive role along with other sectors and in multi- and trans-disciplinary arenas (Shaw, 2020). Six scientific functions have been identified in the context of DRR: assessment of data and knowledge, synthesis of evidence, scientific advice to decision makers, monitoring and review of new information, communication and engagement across sectors, and capacity development for using scientific information (Aitsi-Selmi et al., 2016). Relatively, Priority 1 of the Sendai Framework in understanding risk sees the highest level of engagement and largest role for science and technology compared to the four remaining priority areas (Shaw et al., 2016).

Technological innovations, geospatial tools (e.g. remote sensing; geographic information systems) and big data technologies (e.g. algorithm-based artificial intelligence and machine learning) are rapidly evolving areas of research and development of increasing relevance for disaster risk. Wider applications are emerging, such as related to the capacity to process large amounts of data with to understand the spatiality of risk, exposure and vulnerability, with great potential to have transformative outcomes for DRR and resilience (UK Government Office for Science, 2012).

3.6.2 Methods

A technology-driven approach to DRR has seen an increase in the use of drones, artificial intelligence, robotics, 3D printing, virtual reality and other advanced technologies in both DRR practice and research, such as loss estimation, emergency data management, search and rescue operations, and research and education (Shaw, 2020). Remotely sensed data, real time digital data as well geo-information tools and techniques offer rich inputs for improving the assessment and understanding of complex risks (Rahman and Fang, 2019). GPS, GIS and hand-held portable devices are some of the tools available to complement crowd sourcing data (Aitsi-Selmi et al., 2016). It is, however, important to ensure that data collected using advanced technologies, such as satellite-based spatial data, as well as computer-based technological packages are easily accessible to relevant stakeholders and young researchers (Rahman and Fang, 2019).

3.6.3 Knowledge gaps

Science and technology needs to take into account the complexity of hazards and their interactions, addressing compound risk, NaTech, systemic risk as well as multi-hazards and all hazards (Aitsi-Selmi et al., 2016; Shaw, 2020). More research integrating human behavior and social norms and networks is needed, particularly in in risk perception and risk assessment (Eiser et al., 2012). Eiser et al. argue that the role of behavioral science in DRR has received increasing recognition, yet research-investigating determinants of human behavior within and across social groups remain superficial. More research on how warning systems and policies are perceived and what makes them effective is also needed. Similarly, reviewing the literature on global governance in the context of globally networked risks, Galaz et al. (2017) suggest that the current debate on global risk governance overlooks legitimacy, or people's normative evaluation of international decision making. Whether the public deems institutional arrangements legitimate is critical to their effectiveness.

Traditional, Indigenous knowledge is one category of technology that will remain relevant and critical as technology continues to advance (see Shaw, 2020). It is thus important that the science and technology community engage and collaborate with local communities early on through processes of co-design and co-delivery to ensure the effectiveness, relevance and applicability of outcomes (Shaw, 2020). Information technology can also play important role in scaling up community-based achievements in sustsainability (Aitsi-Selmi et al., 2016)

3.7 Foster inter-disciplinary and multi-stakeholder collaboration for solutions to risk challenges

The importance of and push for inter-disciplinary, transdisciplinary and multi-stakeholder collaboration have been highlighted across numerous areas of disaster science. Undeniably, reducing disaster risk in the context of an increasingly interconnected Anthropocene age is not feasible without joint efforts and consideration of diverse epistemologies. One concrete avenue highlighted in the literature is the integration of DRR with climate change adaptation (CCA), where the links are clear yet much potential is yet to be realized. Capitalizing on synergies and refining disciplinary characteristics of disaster science are needed to ensure fruitful collaboration.

3.7.1 Concepts and frameworks

DRR-CCA integration

As both DRR and CCA are concerned with questions of vulnerability, resilience, risks, hazards, and uncertainties, integrating DRR and CCA has been gaining ground in research and policy (Hore et al., 2018; Islam et al., 2020; Kelman, 2015). Since disaster risk is interpreted as a combination of hazard and vulnerability, climate change can drive or diminish hazards while also influencing vulnerability (Hore et al., 2018; Kelman, 2015). Climate change mitigation and adaptation initiatives themselves can also influence disaster risk (Hore et al., 2018). Thus reasons for integrating CCA and DRR include sharing resources and data, avoiding duplicated efforts and missed opportunities as well as complementing sustainable development efforts (Birkmann and von Teichman, 2010; Hore et al., 2018; Kelman, 2015). Moreover, as DRR has a longer history of being embedded within development and evolving from the hazard paradigm to the vulnerability paradigm, failure to integrate and encompass DRR knowledge and practice in CCA has led to CCA being a scapegoat for DRR and developmental failures

(Hore et al., 2018).

3.7.2 Methods

In order to increase synergistic effort, the research community has pushed for the conceptual integration of CCA as a part of DRR within the larger context of sustainable development (Birkmann and von Teichman, 2010; Hore et al., 2018; Kelman et al., 2015). Birkmann and von Teichman (2010) outline the possibility to integrate CCA into each of DRR cycle of mitigation, preparedness, response and recovery and reconstruction.

Climate change mitigation, on the other hand, is conceptualized as a subset of sustainable development according to Kelman (2015) and as a subset of pollution prevention, under the umbrella of sustainability and development, according to Hore et al. (2018). Hore et al. (2018) also note the overlaps between mitigation and adaptation, as well as between pollution prevention and DRR. Furthermore, scholars have also explored CCA-DRR integration from a governance perspective, through which Forino et al. (2015) propose a conceptual framework linking social, market and state actors through co-management, public-private partnership and private-social partnership. Alternatively, Linnerooth-Bayer and Hochrainer-Stigler(2015) adopt the financing lens and argue that risk financing and risk reduction, as subsets of disaster risk management, can target different layers of risk, thus contributing to and complementing CCA.

3.7.3 Knowledge gaps

The siloed characteristics of disaster and climate change prevail (Birkmann and von Teichman, 2010; Hore et al., 2018; Islam et al., 2020). For example, while both DRR and CCA seeks to reduce vulnerability, so far the two fields have not converged on a mutual definition of the term. Demarcations have been ingrained through long-term processes and debates, hence the separate agreements of 2015 resulting from historical processes and political purposes that render merging them undesirable (Kelman, 2015).

Differences in governance, scales, knowledge and norms, as well as the lack of funding coordination and political influence, present great challenges against CCA-DRR integration (Birkmann and von Teichman, 2010; Islam et al., 2020). Furthermore, integration at the conceptual level often faces an operational gap (Islam et al., 2020). For example, the Sendai framework mentions integrating climate change but does not specify operational details (Kelman, 2015); SDG Goal 13 also makes the connection between CCA and DRR with no details on how it will be realized (Forino et al., 2015).

In addition to integrating DRR and CCA, fostering inter-disciplinary and multi-stakeholder collaboration in DRR also requires further improvement in the disaster and climate change literature’s disciplinary characteristics. Overall, the literature spans a wide range of disciplinary fields. Some areas need more integration across disciplines, while others may benefit from a deeper scope of analysis. For example, the DRR literature is abundant in disciplinary and multidisciplinary works, but the complex interplay among risk factors and systemic risks require more co-produced, transdisciplinary knowledge production (Ismail-Zadeh et al., 2017). The research on climate justice, a cross-cutting theme in nature, on the other hand, insists that existing publications are dispersed across such a large number of journals that more tune-fining is needed to identify the most appropriate channels to communicate research findings (Alves and Mariano, 2018).

3.8 Support regional and national science and knowledge for policy and action

The literature reviewed covers wide and diverse geographical regions; however, there appears to be a geographical imbalance in terms of both where data are collected and where research outputs are produced. An earlier review of disaster science literature published from 2012-16 found that China, USA and Japan are by far the most prolific countries for publishing scholarly literature (Elsevier, 2017). There may be some correlation between scientific output and disaster loss, as research tends to focus on major disaster events and risks with high relevance for the context (e.g. earthquakes and tsunamis in Japan; floods and droughts in China). However, there may still be a disconnect between where disaster impacts are felt and where research is conducted, particular in low and middle income countries (LMICs) (Elsevier, 2017).

The adaptation literature also bears a degree of geographic imbalance. For example, most works on cultural heritage adaptation as well as on climate justice are from scholars in Europe and North America (Alves and Mariano, 2018; Fatorić and Seekamp, 2017); more research on adaptation effectiveness focuses on Asia (dominated by studies on China) and North America (dominated by studies on the U.S.) (Owen, 2020); and adaptation research in SIDs tend to focus on the Pacific, core and near core islands (Klöck and Nunn, 2019). Similarly, the review of CCA-DRR integration research notes limited geographical range targeting key knowledge gap, i.e. policy integration studies are limited to few countries such as Australia, Thailand, Zambia and Indonesia (Islam et al., 2020). Testing different integration frameworks in various contexts and their comparative analysis are missing from the literature (Islam et al., 2020).

Overall, more research in/on/from the periphery and developing and underdeveloped countries are needed. One of the reasons for the imbalance may be the lack of data in remote and under-resourced areas, yet in every region there appears rooms for different thematic focuses.

4 Discussion and conclusions

In this paper, we have provided an overview of the state of current knowledge on disaster risk science, covering the framings, approaches, tools, and knowledge and data gaps. Disaster risk science is constantly evolving, its concepts and framings refined, contested, and redefined across diverse and inter-related disciplines. In the context of increased global connectedness, the evolution of risk understanding from 'natural' to 'systemic' is apparent. It is central to the framings of risk, hazard, vulnerability, resilience, and adaptation, among others, and their cascading, compound, and interacting impacts, which are at the core of this review. The increasing role of the social dimensions of risk and vulnerability has foregrounded local, traditional, and Indigenous knowledges and methodologies as critical components of disaster risk science.

Innovations in scientific methods and technologies have enabled new ways of knowing, understanding, measuring, and assessing. More than ever before, the confluence of these trends and progress calls for meaningful and inclusive collaboration across scales, geographies, and disciplines and progressive governance approaches to risk reduction and management.

Through this exercise, gaps and priorities are emerging with implications for future research. First and foremost, a growing disconnect between knowledge and action is becoming apparent. The desired shift to ex-ante from ex-post approaches to risk management, for example, has not mirrored equally between disaster risk science development and policy and practice. One reason may be the lag between conceptual and theoretical advances and grounded knowledge and empirical data; another the lack of effective science to policy communication. Second, a holistic understanding of risk is lacking. While there is a plethora of quantitative and qualitative approaches to understand the manifestation, perception of and responses to risk, there is yet no integration of approaches that also account for diverse, place-based ontologies and epistemologies. Third, across scales and between regions and nations, knowledge production suffers from significant imbalance and disparities. A future research agenda needs to be conscious of power relations informing and informed by disaster risk science and make space for subalterns studies and locally-produced knowledge to drive progress.

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6 Annex

This box is provided for the authors to further illustrate how this study contributes to IRDR research objectives/ SFDRR targets/ SDGs/ Climate Goals/ Science and technology roadmap actions if applicable.

1. How does this study contribute to IRDR research objectives? (50-150 words)

2. How does this study contribute to SFDRR targets? (50-150 words)

3. How does this study contribute to SDGs and/or Climate Goals targets? (50-150 words)

4. How does this study contribute to S/T roadmap actions? (50-150 words)

Main recommendations to DRR policy if not yet highlighted in the main texts:

6.1 IRDR Box

Indication of contribution to [2]

IRDR Sub-objectives	(at least one)
SFDRR targets	(at least one)
SDGs and/or *Climate Goals* and targets	(at least two)
S/T Roadmap actions	(at least one)

Disclaimer of IRDR

[Insert if required]

[2] Please refer to the hyper-link for the details of each statement. Please fill in with just the number of the item, for example, IRDR sub-objectives: 2.1. Please explain how this study contributes to these targets/objectives in details in the box after the reference part.

Appendix 4.0

Indicative Research Priorities in alignment with Research Priority Areas (outlined in Section 5). These specific research issues and questions are listed here to ensure that the individual inputs made as part of the consultation process are acknowledged and accessible. Many of these are at least partly incorporated into the 9 main research priorities in the Agenda. Input that fully aligns with the 9 priorities is not necessarily included here.

Priority Area 1: Understanding risk creation and perpetuation: systemic, cascading and complex risks.

Indicative Priorities
• Understand the major risks to humanity in all global contexts. • Better understand how risk is created and perpetuated. • How is risk changing in diverse global contexts towards systemic, concatenating, compounding and cascading risk vulnerabilities and exposure? • What are the primary causes / triggers of cascading and complex risk? • How can science and research help us better understand complex interdependencies and tipping points (i.e. between regular hazards and disasters; simple risk to complex and systemic risk)? • How can capacity be built across research and practice in areas of risk science, climate change and sustainable development?

Priority Area 2: Addressing inequalities, injustices and marginalisation.

Indicative Priorities
• Ensure a global focus on social justice and equity with regard to risk, vulnerability and exposure. How can resilience be enhanced to ensure justice and equity (e.g. via the SDGs)? • Enhance understanding of how risk is experienced in complex ways in different communities, acknowledging that already vulnerable communities are generally impacted disproportionately by adverse events (for example, the COVID 19 Pandemic). • Risk science should better support sustainable and equitable development. • Better understand variable resilience and response capacities at diverse scales (local, national, regional) across all global regions. • Can risk science be augmented to better support social change (i.e. behaviour, investment, financial decision making etc) to rapidly counteract intensifying dimensions of risk and the inequitable nature of exposure and vulnerability? • Risk reduction needs to be considered much more comprehensively from the perspective of social, economic and environmental dimensions, across a range of scales. • Ensure the equitable inclusion of alternative knowledge systems, beyond traditional forms of science, in developing solutions and decision-making. • How can we develop an ethos of mutual enrichment and a formative dialogue between diverse knowledge carriers, at all levels of risk governance? • Plural solutions: Emphasis on diversity of implementation, solutions development and communication tools to meet needs of diverse groups (communities, areas and

sectors of practice, disciplines of research).

- How can risk science encourage and empower bottom up/grassroots and community action?
- How can marginalised and informal groups (advocacy, activist etc.) and their knowledge be made visible and legitimised within the diverse context of risk thinking and practice?

Priority Area 3: Enable transformative governance and action to reduce risk.

Indicative Priorities

- Enhance coherence across UN frameworks, agreements, organisations and objectives. How can improving synergies across major global agreements better support coping with complex and systemic risk?
- How can enhanced coherence support trans-disciplinary risk science outputs and impact?
- Undertake a mapping exercise to understand current state of global risk governance.
- Develop governance mechanisms for systemic risk and support-required transitions.
- Support risk informed decision-making and practice (across all sectors, disciplines and within communities).
- Encourage investment (broadly defined to include private and public sector, economic, socio-cultural etc.) in ways that reduces risk vulnerabilities and exposure from a global scale, down the local levels where events are experienced in disparate ways.
- Develop mechanisms to incentivise risk and resilience based decision making in policy and practice across all sectors
- Develop tools that allow practitioners to robustly justify risk-based thinking when defining development strategies (whether for poverty reduction and social development, infrastructure and urban development, or other focus areas).
- What enablers are required to better implement science into policy and practice (i.e. action)?
- How can science be more ‘user friendly’ (i.e. in the private sector, by policy makers, in communities)?
- Can risk science support the strengthening of risk-based decision-making through market-based incentives?
- Foster better relationships and networks between risk science and private sector communities.

Priority Area 4: Understanding the implications of new thinking on hazards.

Indicative Priorities

• How can risk science support improved urban resilience, recognising that population growth and urbanisation are increasing globally? • [Require further input]

Priority Area 5: Harness technologies, innovations, data and knowledge for risk reduction.

Indicative Priorities
• Keep abreast of emerging and future technologies to ensure maximum relevance for alleviating risk vulnerability and exposure. • Can technology enable social change towards risk awareness and behavioural transition at a global level? • How can technology be used encourage the uptake of risk-based information, including in populations and communities that are currently isolated from risk based thinking and decision-making? • How can modelling be enhanced to reduce levels of uncertainty and maximise benefit to reducing societal risk? • Can risk science contribute to enhancing current and/or developing new models that can cope with variables of systemic and complex risk? • Is there potential to develop an open access digital platform, with crowd-sourcing capability to promote transformative action and build societal risk awareness and resilience? • How can technology support trans-disciplinary and multi-sector dialogue and knowledge sharing? • How can technology strengthen linkages and knowledge sharing to improve the risk exposure of emerging economies and geopolitical complex countries (such as enhancing capacity and knowledge sharing linkages to the global south)?

Priority Area 6: Support regional* and national science and knowledge for policy and action.

*As per World Bank Regional Units (worldbank.org)

Region	**Indicative Priorities**
Africa	• Research policy and technical capability • Enhance science and research policy with support of donor agencies for effective science-policy interface to support development. • Governance • Transparent and accountable mechanisms of DRR and CC governance. • Potential for adoption of new approach: 4Ps (Public Private Population Partnership) to strengthen accountability and ownership. • Transboundary risks

	• Transnational/boundary DRM is required, and should be supported by joint DRR research initiatives.
East Asia and the Pacific	• Support alleviating issues with coherence and governance. • Support the implementation of science into policy and governance mechanisms. • Research work needs to be 'ready to implement' (have a implementation methodology the explains the 'how to'). • Cross-disciplinary integration • Engineering should be integrated with DRM. • Multidisciplinary but focused on regional and local projects through to implementation. • Climate Change is a major concern, especially in the Pacific, with associated complexities of mitigation, retreat, climate diaspora. • Climate and Environmental Governance and Justice - 'Who speaks for us?' - Pacific voices under heard on the international stage, even though they are bearing the brunt of emissions from other places. • Complex donor and recipient relationships especially associated with disaster risk finance and recovery mechanisms.
Europe and Central Asia	• Coherence (science and governance) - Enhance a pan-European approach that is highly integrated. • Emphasis on New and Emergent Technologies for 'linked up' systems that lead from knowledge development to solutions and informed decision making. For example, an open access digital platform with crowd-sourcing capability could promote transformative action to build community resilience as the climate changes. • Match the scale of science information to scale of science delivery and decision-making. • Public investment is major force of transformation in the coming decades. DRM should be a core to these investment principles, and this should integrate sectors (i.e. science, public and private sectors). • [Require further input]
Latin America and the Caribbean	• Vulnerability and resilience – capacity building • Enhance local capacities through social Innovation • Emphasis on incorporation of non-scientific knowledge systems to ensure legitimacy of decision-making and solutions, and to encourage local buy-in and support for transition. • Development of methodologies for embedding DRM techniques into sectoral and territorial planning. • Development of analytical DRM models that bind together disaster risk modeling, engineering, and risk finance strategies. • Climate change and intensification of disaster events in

	vulnerable SIDS. • Transnational DRM initiatives. Many of the risk contexts transcend boundaries. • Frameworks to address transnational challenges (i.e. flooding-related risk) are lacking. • Incorporation of non-scientific knowledge systems. • LAC represents dozens of autonomous communities, with their own interpretations of the world, knowledge systems and value tradition for understanding, coping and interacting with nature. This knowledge remains excluded from formal and scientific spaces. • Generate interaction spaces between 'formal' science and other communities of practice.
North America and Canada	• Sea Level Rise (Florida, Louisiana and other coastal low lying areas especially influenced by Hurricanes). Socially challenging questions relating to managed retreat, insurance mechanisms (i.e. who is accountable / pays) and mitigation. • Key questions on effective governance. • [Require further input]
Middle East and North Africa	• [Require further input]
South Asia	• Complex geopolitical and trans-boundary context. • Region of high population growth, limited capacity and prone to hazards due to high relief, active tectonics, complex geological settings and sensitivity to climate change. • Some highly developed and modernising economies, others that are far less developed. • Require enhanced risk assessment and co-ordinated management mechanisms, where often disasters are trans-boundary and geopolitically complex. • Need to include diversity within decision-making. • More research into the integration of science, governance and civil society at local, regional, national scales.

Priority Area 7: Supporting just and equitable transitions, adaptation and risk reduction.

Indicative Priorities
• What are the primary risks in transition, and what can be done about these risks? • [Require further input]

Priority Area 8: Measurement to help drive progress.

Indicative Priorities
• Is it achievable to define and adopt standardised ways of measuring risk? • How can global risk literacy be increased measurably within in the next decade?

- Can the risk science community collectively define an aspirational goal for 'measurable' improvement of risk literacy/awareness, and associated behavioural transformations, at a societal scale?
- Is risk science able to support the development of mechanisms to enhance and incentivise societal behavioural change towards risk awareness (i.e enhanced linkages with financial incentives and insurance mechanisms)?
- There is a lack of agreed to indicators of exposure and vulnerability that capture the issues faced by marginalised and vulnerable people and communities. Can risk science sypport the development of such indicators? An example here is the incorporation of the social vulnerability index (SoVI) into (USA) FEMA's National Risk Index for use in hazards planning and analysis. https://www.fema.gov/flood-maps/products-tools/national-risk-index

Priority Area 9: Foster multi-stakeholder collaboration for solutions to risk challenges.

Indicative Priorities
• Develop mechanisms that support trans-disciplinary and multi-sector understandings of risk, vulnerability and exposure. • Improve collaboration across disciplines, research communities and sectors. • Develop mechanisms that support trans-disciplinary and multi-sector approaches enhance science delivery, inform decision-making, and are effective for building just and equitable solutions. • Broaden and deepen trans-disciplinary and cross-sector networks of dialogue and knowledge sharing. • Developing interconnections to broaden and enhance risk science delivery and impact • How should risk science be communicated and delivered to non-scientific communities? • What are the appropriate ways to engage with communities that are currently isolated from risk-based thinking? • Identify institutional gaps, strategic gaps and epistemological gaps, and develop solutions to overcoming knowledge to action challenges.

Appendix 5.0

The IRDR 2008 Science Plan summary

The 2008 IRDR Science Plan:
On the commencement of the IRDR a science plan (International Council for Science, 2008) was developed to guide the work of the program. This plan is at the end of its intended life, and a new plan has been developed. The IRDR Science Plan was seen as a definitive document to guide the work of the IRDR Community. It was not designed to evolve or take account of the changing contexts of risk and disasters, and perhaps could not have foreseen the speed and extent of change.

As discussed above, the decision was taken to look well beyond the traditional DRR community in doing so.

- The IRDR Science Plan was designed based on the HFA, and developed into a Strategic Plan after establishment of the IRDR.
- The original three research objectives and three cross-cutting themes were framed into actions in six goals: Goal 1- Promoting integrated research, advocacy and awareness-raising. Goal 2- Characterizing hazards, vulnerability, and risk. Goal 3- Understanding decision-making in complex and changing risk contexts. Goal 4- Reducing risk and curbing losses through knowledge-based actions. Goal 5- Networking and network building. Goal 6- Research Support.

The 2008 IRDR Science Plan sought an integrated international science focus on hazards related to geophysical, oceanographic and hydrometeorological trigger events. In particular, this included, but was not limited to investigating: earthquakes; volcanoes; flooding; storms (hurricanes, typhoons, etc.); heat waves; droughts and fires; tsunamis; coastal erosion; landslides; and aspects of climate change. The Science Plan initiated a much more prominent international focus on researching the effects of human activities on creating or enhancing hazards, including land-use practices.

In 2005, the predecessor ISC (then ICSU) Scoping Group emphasized that:

There is a great shortfall in current research on how science is used to shape social and political decision-making in the context of hazards and disasters. These issues also highlight the need for more systematic and reliable information on such events.

Consequently, as well as the generation of new science and data, there was a recognised need for the 2008 Science Plan to guide improved coordination and integration with regard to global data and information across hazards and disciplines.

The focus within the Science Plan on risk reduction, understanding risk patterns and risk-management decisions and their promotion, required emphasis on research at global, regional and local scales. Three broad research objectives were set out as follows:

Objective One - The identification, characterisation and assessment of risks from natural hazards on global, regional and local scales. This included the need to address gaps in knowledge, methodologies and types of information that were preventing the effective application of science to averting disasters and reducing risk.

Objective Two: Understanding effective decision-making in the context of risk management. This included clarification of what 'good' decision-making looks like in complex and changing risk contexts; and an enhanced understanding of how human decisions and the pragmatic factors that constrain or facilitate such decision making can contribute to hazards becoming disasters and/or may mitigate their effects.

Objective Three: Reducing risk and curbing losses through knowledge-based actions. This objective required integration of outputs from the first two objectives to implement and monitor informed risk reduction decisions and through reductions in vulnerability or exposure to hazards.

Three crosscutting themes supported the Science Plan's objectives, including: capacity building (with emphasis on mapping capacity for disaster reduction and building self-sustaining capacity at various levels for different hazards); case study development and demonstration projects; and assessment, data management and monitoring of hazards, risks and disasters.

Based on the preceding objectives and themes, the IRDR Planning Group identified the major programmes and projects that already existed in the field of natural hazards and disasters. In addition, the Planning Group identified and built capacity in new project areas through consultative working groups.