Natural Hazards
https://doi.org/10.1007/s11069-022-05468-8

REVIEW ARTICLE

Exploring the integration of local and scientific knowledge in early warning systems for disaster risk reduction: a review

Thirze D. G. Hermans[1] · Robert Šakić Trogrlić[2] · Marc J. C. van den Homberg[3] · Hannah Bailon[3] · Rebecca Sarku[1] · Anuszka Mosurska[1]

Received: 1 February 2022 / Accepted: 20 June 2022

Abstract

The occurrence and intensity of some natural hazards (e.g. hydro-meteorological) increase due to climate change, with growing exposure and socio-economic vulnerability, leading to mounting risks. In response, Disaster Risk Reduction policy and practice emphasize people-centred Early Warning Systems (EWS). Global policies stress the need for including local knowledge and increasing the literature on integrating local and scientific knowledge for EWS. In this paper, we present a review to understand and outline how local and scientific knowledge integration is framed in EWS, namely: (1) existing integration approaches, (2) where in the EWS integration happens, (3) outcomes, (4) challenges, and (5) enablers. The objective is to critically evaluate integration and highlight critical questions about assumptions, goals, outcomes, and processes. In particular, we unpack the impact of power and knowledges as plural. We find a spectrum of integration between knowledges in EWS, mainly with dichotomy at the start: focus on people or technology. The most popular integration approaches are participatory methods such as *'GIS mapping'* (technology) and methods that focus on *'triangulation'* (people). We find that critical analysis of power relations and social interaction is either missed or framed as a challenge within integration processes. Knowledge is often seen as binary, embedded in the concept of 'integration'. It is important to know what different knowledges can and cannot do in different contexts and acknowledge the hybrid reality of knowledge used for EWS. We argue that how we approach different knowledges in EWS has fundamental implications for the approaches to integration and its meaning. To this end, attention to the social processes, power dynamics, and context is crucial.

Keywords Early warning systems · Knowledge coproduction · Local knowledge · Participation · Integration

✉ Thirze D. G. Hermans
tdghermans@gmail.com

Extended author information available on the last page of the article

Published online: 12 July 2022

1 Introduction

1.1 Early warning systems for natural hazards

Climate change increases the frequency and magnitude of climate-related hazards such as droughts, flooding, cyclones, or storm surges (IPCC 2021). In addition, exposure is growing (UNISDR 2015), while socio-economic, environmental, cultural, and political changes in society, as determinants of disaster vulnerability (Wisner et al. 2003), increase disaster risks worldwide. Global policies have embraced the idea of integrating local knowledge into DRR strategies and acknowledge the connection between social and natural forces in disasters. Priority 1 of the Sendai Framework for Disaster Risk Reduction 2015–2030 (UNISDR 2015) highlights in item 24i the importance of '*the use of traditional, indigenous and local knowledge and practices, as appropriate, to complement scientific knowledge in disaster risk assessment and the development and implementation of policies, strategies, plans and programmes of specific sectors, with a cross-sectoral approach, which should be tailored to localities and to the context*'. The Sustainable Development Goals (SDGs) and the Global Framework for Climate Services (Hewitt et al. 2012) have similar statements on the importance of local knowledge in DRR.

To prevent or mitigate these increasing impacts of disasters due to climate-related hazards, anticipatory action for local contexts is essential (IFRC 2021). In 2008, the Red Cross Red Crescent movement introduced Forecast-based Financing (FbF) as one of the first forms of anticipatory action (van den Homberg et al. 2020). FbF enables access to the so-called Disaster Response Emergency Fund, a funding source habitually only available for humanitarian response, before a disaster has happened. By now, many humanitarian agencies are working together on achieving a similar transformation for multiple natural hazard types. Anticipatory action is part of the preparedness component of DRR and relies on an adequate Early Warning System (EWS). In fact, anticipatory action requires that existing EWS evolve. The monitoring and forecasting component of the EWS has to go from giving a warning about what the weather will be to a warning about what the weather will do. The World Meteorological Organization calls this impact-based forecasting (IBF), developing a forecast of the potential consequences of a climate hazard event in terms of its effects on people, infrastructure, etc. (World Meteorological Organization 2021). In addition, preparedness as part of DRR and EWS has to transform. With anticipatory action, local organizations and the to be affected people are given the means to take early action when a forecast exceeds a predetermined probability and magnitude (in short, a trigger), leading to a significant humanitarian impact. The development of these triggers and the design of the early actions require detailed information on and understanding of the local context and lean on both local and scientific knowledge.

It is clear that from this practitioner's point of view, EWS is essential and a major process tool to develop these new DRR strategies for climate related hazards, in particular anticipatory action. The United Nations Office for Disaster Risk Reduction defines an EWS for natural hazards as '*an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events*' (UNDRR 2021). EWS have four components (UNDRR 2021):

1. Risk knowledge: Assessing risk to identify a hazard, vulnerability, and exposure to set priorities and strategies.
2. Monitoring and forecasting: Monitoring and timely estimates of hazard parameters, including analysing hazard magnitude and impact.
3. Dissemination and communication: Communication systems and approaches to deliver warning messages to affected areas, institutions, and actors.
4. Preparedness and Response: Development and coordination of preparedness activities and action plan to mitigate disaster impact.

All these four components have to work together seamlessly (end to end) and in a people-centred way to make an EWS effective. To this end, an EWS provides understandable, timely, and actionable information to those at risk. However, in reality, EWS have poor reach into the last mile due to, among others, insufficient capacity and funding for National Meteorological and Hydrological Services, resulting in the bare minimum and technologies copied from other contexts (van denHomberg and McQuistan 2019). Poor response to the scientific content of warnings in the local context also plays a role (Calvel et al. 2020). There is often not enough translation of the scientific content to the local context and terminology. Also, often forecasts are relevant only at a too aggregated spatial scale and are consequently not local enough for communities to be of value. This has increased the recent literature on integrating local knowledge with scientific knowledge in the EWS. However, stock-taking of lessons learned and critical evaluation about local knowledge and scientific knowledge integration process in EWS remains unavailable.

1.2 Objective

In this review, we use the above definition of an EWS and its four components as a lens, given that the four components cover various phases of the DRR cycle (e.g. mitigation, preparedness, response). Also, practitioners and policy makers often use the EWS approach in their DRR activities especially now with the paradigm shift from response to anticipatory action. Therefore, the lessons learned by using the EWS perspective will allow us to draw lessons also for the wider DRR practice. Our review focuses on identifying and critically evaluating the literature on local and scientific knowledge integration, thereby identifying approaches, challenges, outcomes, and enablers of integration. In addition, we pay attention to discussing approaches to knowledge construction (e.g. knowledge plurality) and power dynamics. We aim to address the following five research questions through a realist review (Pawson et al. 2005; Thompson et al. 2010) of the available literature:

- What are the existing practices for integrating local and scientific knowledge for Early Warning Systems (EWS) in Disaster Risk Reduction (DRR)?
- Where and how in the four pillars of an EWS are these knowledge systems integrated?
- What are the outcomes of integrating local and scientific knowledge in EWS?
- What are the challenges for integrating local and scientific knowledge in EWS?
- What are the enablers for the integration, and how can these be taken forward to aid operationalization of integration in practice?

The paper will first discuss the theoretical background on types of knowledge and knowledge integration in EWS, followed by the review methodology and positionality. This is followed by the Results section, which is ordered according to the research questions:

the literature meta-analysis (4.1), practices for knowledge integration (4.2), location in the four EWS pillars (4.3), outcomes of integration (4.4), challenges (4.5), and enablers (4.6). Lastly, the discussion will focus on the extent and quality of integration, and the implications for EWS, through three lenses: *approaches to 'integration'*, *on 'successful' integration and approaches to knowledge*, and *a way forward: learning across*. We pay particular attention here to unpacking the impact of power and knowledges as plural.

2 Theoretical background

2.1 Types of knowledge

Arguably, what defines local knowledge is that it is distinct from scientific knowledge. In exploring this distinction, scientific knowledge is often approached as a formal agreed methodology or education (Gaillard and Mercer 2012; Mercer 2012). Local knowledge then concerns the native and intrinsic ways of making predictions based on the accumulation of knowledge by people who live in close ties with the natural environment and are associated with local culture and long-term settlement in communities (Ingram et al. 2002; Codjoe et al. 2014; Derbile et al. 2016; Muita et al. 2016). Local knowledge also has alternative names, often used with similar meanings (Iloka 2016): e.g. Indigenous Knowledge (IK), traditional knowledge (TK), traditional ecological knowledge (TEK), Indigenous technical knowledge (ITK). In the context of DRR, the meaning of local knowledge refers to the experience of local surroundings, identification, and monitoring of indicators that point to a possibility of hazards, coping and adaptation to disaster risks, and communication of risks (Dekens 2007). These observations involve the use of local knowledge indicators such as atmospheric conditions (e.g. wind), celestial elements (e.g. sun), fauna (e.g. ants), and flora (trees) to respond or anticipate disasters (Chang'a et al. 2010; Chanza and Mafongova 2017). Within this approach, local knowledge also follows a rigorous process based on observations of biophysical indicators, experimentation, and analysis to build cause–effect relationships between indicators and their predictive outcomes concerning current and future conditions (Balehegn et al. 2019). This questions if 'rigour' and 'formal agreed' are adequate in defining a distinction. In this review, we use the term local knowledge as an umbrella term, covering the variety in the used names and dichotomy in the reviewed literature.

Science and scientific knowledge are not objective entities but socially constructed and embedded in histories of colonialism (Tuhiwai Smith 2004). Prior to colonization, groups such as Indigenous peoples had sophisticated knowledges that were inseparable from their cosmologies and worldviews (Tuhiwai Smith 2004). Colonialism, in which science played a pivotal role, divided this knowledge into disciplines (thus taking away from its rich meanings) and labelled it as 'anecdotal', ignoring that local knowledge itself is evidence-based, has undergone its own processes of peer review (it is accepted by communities), and has been used for thousands of years for decision-making (Alessa et al. 2016). The separation of local and scientific knowledge is thus not clear (Agrawal 1995), despite it being operationalized as such in much DRR research and practice. Some research has sought to push back against this (e.g. Yeh 2016), but distinctions between the two still prevail. For instance, many refer to how local knowledge often needs to be validated by Western science, clearly reflecting a hierarchy. Framing integration this way not only reflects epistemic injustice (whereby the knowledge of some groups is marginalized) (Tsosie 2017), but also has very real practical consequences for collaboration and trust building.

An additional and related concern about the dichotomy between Western science and local knowledge is that neither of these bodies of knowledge are homogenous: within science, various ontologies and epistemologies do not agree with each other (Agrawal 1995; Barber and Haney 2016). Similarly, local knowledge—including Indigenous cosmologies—reflects different groups' worldviews and thus will never be identical and could also conflict with each other. They also interact with each other, have connected histories, and evolve as conditions change (Agrawal 1995). Just as many local people will hold some scientific knowledge, as researchers, we too hold local knowledge (Barber and Haney 2016). Additionally, Indigenous methodologies are often used by Indigenous people in academic research (e.g. Bessarab and Ng'andu 2010). This can further blur the distinction between local and scientific knowledge leading to knowledge hybridity.

2.2 Knowledge integration in EWS

Several frameworks and scholars have called for ways to integrate both knowledge systems for disaster risk management (Gagnon and Berteaux 2009; Ziervogel and Opere 2010; Plotz et al. 2017). However, varied views and definitions on knowledge integration exist. Knowledge integration is the combination of specialized knowledge to reach considerable results (Berggren et al. 2011). The concept is also interpreted as a process of transforming individual knowledge into collective knowledge (Okhuysen and Eisenhardt 2002). In this study, knowledge integration is defined as a collective process of synthesizing or combining specialized yet differentiated local and scientific knowledge possessed by local people and scientists into a common knowledge that is efficient, flexible, and within the scope of decision-making.

Although writing on the role of local knowledge in DRR started in the 1970s, it increased rapidly after the Indian Ocean Tsunami in 2004 and Cyclone Zoe in 2002 (Solomon island) (Yates and Anderson-Berry 2004; Arunotai 2008; Gaillard et al. 2008; Lin and Chang 2020). Despite this surge in reporting of local knowledge in EWS and DRR (Mercer et al. 2010) and institutional calls for people-centred approaches, many of these studies and reports only called for further integration between local and scientific knowledge without providing guidelines on how to do so or examples of successful integration (Kagunyu et al. 2011; Johnston 2015). The call for integration is justified by various arguments: needed to make scientific knowledge and various technologies (e.g. EWS) appropriate for local contexts (Mercer and Kelman 2009; Walshe and Nunn 2012), a means for mobilizing community capacity (Tran et al. 2009), and as a way of 'banking' on the strengths of both local and scientific knowledge; as Mercer (2012) argues, the limitations of one knowledge system can be addressed by the strengths of the other, and vice versa.

There are few concrete examples of frameworks that have outlined ways of combining local and scientific knowledge within the forecasting or monitoring of natural hazards (Mercer et al. 2010; Hiwasaki et al. 2014; Kniveton et al. 2015; Plotz et al. 2017) or what challenges exist for a potential integrating roadmap (Gaillard and Mercer 2012). Mercer et al. (2010), for example, suggest a four-step approach of (1) community engagement, (2) identification of vulnerability factors, (3) identification of local and scientific strategies, and (4) then developing an integrated strategy. These steps do not map directly onto the EWS stages, as the integration can be used for each separate stage. However, the first and second steps connect with the first EWS stage of risk knowledge. This shows that efforts for integration can occur in the different EWS stages, with distinctly different approaches forming a spectrum of ranges of integration.

The limited literature on concrete integration frameworks contrasts with the increase in the use of 'integration' in the context of EWS, indicating there are underexplored questions around what represents equitable knowledge integration and how knowledge is legitimized and where and who legitimizes it. To address these questions, there is a need to understand the assumptions, most common approaches, challenges, and best practices, to evaluate the claimed 'benefits' to the four stages within the EWS.

3 Methodology

To explore how local and scientific knowledge have been integrated within the EWS, a realist systematic literature review was conducted. The focus of a realist review is on in-depth and qualitative analysis, and aims to seek an explanation rather than an empirical truth (Pawson et al. 2005; Thompson et al. 2010). In this study (Fig. 1), peer-reviewed literature was searched via Scopus (Elsevier) and Web of Science (Thomson), the two largest scientific databases for the social sciences and environmental sciences. As found through our search on the academic databases, the literature reflects the work of the people with power in terms of access and agenda setting in the current context of EWS. Many different humanitarian and development actors are active in DRR, whereby they publish their work mostly in grey literature. Therefore, we also conducted a search for grey literature. This

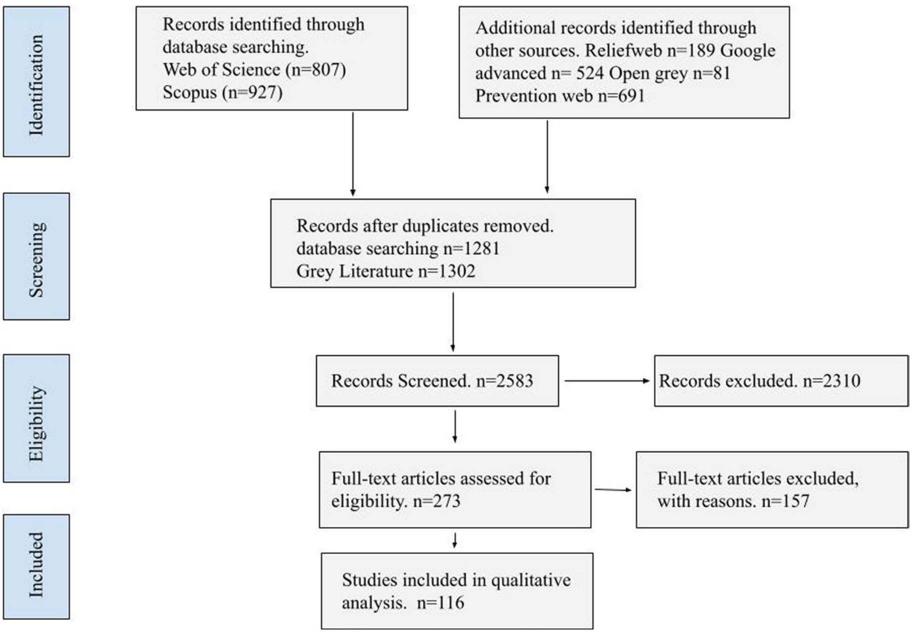

Fig. 1 Literature flow diagram based on Moher et al. (2009)

Table 1 Search string used on 2/09/2021 for Web of Science, Scopus and grey literature search

'Local knowledge' OR 'traditional knowledge' OR 'indigenous knowledge'
AND
'Early warning system' OR 'community*based*Early*warning*system' OR 'community*managed*early*warning*system' OR 'Disaster Risk Reduction' OR 'climate services' OR 'Forecast*' OR 'Early Action' OR 'Impact*based forecast*' OR 'flood' OR 'drought' OR 'landslide' OR 'cyclone' OR 'Hurricane' OR 'Typhoon'

Table 2 Eligibility criteria for the literature review

Included	Excluded
English only Addition/integration/coproduction or any other form of a combination of local knowledge with scientific knowledge In the scope of Early Warning Systems (EWS) and Disaster Risk Reduction (DRR) From 2004 (Indian Ocean Tsunami) to 2021	Only addressing documentation of local knowledge or scientific knowledge for EWS and DRR, not including integration Addressing EWS and DRR outside 'environmental' hazards Commentaries, opinion papers, discussion papers, and editorials

was done via Opengrey, Advanced google search, Reliefweb and Prevention web databases (Godin et al. 2015; Chmutina et al. 2019; Giang et al. 2019).

To capture the variety of literature on this topic and the possibility that some of these articles may find themselves in adjacent fields of literature, various search terms were tested. The exploratory analysis of search terms also yielded literature from the Climate Change Adaptation and Citizen science domains. We excluded these on the ground that the focus is on the framework of Early Warning within DRR (Table 1). Due to EWS and anticipatory action framing in the context of climate change, our focus is on the climate related hazards (e.g. hydro-meteorological). Landslides are in the geophysical hazard domain, but we included them because they are often climate induced (e.g. rainfall-triggered landslides). The resulting search string includes the various terms for local knowledge and Early Warning in DRR.

After literature collection (WoS n = 807, Scopus n = 927, Opengrey n = 81, Preventionweb n = 691, Reliefweb n = 189, Google advanced n = 524) all duplicates were removed and articles were firstly screened on title and abstracts. We included articles from 2004 onwards since the Indian Ocean Tsunami increased attention to the role of local knowledge in wider DRR literature (Rai and Khawas 2019). In the second screening, the full text was evaluated according to the selection criteria (Table 2).

Finally, a total of 116 articles were selected for analysis. We firstly performed a meta-analysis of the articles and reports in a spreadsheet, recording the year of publication, journal, geographic focus, and hazard type according to the international disaster database classification (UNDRR 2020). The next step involved deductive thematic analysis (Braun and Clarke 2006) for all five research questions. The themes within each research questions emerged from the literature and were grouped inductively based on grounded theory approach (Glaser and Strauss 1967), forming the qualitative synthesis coding groups. Only for theme 2 were the qualitatively codes present, according to the four components of the EWS. Our review also included articles that approach knowledge integration beyond EWS and in the wider field of DRR. Due to the broad framing of EWS and its four components

(Sect. 1.1), these articles were also of interest. For instance, the first pillar of EWS is ‘Risk knowledge’ (which also includes risk assessments), which means that articles dealing on integration in risk assessments were also of interest in our review despite their original focus being not on EWS.

3.1 Local knowledge

In this review, we use the term local knowledge from now onwards, even if another term was used in the reviewed studies. This term is used for its more comprehensive conceptual application, meaning all the disaster risk-related knowledge by people in an area, as outlined above.

3.2 Positionality statement

Although some authors are descendants of IK and local knowledge holders, the authors are not part of communities perceived as local knowledge holders. The authors have received mostly scientific knowledge education. Based on this position, our study does not delve into local knowledge and does not assume to understand the epistemic processes. The aim is to reflect on critical questions for the scientific knowledge audience on what integration could mean and what should be questioned.

4 Results

4.1 Literature meta-analysis

A total of 116 papers were identified in the study, 17 of which are from grey literature and 100 peer-reviewed publications. Between 2004 and 2021, there was an upward trend in the number of articles focusing on the integration of local and scientific knowledge (Fig. 2). The years 2019–2021 have the greatest number of articles (n = 48), while 2004–2008 had the least number of articles (n = 5). Over 70% (n = 92) of articles focussed on countries in Asia, Africa, Oceania, and South America (Fig. 3). In addition, the majority of articles with a global or multi-country perspective (n = 17) show results taken from disaster-prone countries in Asia and Africa. Only 11 articles concentrate on European and North American countries, which make up 9% of the total review. Lastly, most articles focused on multiple single hazards (n = 43) and hydrological hazards (n = 40) (Fig. 3).

4.2 Existing practices for integrating knowledges

There is a growing consensus among scholars that there is a need to incorporate local and scientific knowledge in DRR more generally (Smith et al. 2017; Rai and Khawas 2019; Bwambale et al. 2020), and in the creation of EWS more specifically. Pathways identified in the literature for combining knowledges can be classified into 10 broad categories indicating different levels of integration (Table 3).

Participatory approaches were seen as the most concrete way to incorporate local knowledge with scientific knowledge (e.g. Mercer and Kelman 2009; Giordano et al. 2013; Cruz-Bello et al. 2018; Cuaton and Su 2020). Participatory approaches are divided into

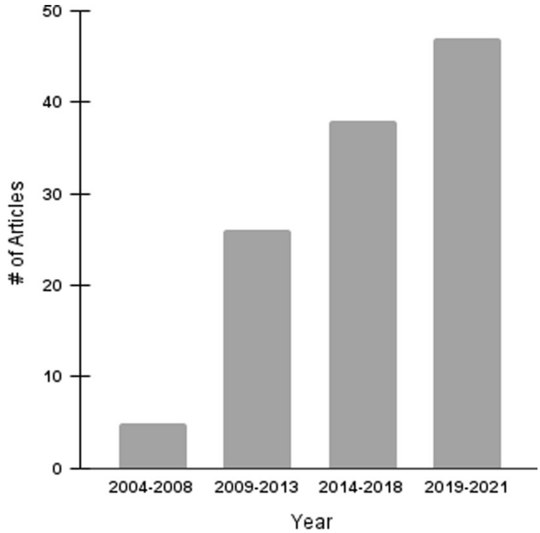

Fig. 2 Number (#) of articles over the years covered in this review: 2004–2021

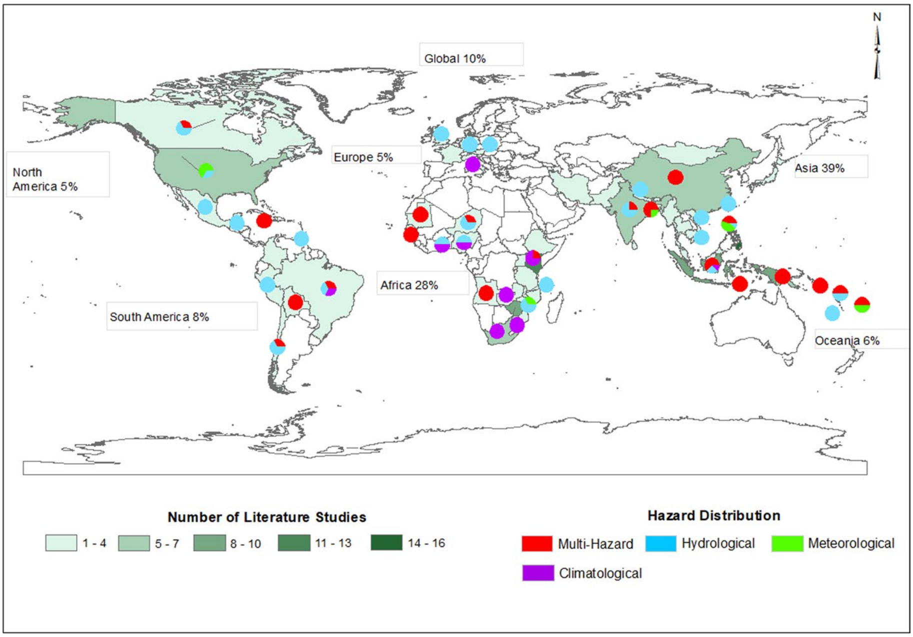

Fig. 3 Map showing the number of literature studies and hazard type per country. Some papers focused on multiple countries, which have been counted for each country. 12 articles had a global focused and could not be assigned to a country

two: community engagement or bringing together community members for discussions, and participatory mapping (which also includes community engagement, but was identified as a separate category due to its technical focus).

Table 3 Pathways for combining local knowledge and scientific knowledge. Number (#) of papers per theme and explanation of the theme. Papers may fall into more than one category

Theme	#	Explanation
Participatory approaches focused on community engagement	64	Bringing together community members people for discussion
Participatory GIS and mapping	45	Coproduction of maps (paper and digital in GIS) integrating inputs of local people
Local knowledge as a starting point for knowledge and triangulation	45	Focusing on the present local knowledge in an area and the way people triangulate this knowledge type with scientific knowledge or DRR processes
Tailoring practices to local levels	28	Using local knowledge to inform and adapt the communication approach of DRR practices based on scientific knowledge
Local and scientific knowledge comparison	21	Comparing local and scientific knowledge and if local knowledge can be validated by scientific knowledge
Forecast technology	18	Focus on how local knowledge is used in forecasting extreme weather and natural hazards
Education	13	Integration of both local and scientific knowledge in education systems and programmes
Infrastructure design	8	Combining knowledges for the design and evaluation of existing and future infrastructures
Citizen/CBON	7	Creation of citizen science or CBON programmes and frameworks
Institutional mechanisms	4	Focus on the internal institutional processes and communication between different organizations, governments etc

Adopting ethnographic methods, including focus group discussion and key informant interviews, offers an opportunity to unveil local knowledge that can improve policies in reducing disaster risk (Cronin et al. 2004; Glaser et al. 2008; Kelman et al. 2012; Tiepolo and Braccio 2017; Ebhuoma 2020; Klonner et al. 2021; Pauli et al. 2021). These methods use past experiences of locals to discover facts, relationships, and new 'truths' surrounding vulnerability to hazards (Mercer and Kelman 2009). A common goal of these community engagement activities is to develop an integrated strategy for DRR by combining local and scientific knowledge bases.

Similar to scholars' community engagement approach, authors also create maps or information systems with local people. Employing a participatory geographic information system (PGIS) or participatory mapping approach contributes to addressing and understanding vulnerabilities through spatially explicit mapping local knowledge (Tran et al. 2009; Valdivia et al. 2010; Giordano et al. 2013; Hung and Chen 2013; Cruz-Bello et al. 2018). This method values the mapping products just as much as the process and enriches academic research by using inclusionary approaches to knowledge production. Overall, there is an emphasis on multi-stakeholder participation in both types of participatory approaches through workshops, meetings, hazard, vulnerability, and capacity and creating a comprehensive disaster historical profile.

Local knowledge as a starting point in knowledge production and its triangulation with scientific knowledge is another common method in our review. Authors seek to ask: 'what sources of early warning information do locals use and how do they utilize it?', as covered by three recent publications. Evidence shows that locals use top-down information from official sources (e.g. government reports) and scientific data but convert it by fitting their unique environmental and social context into this information (Lin and Chang 2020). Although the majority have access to forecasts and predictions, through radios, they did not automatically apply this information to adaptation and risk reduction actions (Grey 2019). Šakić Trogrlić et al. (2019) pointed to the rather complex triangulation process between locally sourced information and official warning available to these communities. What happens on the ground (i.e. triangulation) is often executed in an informal and unstructured manner between different knowledge types. Factors including understanding of the forecast, perceived accuracy of the information, timeous receipt of information, and ability to translate information affect how they would use the scientific data.

In contrast to taking local knowledge as a starting point, another frequently used approach identified in the literature is to validate scientific knowledge with local knowledge or vice versa. Here, researchers' aim in most cases is to validate local indicators through a comparison of LK and scientific measurement or to find a scientific explanation (Chisadza et al. 2014; Hiwasaki et al. 2014). Underlying expectations are the ability to match, overlay or connect local and scientific knowledge.

Practice to inform and adapt the communication approach of DRR practices based on scientific knowledge has also been seen as an approach to integrating local and scientific knowledge. For instance, bridging the strengths of seasonal climate forecasts and local knowledge to deliver an effective drought EWS (Glaser et al. 2008; Walshe and Nunn 2012; Masinde 2015; Rangecroft et al. 2018; DeLorme et al. 2020). Tailoring DRR practices to include local knowledge is suggested to be effective for downscaling and providing easily accessible and understandable information. In relation to tailor-fit practices, incorporating the combination of local and scientific knowledge in educational systems and creating citizen-based programmes are also helpful in increasing the integration of locals and their knowledge. Educating the young can raise awareness of risk and vulnerability among marginalized groups in high-risk areas (Baudoin et al. 2014; Masinde 2020). As a result, opportunities for risk preparedness are identified, allowing for individual and community levels adaptation.

4.3 Focus in the four pillars of Early Warning Systems for integrating knowledges

A significant body of literature explored the risk knowledge pillar in EWS related to natural hazards (Table 4).

The frequent use of participatory methods and participatory mapping also leads to most integration happening in the risk knowledge, and preparedness and response phases of the EWS, under the banner of ‘hazard mapping’ or ‘vulnerability mapping’. There is also a focus on the documentation of both local and scientific knowledge. However, there might not be a concrete database of insights from both branches, but there is almost always an effort to document and maintain these knowledges.

On monitoring and forecasting in EWS, several papers incorporate local risk knowledge into developing monitoring and forecasting tools mainly for slow onset hazards (i.e. drought) (Guthiga and Newsham 2011; Hiwasaki et al. 2014; Masinde 2015; Acharya and Prakash 2019; Syamsidik et al. 2020; Tiepolo et al. 2021). Researchers who focus on methods such as forecast technologies and local knowledge validation tend to incorporate results in the monitoring and forecasting phase. These may be attributed to how maps are used to create forecasting models which are strengthened by input from local actors.

There seems to be less focus on how local and scientific knowledge are integrated to communicate risk and impact of disasters. However, this component is crucial to EWS and often a reason for EWS failing to deliver in practice. The line between local and scientific knowledge is vague in the communication and dissemination phase, whereas clearer borders are depicted in other phases. This can be due to two reasons. First, in most EWS, the nature of communication is unidirectional and goes from a central and national point (i.e. government) to subnational level. This top-down approach can result in not everyone having access to crucial information during a disaster. Second, less attention is paid to the process of information triangulation of disasters in EWS.

4.4 Outcomes of integrating knowledges

Scholars mainly report positive results of integration methods, with 99 papers having positive outcomes. Common reported positive results are *‘better action/communication’, ‘local adaptation of EWS’*, *‘reducing risk’, ‘increasing trust and understanding’, ‘increasing awareness of hazard and vulnerability’,* or *‘capacity building’.* A consensus is that there is a positive perception of sharing, preserving, and combining local and scientific knowledge. However, only 12 papers gave a more neutral view, also highlighting disadvantages. For instance, Acharya and Prakash (2019), discussing local knowledge of flood

Table 4 Number (#) of papers per pillar in the Early Warning Systems (EWS). Papers may fall into more than one category

Pillars in EWS	# papers
Risk Knowledge	73
Monitoring and Forecasting	46
Dissemination and Communication	31
Preparedness and Response	43

forecasting in India, note that gender discrimination was evident in the integration. Women did not receive news of floods directly from officials and had to wait for the men in their household to bring the news to them. A main driver for this finding is that the message is aired through the radio, which needs mediation and interpretation, which is a role played by men. Hence, women become dependent on men to obtain official flood information. Klonner et al. (2016) discuss that only little work was done in incorporating volunteered geographic information in natural hazard analysis. Research needs to focus even more on the interaction of humans and the environment to gain a more holistic understanding of natural hazards. For papers coded under 'local use' and 'triangulation', outcomes were not normatively described either as positive or negative but focused on how triangulation in local areas occurs. On the outcomes for the scientific community, there was a similar trend in emphasizing positive results, with few reflecting on the process of integration.

4.5 Challenges for the integration of local and scientific knowledge in EWS

Our literature review showed multiple obstacles that hinder integration, as shown in Table 5.

Among these challenges, obtaining access to different sorts of resources, including human and financial resources and short time frames emerged to be the most prominent. Ensuring that locals can participate requires a concerted effort to reach out to local stakeholders, request funding for research, and the time to execute the studies (Tran et al. 2009; Magee et al. 2016; Plotz et al. 2017; Klimeš et al. 2019). Despite the goal of incorporating local and scientific knowledge, uneven power dynamics are still rampant in DRR policies and programmes, identified as the second and third most common challenge in our review. In this power dynamics, knowledge hierarchy remains the biggest issue as there can still be a preference for scientific knowledge in research led projects leading to a perception of local knowledge as less valuable. In some contexts, there is more trust in scientific forecasts due to improvements in forecasting models. Hence, even locals shy away from their knowledge and can rely on scientific data (Kniveton et al. 2015).

However, what remains a crucial issue from these papers is the often reported lack of trust between local, scientific, and practitioner communities. Various papers also report that locals with strong beliefs in their knowledge are often sceptical of the new scientific data based on large-scale approaches they receive, as there is still uncertainty with scientific knowledge, such as limited forecast skill of weather and impact-based forecasts and limited resolution and accuracy of risk and impact maps. Locals also experience that many international or national NGOs and governmental organizations do not have the right knowledge, skills, and resources to act early or respond fast after a disaster, for example, if there is a long delay before help arrives (Taylor et al. 2020). This is also tied to a lack of confidence in institutions like the government and organizations that work with communities on DRR. This lack of trust can be rooted in the fact that information at a local level is often not captured in scientific data, and thus, locals feel 'left out' in the discussions of EWS (Gwenzi et al. 2016).

Another highly reported challenge and an issue related to power relations affecting the incorporation of local and scientific knowledge is the ability of locals to 'understand' technological systems. This includes limited access to the necessary technology (such as a smartphone with the internet). They are not empowered and capacitated to understand the scientific weather reports that come from meteorological agencies (Gaillard and Mercer 2012; Carby 2015; Mutasa 2015; Rai and Khawas 2019). If this continues, the imposition

Table 5 Number (#) of papers per challenge theme for knowledge integration in EWS. Explanation refers to interpretation of the theme. Papers may fall into more than one category

Challenge	#	Explanation
Varying perceptions and understanding of knowledge of risk and EWS	56	Varying epistemologies, ontologies on what constitutes disaster risk and what is a valid form of knowledge lead to different understandings of early warnings, thus affecting the understanding of technology systems
Dominance of scientific knowledge	41	Unbalanced perception towards local and scientific knowledge wherein scientific knowledge is still viewed as more valuable;
Power relations between different stakeholders	40	The positionality of higher-level stakeholders and outsiders is reflected in the integration processes and marginalized groups are often excluded in the process of setting up the EWS in a region
Trust issues	32	Relations between stakeholders in sharing knowledge and believing that knowledge to be correct is built on trust, which is often lacking
Communication Challenges	33	Different cultures and approaches to communication can lead to misunderstanding
Model and forecast uncertainty	28	Uncertainties of forecasts and models are challenging to communicate and transfer to a local scale
Documentation and intergenerational transmission of local knowledge	23	Documentation of local knowledge and transmission of local knowledge to younger generations
Environmental changes	21	Changes in the environment, such as climate change, make knowledge about the environment less reliable
Access to resources	15	Integration can be expensive and time-consuming, and there is a lack of resources to integrate local and scientific knowledge fully
Local knowledge not possible to be scaled up	6	Due to LK being context-based, integrating local and scientific knowledge in a project in a specific region cannot be applied in other regions or for individual cases. There is no community benefit due to different contexts

of scientific–technocratic knowledge may only enhance vulnerability instead of building communities' inner strengths and capabilities (Choudhury et al. 2021). The wording of 'understand' shifts the responsibility to the locals and does not elaborate on what understanding requires, e.g. technical knowledge or translation of information to other contexts. Only some papers reported that communities and researchers have different views on risk and hazard, especially due to the approach to scale or lack of understanding by researchers of place-based local knowledge.

Another challenge is how to communicate scientific knowledge. As an example, Klonner (2016) suggests a lack of understanding of which channels and content formats are best suited to communicate the local and scientific knowledge. This could lead to the insufficient applicability of the information in a hazard analysis context and a lack of the information being received, understood and acted upon. Translation to the local language is also a challenge in communication as most locals can only understand warnings in their local language (Pennesi 2007; Rangecroft et al. 2018; Grey 2019). Where some papers claim knowledge understanding is a challenge, most frequently the understanding of scientific knowledge by locals, other papers approach this as a communication challenge. Overall, we also recognize that there is a focus on internal constraints and little mentioning of external forces (e.g. globalization, market pressures, multi-scale environment threats), making integration difficult, as discussed in Loch and Riechers (2021).

4.6 Enablers for the integration of local and scientific knowledge in EWS

There is an abundance of enablers suggested in the literature (Table 6), to help scholars integrate local and scientific knowledge better, as compared to the reported challenges and inhibitors.

To boost local and scientific knowledge integration, it is key to obey local customs and implement knowledge on the locals' own terms. This can also be perceived as a method to counter the unequal power relations in developing EWS. There could also be an assurance that components of the EWS, such as Monitoring and Forecasting, can be made in the own terms of locals (Ebhuoma 2020). It is important that locals maintain their identities and perhaps develop their own knowledge independently (Mutasa 2015). This can avoid epistemological and ontological confrontations (e.g. what constitutes knowledge and how can knowledge be gained). Moreover, local communities must understand issues of hazard and vulnerability in their own terms and use that to decide if they want to proceed with the 'integration process' (Mercer et al. 2010).

Locals should be able to understand the different methods used to develop and run an EWS to be able to engage in the codevelopment of an EWS or become an active recipients of the warnings of an EWS. This can be done by using local language and adapting to local customs within the EWS process. This will help empower local communities to understand disasters and their risk in the best way possible. Pennesi et al. (2007) give concrete examples of locally adapted communication, including various aspects such as cultural context, word use, multiple definitions, the validity of non-scientific concepts, education, translation, and explanation of the limitations of the research. Early and ongoing dialogues with local communities and meaningful communication help address emerging issues with collaborations, especially with integrating different methods.

Finally, building trust is important and can only be built up over a large span of time. One cannot just come into communities without the necessary processes of creating trust between stakeholders. This is identified as one of the main challenges but equally often

Table 6 Number (#) of papers mentioning the enabler theme. Explanation elaborates on the interpretation of the theme. Papers may fall into more than one category

Enablers	#	Explanation
Safeguard measures for interaction	38	Ensuring that there are safeguard measures in place to reduce enforcement of outsider assumptions; compensate participants for participation
Local adaptation and focus	36	Local customs and local knowledge approach; Adhere to local customs, and their influence, leaving local knowledge for EWS on its terms
Trust building	27	Focus on activities that build trust between stakeholders
Considerate and tailored communication	27	Focus on making results easily understandable, thinking about uncertainties and local language use
Particular method suggested	25	The best practice suggestion is a particular method of integration; often the specific presented method
Education and training for locals	25	Emphasis on integrating local and scientific knowledge hybridity in educational programmes such as in schools (children) and training with the project or programme for different stakeholders
Documentation and promotion to younger generation	22	Document local knowledge and involve the younger generation in local knowledge understanding and use
Develop knowledges separately	17	Ensuring there is respect between stakeholders and their knowledge, and this avoids epistemological and ontological conflicts
Multiple sources of local knowledge	17	When integrating local and scientific knowledge, use multiple sources (e.g. people, reports), in particular to identify local knowledge
Systematic process of integration	16	Using a structured and replicable way of bringing people together in the process of knowledge integration to validate local knowledge and integrate knowledges
Local knowledge validation	10	More work on validating local knowledge
Bottom-up and top-down approaches	4	Use a combination of top-down and bottom-up approaches to integrate local and scientific knowledge
Reiterative cycles	3	Throughout the integration process, have reiterative cycles of feedback, allowing all involved stakeholders to have an ongoing opportunity to input
Ongoing commitment	1	When working on integration, ensure there is an ongoing engagement and work with the stakeholders and participants. This also means from the start planning commitment

suggested as an enabler. However, concrete ways of building trust are rarely suggested, and it often remains pitched only as a concept. Trust building is needed between the government, local actors, DRR actors, and project implementers. External actors must improve their efforts in nurturing local peoples' genuine participation in the assessment of their local knowledge skills and resources (Ton et al. 2017; Andersson et al. 2020; Cuaton and Su 2020). Intellectual honesty by researchers must also be required to admit the uncertainties in the scientific methods they use (Guthiga and Newsham 2011). In sum, building an ethical and trustworthy relationship through interaction between stakeholders is a must to ensure that integration is appropriate and can lead to creating an effective EWS for all stakeholders.

5 Discussion

The meta-analysis of the literature shows that most publications are in relation to case studies in Africa and Asia, and are mostly on multi-hazards and hydrological hazards. Over time, there is an increase in publications on the integration of knowledges in EWS (Fig. 2). In addition to the increased attention to local knowledge in DRR after the Indian Ocean Tsunami of 2004 (Rai and Khawas 2019) the general push for community participation in the Hyogo Framework for Action (2005–2015) and Sendai Framework (2015–2030), as global DRR policies, have provided a justification for more work on integrating local and scientific knowledge. However, the promotion in these frameworks as justification for knowledge integration has not automatically led to reflection on the quality of knowledges' representation with the framing of 'integration'. Our discussion focuses on this aspect and gives a critical evaluation through three lenses: *Approaches to 'integration', On 'successful' integration and approaches to knowledge* and *A way forward: learning across.*

5.1 Approaches to 'integration'

5.1.1 Spectrum of 'integration'

Our literature review shows that participatory methods (both focused on community engagement and GIS and mapping) are the most popular form of 'integrating' knowledges. This trend is most likely embedded in the popularity of participatory methodologies in other fields, such as participatory rural appraisals (e.g. Chambers 1994). In the literature on participatory methods, or the later introduced citizen science and coproduction, 'ladders' of the level of participation are often created (e.g. Arnstein 1969; Walker et al. 2021). These 'ladders' provide a ranking of the level of participation, from low to high. Similarly, the identified forms of integration in this study also represent different forms of integration connected to discussions about 'ladders' in citizen science, coproduction, or participatory approach literature.

Noticeable is that rarely concrete models of integration are given (Mercer et al. 2010; Gaillard and Mercer 2012; Hiwasaki et al. 2014; Kniveton et al. 2015; Tiepolo et al. 2019), where the process of integration is outlined. This challenges our ability to establish an explicit 'ladder of integration' here,

but we can identify extremes. The focus on local and scientific knowledge validation is low on the ladder of integration, whereas certain types of participatory approaches will be high on the ladder. What we can deduct from Table 3 is a difference in the timing of 'integration' within the overall integration process. A number of papers (n = 19) suggest developing knowledges separately due to their epistemological and ontological differences (e.g. Dube et al. 2016). Guthiga and Newsham (2011) give an example where rainmakers suspected that meteorologists would steal their knowledge. Safeguarding the relations and the epistemic process was done through the separation of duties and knowledge construction. The safeguarding also addresses the concern of separating knowledge from its local context, which can have significant risks for local communities, such as misinterpretation (Agrawal 2002). On the other hand, some have suggested that addressing the most commonly mentioned challenges (e.g. finding common ground, reaching an understanding, and achieving trust; Table 5) can be achieved by including dialogue throughout the integration process. The openness can contribute to a better understanding of other epistemic processes, and the respectful discussions can build trust relations. Therefore, there are mixed suggestions on the type of integration process that is most appropriate.

5.1.2 'Integration' starting point dichotomy

Further unpacking the differences in integration approaches, we identify a contrast in the starting point of the integration process: the people or the technology. 'The people' starting point focuses on what scientific knowledge reaches the local context and how this is triangulated with other knowledges as well as which processes people have within their community, such as passing local knowledge on from generation to generation or how people act on their own local knowledge (e.g. Gwenzi et al. 2016; Šakić Trogrlić et al. 2019). Within this category, there are also two papers (Baudoin et al. 2014; Marin et al. 2020) approaching integration as an organizational matter of education, policy, and representation of government and community organizations. 'The technology' as a starting point represents the scientific knowledge side (e.g. the use of forecasts based on meteorological and hydrological scientific models, hazard maps based on scientific data sets) and centres on ways to include the local knowledge in a pre-defined scientific knowledge process or how local knowledge can be integrated with already established scientific procedures and tools (e.g. mapping, GIS or the weather forecast technology) (Tran et al. 2009; Valdivia et al. 2010; Giordano et al. 2013; Hung and Chen 2013; Cruz-Bello et al. 2018).

Reflecting on this dichotomy, the latter comes from a technocratic point of view (Hewitt 1983), whereas the first is embedded in knowledge as a social construct. This dichotomy can also be observed in the framing of challenges for integration; for example, some papers mention *'communication challenges'*, where improvement is needed on the communicators' side, whereas others frame it as a *'lack of understanding'* of the technical methods and processes by the participants. Within the analysis of the enablers, there are mostly themes connected to social interaction, such as the *'safeguard measures for interaction', 'local adaptation and focus', 'trust building'*. These should address the major identified challenges of *'dominance of scientific knowledge'* in the process of integration and associated *'power relations'*. There is, however, little elaboration in the literature on what should be changed, which suggests that current narratives of integration are limited in their attention to social processes.

5.1.3 Power in 'integration' processes

The above categorization of integration, from spectrum to dichotomy, raises the question of what 'integration' is. Integration could be defined as the combination of elements to form a whole, although in most literature, it implies incorporation of one component into another (Tengö et al. 2014). For example, papers such as Ahmed et al. (2019), Grey (2019), Hiwasaki et al. (2015), Lin and Chang (2020) approach integration as the validation of local knowledge observations and indicators. Hiwasaki et al. (2015) outline where local and scientific knowledge overlap or local knowledge can be validated by scientific knowledge. This framework envisioned a more important role of science compared to Mercer et al.'s framework (2010), where the focus lies on first understanding vulnerability factors in the 'integration' process and then developing separate knowledge strategies, which can be negotiated into an integrated strategy. Hiwasaki et al. 's approach (2015) to integration builds on the premise that only local knowledge indicators which can be backed up by scientific knowledge are feasible for integration. Such an approach pays no attention to the implications of power relations within the local level (Šakić Trogrlić et al. 2021) and between the scientists and participants, but highly influences what knowledge serves as input for the integration process and who has power over what this process looks like. When local knowledge is sought to inform environmental decision-making in EWS, it implies that local people are considered mere stakeholders instead of self-determining nations with rights and responsibilities regarding their knowledge systems. Local knowledge is not respected when knowledge is treated as mere data to back or authenticate scientific knowledge (Latulippe and Klenk 2020).

Power relations and knowledge legitimization are rarely discussed or reflected on. However, Balay-As et al. (2018) deconstruct power dynamics to provide ways for more meaningful participation. They suggest factors such as gender, social status, and community relationships need to be considered to create more equal opportunity for participation. Their observations show that factors such as education level and influence affect who takes decisions and is allowed to participate in knowledge construction processes. This is prevalent on both local and global scales, e.g. researchers from the national level working at the local level or from the Global North working on knowledge integration in the Global South (esp. since most studies in our review take place in the Global South). This means there is a need to acknowledge the social interaction and processes besides the most common 'technocratic' scientific knowledge integration process.

5.2 On 'successful' integration and approaches to knowledge

Overall, 95% of the reviewed literature only reported positive outcomes from their 'integration' efforts. These justifications fit the call for local knowledge integration in global DRR policies. The representation of mostly positive outcomes in the 'integration' literature can also be found in the citizen science scholarship. Most of these positive results are potential or inferred (Walker et al. 2021). Measuring the outcomes of the process of integration is challenging, and few do so. Positive outcomes were reported by Kniveton et al. (2015), where participatory downscaling weather and climate forecasts improved human capital and crop decision-making, resulting in higher yields and early action. However, Klimeš (2019) points out that success is often short term, suggesting that there were no transformative changes beyond the project timeframe. Equally, in the case of participatory GIS mapping, Cruz-Bello (2018) mentioned there was no training in GIS for the community. These reflections raise the question of who benefits from the integration, how success is measured and on what timescale.

The trend of reporting positive outcomes of integration is partly due to 'romanticization' of local knowledge, as discussed in (Antweiler 1998; Wohling 2009; Obermeister 2019).

To address this challenge, it is important to reflect on what local and scientific knowledge can or cannot do, e.g. exaggerating the role of local knowledge in 'solving' problems created by bigger issues such as environmental degradation and climate change intensifying flooding at local levels. Equally, Walshe & Nunn (2012) and Dube et al. (2016) reported local knowledge use was regarded as more relevant in the community's particular situations, and non-local knowledge is considered alien and less useful, particularly when the information is in an unfamiliar technical nature. The need to acknowledge the importance of local knowledge besides the standardized scientific knowledge does not mean it is appropriate in every context to 'integrate' knowledges. In our review, various papers (n = 19) suggest developing knowledge separately to ensure value systems are safeguarded and accounted for. The literature on triangulation, social, and interaction dynamics ('the people' focus in integration approach) can support the understanding of knowledge use in different contexts. To this end, Dube et al. (2016) highlight that integration or 'coproduction' is not something newly invented by the scientific knowledge community, but has always taken place.

Current scientific knowledge approaches often map knowledges as binary, namely local and scientific knowledge (e.g. Ziervogel and Opere 2010; Masinde 2015), as opposed to approaching knowledge as plural. The literature focusing on triangulation acknowledge that all knowledge systems are dynamic and ultimately hybrid, as no knowledge system has developed in isolation (e.g. Lauer 2012; Mutasa 2015; Dube et al. 2016; Lin and Chang 2020). The search for which knowledge is the most distinct risks marginalizing the other knowledge, makes one knowledge dominant and challenges equal 'integration' (Mutasa 2015). Consequently, the relationships that compose knowledge integration maybe transactional and extractive (Latulippe and Klenk 2020). Also, the literature on knowledge integration seems to uphold the notion that research is an activity that can be separated from the knowledge holders, practices, and local politics, such as peer-reviewed processes (Klenk and Meehan 2017). With this perspective, knowledge integration is projected in some literature as the sole advisor or facilitator of knowledge systems instead of being instrumental and constitutive of how different trajectories and futures (van der Molen 2018) can be attained in the EWS sector.

In reality, the mixture leads to useful action, although the composition may differ for different groups (Mercer et al. 2012). For example, younger generations who have been exposed more to scientific knowledge are more attracted to and trust technocratic scientific knowledge (Choudhury et al. 2021). However, there is also a risk that local knowledge may 'disappear' since it is usually expressed orally by older generations and rarely documented; hence, such knowledge may disappear with the passage of older generations (Chang'a et al. 2010; Chanza and Mafongova 2017). Additionally, there are knowledge synergies in terms of time and spatial scales or understanding of ecological processes. Our understanding of knowledge (e.g. binary or plural) has fundamental implications for what integration means and how it is approached (e.g. the identified dichotomy at the starting point of integration processes).

5.3 A way forward: from 'integration' to 'learning across'

The wording of integration in itself seems to underline a dichotomy of knowledges, where one is incorporated with another. As Tengö et al. (2014, p. 43) point out, '*it is important to differentiate among (a) integration of knowledge, (b) parallel approaches to developing synergies across knowledge systems, and (c) coproduction of knowledge*'. As opposed to the integration, a parallel approach centres around complementaries and synergies across knowledges. Coproduction implies the ongoing conjoint process of knowledge construction throughout all phases in the process. As our EWS literature review outlines, different contexts (and each EWS component) may require different approaches. It will also be necessary to regularly 'recalibrate' the integration as changes can take place in both LK due to, for example, climate change or changes in LK holders (e.g. migrants that settle in an area to which they are new) and SK due to, for example, advances in science or new and better measurement data. However, the most common identified challenges in the literature (e.g. *'Varying perceptions and understanding of knowledge of risk and EWS', 'trust' and 'power relations')* lay in the domain of social dynamics and relations. This implies that attention to process facilitation, assumptions and power dynamics (e.g. what form of 'integration', is it realistic or romanticized, who benefits from the outcomes) is as important as the technocratic knowledge on EWS. Moving from 'integration' to learning across knowledges can provide space for a plurality of knowledge and process adaptation to the local context.

We end this discussion with a word of caution. It would be incorrect to interpret the preceding discussion as suggesting that integration of knowledges should not be pursued. We need insights from multiple complementary knowledges to address complex challenges in EWS and DRR. Even conflicting evidence between knowledges is valuable and should not be hidden, as it can help develop knowledge for appropriate decision-making. Our goal has been to evaluate the current literature and highlight that efforts of 'integration' require asking some critical questions about the assumptions, goals, outcomes, and process. Similar discussions can be found in the fields of Climate Change Adaptation or Climate Services. These learnings and challenges can be more widely applied and connect discussions across fields.

6 Conclusion

In this realist systematic review, we aim to understand and outline how local and scientific knowledge integration is framed in EWS in DRR. We focus on: (1) existing approaches to integration, (2) where in the EWS integration is happening, (3) challenges of integration, (4) outcomes of integration, and (5) enablers of integration. Secondly, we critically discuss the extent and quality of 'integration', and what this means for EWS outcomes. Our goal has been to evaluate the current literature and highlight that efforts of 'integration' require asking some critical questions about the assumptions, goals, outcomes and process.

Our meta-analysis shows an increase in publications since 2004 (Indian Ocean Tsunami) on the integration of local and scientific knowledge for EWS, with a focus on the Global South, and multi-hazards and hydrological hazards. Focusing on the approaches and framing of integration, there is a spectrum of integration, with a starting point dichotomy: a focus on the people or the technology. Most popular integration approaches are *'participatory methods for community engagement'*, *'participatory GIS mapping'* (technology), and *'triangulation'* (people). The current processes of integration are often limited in their attention to social interaction and power relations. This is represented in the most cited challenges: *'Varying perceptions and understanding of knowledge of risk and EWS', 'Dominance of scientific knowledge' 'Trust issues' and 'Power relations'* and suggested enablers: *'Trust building', 'Local adaptation and focus', 'Safeguard measures for interaction'.* However, these challenges and enablers are rarely unpacked. We found that current forms of integration disregard implications of power dynamics and of approaching knowledge as binary instead of plural.

In current integration approaches, the knowledge approach is often binary and one-off, and critical evaluation shows that it is crucial to understand what knowledge can and cannot address in different contexts and across time and space. Integration as an ultimate problem solver should therefore not be blindly assumed. Equally, we do need insights from multiple complementary knowledges to address complex challenges in EWS and DRR. We argue that how we approach different knowledges in EWS has fundamental implications for the approaches to integration and its meaning. This includes acknowledgement of hybrid knowledge use as a reality for EWS, and the role of social relations and power dynamics. Moving from 'integration' to learning across knowledges provides space for a plurality of knowledge and process adaptation to the local context.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11069-022-05468-8.

Acknowledgements We gratefully acknowledge funding from the UK Research and Innovation as part of the NERC Science for Humanitarian Emergencies and Relief programme under IPACE-Malawi (NE/S005900/1). We greatly appreciate the feedback from Dr Stephen Whitfield on an earlier version of the manuscript. In addition, Marc van den Homberg was partly supported by the Netherlands Red Cross Princess Margriet Fund and the The Innovative Approaches to Response Preparedness program, funded by the IKEA Foundation.

Author's contributions TH, RST, and MvdH were responsible for conceptualization and methodology; TH, HB, and RST carried out formal analysis and investigation; TH and HB wrote the original draft; all authors were involved in writing, framing, reviewing, and editing; and MvdH and HB took part in visualization. All authors read and approved the final manuscript.

Funding This work was supported by NERC Science for Humanitarian Emergencies and Relief programme under IPACE-Malawi (NE/S005900/1). In addition, Marc van den Homberg was partly supported by the Netherlands Red Cross Princess Margriet Fund and the The Innovative Approaches to Response Preparedness program, funded by the IKEA Foundation.

Declarations

Conflict of interest Authors have no competing interest to declare that are relevant to the content of this article.

References

Acharya A, Prakash A (2019) When the river talks to its people: local knowledge-based flood forecasting in Gandak River basin, India. Environ Dev 31:55–67. https://doi.org/10.1016/j.envdev.2018.12.003

Agrawal A (1995) Dismantling the divide between indigenous and scientific knowledge. Dev Change 26:413–439. https://doi.org/10.1111/j.1467-7660.1995.tb00560.x

Agrawal A (2002) Indigenous knowledge and the politics of classification. Int Soc Sci J 54:287–297. https://doi.org/10.1111/1468-2451.00382

Ahmed B, Sammonds P, Saville NM et al (2019) Indigenous mountain people's risk perception to environmental hazards in border conflict areas. Int J Disaster Risk Reduct 35:101063. https://doi.org/10.1016/j.ijdrr.2019.01.002

Alessa L, Kliskey A, Gamble J et al (2016) The role of Indigenous science and local knowledge in integrated observing systems: moving toward adaptive capacity indices and early warning systems. Sustain Sci 11:91–102. https://doi.org/10.1007/s11625-015-0295-7

Andersson L, Wilk J, Graham LP et al (2020) Local early warning systems for drought—Could they add value to nationally disseminated seasonal climate forecasts? Weather Clim Extrem 28:100241. https://doi.org/10.1016/j.wace.2019.100241

Antweiler C (1998) Local Knowledge and Local Knowing. An Anthropological Analysis of Contested "Cultural Products'' in the Context of Development." Source Anthr, pp 469–494

Arnstein SR (1969) A Ladder of Citizen Participation. J Am Inst Planners 35:216–224

Arunotai N (2008) Saved by an old legend and a keen observation: the case of Moken Sea Nomads in Thailand. In: Shaw R, Uy N, Baumwoll J (eds) Indigenous knowledge for disaster risk reduction: good practices and lessons learnt from the Asia-Pacific Region. UNISDR Asia and Pacific, Bangkok, pp 73–78

Balay-As M, Marlowe J, Gaillard JC (2018) Deconstructing the binary between indigenous and scientific knowledge in disaster risk reduction: approaches to high impact weather hazards. Int J Disaster Risk Reduct 30:18–24. https://doi.org/10.1016/j.ijdrr.2018.03.013

Balehegn M, Balehey S, Fu C, Liang W (2019) Indigenous weather and climate forecasting knowledge among Afar pastoralists of north eastern Ethiopia: Role in adaptation to weather and climate variability. Pastoralism 9:143. https://doi.org/10.1186/s13570-019-0143-y

Barber K, Haney TJ (2016) The experiential gap in disaster research: Feminist epistemology and the contribution of local affected researchers. Sociol Spectr 36:57–74. https://doi.org/10.1080/02732173.2015.1086287

Baudoin M-A, Henly-Shepard S, Fernando N, et al (2014) Early warning systems and livelihood resilience: Exploring opportunities for community participation. UNU-EHS Working Paper Series, No.11. Bonn, Germany

Berggren C, Bergek A, Bengtsson L, Söderlund J (2011) Exploring Knowledge Integration and Innovation. In: Berggren C, Bergek A, Bengtsson L, et al. (eds) Knowledge Integration and Innovation: Critical Challenges Facing International Technology-based Firms. Oxford University Press, Oxford, UK

Bessarab D, Ng'andu B (2010) Yarning about yarning as a legitimate method in indigenous research. Int J Crit Indig Stud 3:37–50. https://doi.org/10.5204/ijcis.v3i1.57

Braun V, Clarke V (2006) Using thematic analysis in psychology. Qual Res Psychol 3:77–101. https://doi.org/10.1191/1478088706qp063oa

Bwambale B, Nyeko M, Muhumuza M, Kervyn M (2020) Questioning knowledge foundation: What is the best way to integrate knowledge to achieve substantial disaster risk reduction? Int J Disaster Risk Reduct 51:101850. https://doi.org/10.1016/J.IJDRR.2020.101850

Calvel A, Werner M, van den Homberg M et al (2020) Communication structures and decision making cues and criteria to support effective drought warning in Central Malawi. Front Clim 16:578327. https://doi.org/10.3389/FCLIM.2020.578327

Carby B (2015) Beyond the community: Integrating local and scientific knowledge in the formal development approval process in Jamaica. Environ Hazards 14:252–269. https://doi.org/10.1080/17477891.2015.1058740

Chambers R (1994) The Origins and Practice of Participatory Rural Appraisal. World Dev 22:953–969. https://doi.org/10.1016/0305-750X(94)90141-4

Chang'a L, Yanda P, Ngana J (2010) Indigenous knowledge in seasonal rainfall prediction in Tanzania: a case of the South-western Highland of Tanzania. J Geogr Reg Plan 3:66–72

Chanza N, Mafongova PL (2017) Indigenous-based climate science from the Zimbabwean experience: From impact identification, mitigation and adaptation. . In: Mafongoya PL, Ajayi O (eds) Indigenous Knowledge Systems and Climate Change Management in Africa. CTA, Wageningen, The Netherlands

Chisadza B, Tumbare MJ, Nyabeze WR, Nhapi I (2014) Validation of local knowledge drought forecasting systems in the Limpopo River Basin in Southern Africa. Disaster Prev Manag 23:551–566. https://doi.org/10.1108/DPM-02-2014-0032

Chmutina K, Von Meding J, Bosher LS (2019) Language matters: Dangers of the "natural disaster" misnomer

Choudhury MUI, Emdad Haque C, Nishat A, Byrne S (2021) Social learning for building community resilience to cyclones: Role of indigenous and local knowledge, power, and institutions in coastal bangladesh. Ecol Soc 26:105. https://doi.org/10.5751/ES-12107-260105

Codjoe SNA, Owusu G, Burkett V (2014) Perception, experience, and indigenous knowledge of climate change and variability: The case of Accra, a sub-Saharan African city. Reg Environ Chang 14:369–383. https://doi.org/10.1007/S10113-013-0500-0/TABLES/3

Cronin SJ, Gaylord DR, Charley D et al (2004) Participatory methods of incorporating scientific with traditional knowledge for volcanic hazard management on Ambae Island, Vanuatu. Bull Volcanol 66:652–668. https://doi.org/10.1007/s00445-004-0347-9

Cruz-Bello GM, Alfie-Cohen M, Morales-Zaragoza NA, et al (2018) Flood vulnerability reduction, using a partial participatory GIS approach. A study case in Baja California Sur, Mexico. In: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives. pp 185–190

Cuaton GP, Su Y (2020) Local-indigenous knowledge on disaster risk reduction: Insights from the Mamanwa indigenous peoples in Basey, Samar after Typhoon Haiyan in the Philippines. Int J Disaster Risk Reduct 48:101596. https://doi.org/10.1016/j.ijdrr.2020.101596

Dekens J (2007) Local Knowledge for Disaster Preparedness: A literature Review. Nepal, Kathmandu

DeLorme DE, Stephens SH, Bilskie MV, Hagen SC (2020) Coastal decision-makers' perspectives on updating storm surge guidance tools. J Contingencies Cris Manag 28:158–168. https://doi.org/10.1111/1468-5973.12291

Derbile EK, Jarawura FX, Dombo MY (2016) Climate change, local knowledge and climate change adaptation in Ghana. Adapt to Clim Chang Var Rural West Africa 83–102. https://doi.org/10.1007/978-3-319-31499-0_6

Dube T, Moyo P, Ndlovu S, Phiri K (2016) Towards a framework for the integration of traditional ecological knowledge and meteorological science in seasonal climate forecasting: the case of smallholder farmers in Zimbabwe. J Hum Ecol 54:49–58. https://doi.org/10.1080/09709274.2016.11906986

Ebhuoma EE (2020) A framework for integrating scientific forecasts with indigenous systems of weather forecasting in southern Nigeria. Dev Pract 30:472–484. https://doi.org/10.1080/09614524.2020.1723494

Gagnon CA, Berteaux D (2009) Integrating traditional ecological knowledge and ecological science: A question of scale. Ecol Soc 14. https://doi.org/10.5751/ES-02923-140219

Gaillard JC, Clavé E, Vibert O et al (2008) Ethnic groups' response to the 26 December 2004 earthquake and tsunami in Aceh, Indonesia. Nat Hazards 47:17–38. https://doi.org/10.1007/s11069-007-9193-3

Gaillard JC, Mercer J (2012) From knowledge to action: Bridging gaps in disaster risk reduction. Prog Hum Geogr 37:93–114. https://doi.org/10.1177/0309132512446717

Giang HTN, Ahmed AM, Fala RY et al (2019) Methodological steps used by authors of systematic reviews and meta-analyses of clinical trials: a cross-sectional study. BMC Med Res Methodol 19. https://doi.org/10.1186/s12874-019-0780-2

Giordano R, Preziosi E, Romano E (2013) Integration of local and scientific knowledge to support drought impact monitoring: Some hints from an Italian case study. Nat Hazards 69:523–544. https://doi.org/10.1007/s11069-013-0724-9

Glaser BG, Strauss AL (1967) The Discovery of Grounded Theory: Strategies for Qualitative Research. AldineTransaction, New Brunswick, USA

Glaser S, Glaser R, Drescher A, et al (2008) Geo-communication for risk assessment and catastrophe prevention of flood events in the coastal areas of Chennai. In: Proc. iEMSs 4th Biennial Meeting - Int. Congress on Environmental Modelling and Software: Integrating Sciences and Information Technology for Environmental Assessment and Decision Making, iEMSs 2008. pp 1569–1577

Godin K, Stapleton J, Kirkpatrick SI et al (2015). Applying Systematic Review Search Methods to the Grey Literature: a Case Study Examining Guidelines for School-Based Breakfast Programs in Canada. https://doi.org/10.1186/s13643-015-0125-0

Grey MS (2019) Accessing seasonal weather forecasts and drought prediction information for rural households in Chirumhanzu district, Zimbabwe. Jàmbá J Disaster Risk Stud 11:1–9. https://doi.org/10.4102/jamba.v11i1.777

Guthiga P, Newsham A (2011) Meteorologists Meeting Rainmakers: Indigenous Knowledge and Climate Policy Processes in Kenya. IDS Bull 42:104–109. https://doi.org/10.1111/j.1759-5436.2011.00228.x

Gwenzi J, Mashonjowa E, Mafongoya P et al (2016) The use of Indigenous Knowledge Systems for short and long range rainfall prediction and farmers' perceptions of science-based. Int J Clim Chang Strateg Manag a 8:440–462. https://doi.org/10.1111/j.1540-8191.2009.00972.x

Hewitt C, Mason S, Walland D (2012). The Global Framework for Climate Services. https://doi.org/10.1038/nclimate1745

Hewitt K (1983) The idea of calamity in a technocratic age. Interpret Calam 3–32. https://doi.org/10.4324/9780429329579-1/IDEA-CALAMITY-TECHNOCRATIC-AGE-KENNETH-HEWITT

Hiwasaki L, Luna E, Adriano Marçal J et al (2015) Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia. Clim Change 128:35–56. https://doi.org/10.1007/s10584-014-1288-8

Hiwasaki L, Luna E, Syamsidik SR (2014) Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. Int J Disaster Risk Reduct 10:15–27. https://doi.org/10.1016/j.ijdrr.2014.07.007

van den Homberg M, McQuistan C (2019) Technology for climate justice: a reporting framework for loss and damage as part of key global agreements. In: Mechler R, Bouwer LM, Schinko T et al (eds) Loss and Damage from Climate Change. Springer, pp 513–545

Hung HC, Chen LY (2013) Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: Application to the river basin management in Taiwan. Clim Change 120:491–507. https://doi.org/10.1007/s10584-013-0819-z

IFRC (2021) IFRC Operational Framework for Anticipatory Action 2021–2025

Iloka NG (2016) Indigenous knowledge for disaster risk reduction: An African perspective. Jàmbá J Disaster Risk Stud 8:1–7. https://doi.org/10.4102/jamba.v8i1.272

Ingram KT, Roncoli MC, Kirshen PH (2002) Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. Agric Syst 74:331–349. https://doi.org/10.1016/S0308-521X(02)00044-6

IPCC (2021) Climate Change 2021: The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press., Cambridge, United Kingdom

Johnston I (2015) Traditional warning signs of cyclones on remote islands in Fiji and Tonga. Environ Hazards 14:210–223. https://doi.org/10.1080/17477891.2015.1046156

Kagunyu A, Wandibba S, Wanjohi JG (2011). The Use of Indigenous Climate Forecasting Methods by the Pastoralists of Northern Kenya. https://doi.org/10.1186/s13570-016-0054-0

Kelman I, Mercer J, Gaillard J (2012) Indigenous knowledge and disaster risk reduction. Geography 97:12–21

Kiger ME, Varpio L Medical Teacher Thematic analysis of qualitative data: AMEE Guide No. 131 Thematic analysis of qualitative data: AMEE Guide No. 131. Doi: https://doi.org/10.1080/0142159X.2020.1755030

Klenk NL, Meehan K (2017) Transdisciplinary sustainability research beyond engagement models: Toward adventures in relevance. Environ Sci Policy 78:27–35. https://doi.org/10.1016/J.ENVSCI.2017.09.006

Klimeš J, Rosario AM, Vargas R et al (2019) Community participation in landslide risk reduction: a case history from Central Andes, Peru. Landslides 16:1763–1777. https://doi.org/10.1007/s10346-019-01203-w

Klonner C, Hartmann M, Dischl R, et al (2021) The Sketch Map Tool Facilitates the Assessment of OpenStreetMap Data for Participatory Mapping. ISPRS Int J Geo-Information 2021, 10:130. Doi: https://doi.org/10.3390/IJGI10030130

Klonner C, Marx S, Usón T et al (2016) Volunteered geographic information in natural hazard analysis: a systematic literature review of current approaches with a focus on preparedness and mitigation. ISPRS Int J Geo-Information 5:103. https://doi.org/10.3390/ijgi5070103

Kniveton D, Visman E, Tall A et al (2015) Dealing with uncertainty: integrating local and scientific knowledge of the climate and weather. Disasters 39:s35–s53. https://doi.org/10.1111/disa.12108

Latulippe N, Klenk N (2020) Making room and moving over: knowledge co-production, Indigenous knowledge sovereignty and the politics of global environmental change decision-making. Curr Opin Environ Sustain 42:7–14. https://doi.org/10.1016/J.COSUST.2019.10.010

Lauer M (2012) Oral traditions or situated practices? Understanding how indigenous communities respond to environmental disasters. Hum Organ 71:176–187. https://doi.org/10.17730/humo.71.2.j0w0101277ww6084

Lin PSS, Chang KM (2020) Metamorphosis from local knowledge to involuted disaster knowledge for disaster governance in a landslide-prone tribal community in Taiwan. Int J Disaster Risk Reduct 42:101339. https://doi.org/10.1016/j.ijdrr.2019.101339

Loch TK, Riechers M (2021) Integrating indigenous and local knowledge in management and research on coastal ecosystems in the Global South: a literature review. Ocean Coast Manag 212. https://doi.org/10.1016/J.OCECOAMAN.2021.105821

Magee AD, Verdon-Kidd DC, Kiem AS, Royle SA (2016) Tropical cyclone perceptions, impacts and adaptation in the Southwest Pacific: an urban perspective from Fiji, Vanuatu and Tonga. Nat Hazards Earth Syst Sci 16:1091–1105. https://doi.org/10.5194/nhess-16-1091-2016

Marin J, Cortés J, Aliste E, Campos J (2020) Scientific controversy as a disaster risk factor: The 2007 seismic crisis in Patagonia. Chile Int J Disaster Risk Reduct 49:101639. https://doi.org/10.1016/J.IJDRR.2020.101639

Masinde M (2015) An innovative drought early warning system for sub-Saharan Africa: integrating modern and indigenous approaches. Technol Innov Dev 7:8–25. https://doi.org/10.1080/20421338.2014.971558

Masinde M (2020) ITIKI Success story: classic application of design thinking. 2020 IST-Africa Conf IST-Africa 2020

Mercer J (2012) Knowledge and disaster risk reduction. In: Wisner B, Gaillard JC, Kelman I (eds) Handbook of hazards and disaster risk reduction. Routledge, Abingdon, Oxon, pp 89–100

Mercer J, Gaillard JC, Crowley K et al (2012) Culture and disaster risk reduction: lessons and opportunities. Environ Hazards 11:74–95. https://doi.org/10.1080/17477891.2011.609876

Mercer J, Kelman I (2009) Disaster risk reduction in Papua New Guinea: Integrating indigenous and scientific knowledge. In: Indigenous Knowledge and Disaster Risk Reduction: From Practice to Policy. pp 293–312

Mercer J, Kelman I, Taranis L, Suchet-Pearson S (2010) Framework for integrating indigenous and scientific knowledge for disaster risk reduction. Disasters 34:214–239. https://doi.org/10.1111/j.1467-7717.2009.01126.x

Moher D, Liberati A, Tetzlaff J et al (2009) Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLOS Med 6:e1000097. https://doi.org/10.1371/JOURNAL.PMED.1000097

Muita RR, van Ogtrop F, Ampt P, Vervoort RW (2016) Managing the water cycle in Kenyan small-scale maize farming systems: Part 1. Farmer perceptions of drought and climate variability. Wiley Interdiscip Rev Water 3:105–125. https://doi.org/10.1002/WAT2.1118

Mutasa M (2015) Knowledge apartheid in disaster risk management discourse: Is marrying indigenous and scientific knowledge the missing link? Jamba J Disaster Risk Stud 7:1–10. https://doi.org/10.4102/jamba.v7i1.150

Obermeister N (2019) Local knowledge, global ambitions: IPBES and the advent of multi-scale models and scenarios. Sustain Sci 14:843–856. https://doi.org/10.1007/s11625-018-0616-8

Okhuysen GA, Eisenhardt KM (2002) Integrating Knowledge in Groups: How Formal Interventions Enable Flexibility, 13. Doi: https://doi.org/10.1287/ORSC.13.4.370.2947

Pauli N, Williams M, Henningsen S et al (2021) "Listening to the sounds of the water": bringing together local knowledge and biophysical data to understand climate-related hazard dynamics. Int J Disaster Risk Sci 12:326–340. https://doi.org/10.1007/S13753-021-00336-8/TABLES/3

Pawson R, Greenhalgh T, Harvey G, Walshe K (2005) Realist review: a new method of systematic review designed for complex policy interventions. J Heal Serv Res Policy 10:21–34. https://doi.org/10.1258/1355819054308530

Pennesi K (2007) Improving forecast communication: Linguistic and cultural considerations. Bull Am Meteorol Soc 88:1033–1044. https://doi.org/10.1175/BAMS-88-7-1033

Plotz RD, Chambers LE, Finn CK (2017) The best of both worlds: a decision-making framework for combining traditional and contemporary forecast systems. J Appl Meteorol Climatol 56:2377–2392. https://doi.org/10.1175/JAMC-D-17-0012.1

Rai P, Khawas V (2019) Traditonal knowledge system in disaster risk reducton: exploraton, acknowledgement and propositon. Jamba J Disaster Risk Stud 11:1–7. https://doi.org/10.4102/JAMBA.V11I1.484

Rangecroft S, Rohse M, Makaya E, Van Loon A (2018) Hydrological modelling as a tool for interdisciplinary workshops on future drought. Prog Phys Geogr 42:237–256. https://doi.org/10.1177/0309133318766802

Šakić Trogrlić R, Duncan M, Wright G et al (2021) External stakeholders' attitudes towards and engagement with local knowledge in disaster risk reduction: are we only paying lip service? Int J Disaster Risk Reduct 58:102196. https://doi.org/10.1016/J.IJDRR.2021.102196

Šakić Trogrlić R, Wright G, Duncan M et al (2019) Characterising local knowledge across the flood risk management cycle: a case study of Southern Malawi. Sustainability 11:1681. https://doi.org/10.3390/su11061681

Smith PJ, Brown S, Dugar S (2017) Community-based early warning systems for flood risk mitigation in Nepal. Hazards Earth Syst Sci 17:423–437. https://doi.org/10.5194/nhess-17-423-2017

Syamsidik RTM, Suppasri A et al (2020) Challenges in increasing community preparedness against tsunami hazards in tsunami-prone small islands around Sumatra. Indonesia Int J Disaster Risk Reduct 47:101572. https://doi.org/10.1016/J.IJDRR.2020.101572

Taylor FE, Millington JDA, Jacob E et al (2020) Messy maps: Qualitative GIS representations of resilience. Landsc Urban Plan 198:103771. https://doi.org/10.1016/J.LANDURBPLAN.2020.103771

Tengö M, Brondizio ES, Elmqvist T et al (2014) Connecting diverse knowledge systems for enhanced ecosystem governance: The multiple evidence base approach. Ambio 43:579–591. https://doi.org/10.1007/s13280-014-0501-3

Thompson HE, Berrang-Ford L, Ford JD (2010) Climate change and food security in Sub-Saharan Africa: a systematic literature review. Sustainability 2:2719–2733. https://doi.org/10.3390/su2082719

Tiepolo M, Bacci M, Braccio S, Bechis S (2019) Multi-hazard risk assessment at community level integrating local and scientific knowledge in the Hodh Chargui. Mauritania Sustain 11:5063. https://doi.org/10.3390/su11185063

Tiepolo M, Belcore E, Braccio S et al (2021) Method for fluvial and pluvial flood risk assessment in rural settlements. MethodsX 8:101463. https://doi.org/10.1016/J.MEX.2021.101463

Tiepolo M, Braccio S (2017) Local and scientific knowledge integration for multi-risk assessment in rural Niger. In: Tiepolo M, Pezzoli A, Tarchiani V (eds) Renewing Local Planning to Face Climate Change in the Tropics. Springer Open, pp 227–245

Ton KT, Gaillard JC, Cadag JR, Naing A (2017) It takes two to tango: integrating meteorological knowledge and actions for disaster risk reduction. Clim Dev 9:479–492. https://doi.org/10.1080/17565529.2016.1174658

Tran P, Shaw R, Chantry G, Norton J (2009) GIS and local knowledge in disaster management: a case study of flood risk mapping in Viet Nam. Disasters 33:152–169. https://doi.org/10.1111/j.1467-7717.2008.01067.x

Trogrlić RŠ, Wright GB, Duncan MJ et al (2019) Characterising local knowledge across the flood risk management cycle: A case study of Southern Malawi. Sustain 11:181. https://doi.org/10.3390/su11061681

Tsosie R (2017) Indigenous Peoples, Anthropology, and the Legacy of Epistemic Injustice 1. Routledge Handb Epistemic Injustice 356–369. https://doi.org/10.4324/9781315212043-35

Tuhiwai Smith L (2004) Decolonizing Methodologies: Research and indigenous peoples. Zed Books, London, UK

UNDRR (2021) Early warning system. https://www.undrr.org/terminology/early-warning-system. Accessed 16 Dec 2021

UNDRR (2020) Hazard Definition & classification review: Technical Report. https://www.undrr.org/publication/hazard-definition-and-classification-reviewFdi

UNISDR (2015) Sendai Framework for Disaster Risk Reduction 2015–2030. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

Valdivia C, Seth A, Gilles JL et al (2010) Adapting to climate change in Andean ecosystems: Landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. Ann As Am Geogr 100:818–834. https://doi.org/10.1080/00045608.2010.500198

van den Homberg MJC, Gevaert CM, Georgiadou Y (2020) The Changing face of accountability in humanitarianism: using artificial intelligence for anticipatory action. Polit Gov 8:456–467. https://doi.org/10.17645/PAG.V8I4.3158

van der Molen F (2018) How knowledge enables governance: the coproduction of environmental governance capacity. Environ Sci Policy 87:18–25. https://doi.org/10.1016/J.ENVSCI.2018.05.016

Walker DW, Smigaj M, Tani M (2021) The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. Wiley Interdiscip Rev Water 8:1–32. https://doi.org/10.1002/wat2.1488

Walshe RA, Nunn PD (2012) Integration of indigenous knowledge and disaster risk reduction: a case study from Baie Martelli, Pentecost Island, Vanuatu. Int J Disaster Risk Sci 3:185–194. https://doi.org/10.1007/s13753-012-0019-x

Wisner B, Blaikie P, Cannon T, Davis I (2003) At Risk. Natural Hazards, people's vulnerability and disasters. Routledge, London, UK and New York, USA

Wohling M (2009) The problem of scale in indigenous knowledge: A perspective from Northern Australia. Ecol Soc 14. https://doi.org/10.5751/ES-02574-140101

World Meteorological Organization (2021) WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services (WMO-No. 1150), Part II: Putting Multi-Hazard IBFWS into Practice. WMO, Geneva

Yates L, Anderson-Berry L (2004) The societal and environmental impacts of cyclone zoë and the effectiveness of the tropical cyclone warning systems in Tikopia and Anuta Solomon Islands. Aust J Emerg Manag 19:16–20

Yeh ET (2016) 'How can experience of local residents be "knowledge"?' Challenges in interdisciplinary climate change research. Area 48:34–40. https://doi.org/10.1111/AREA.12189

Ziervogel G, Opere A (2010) Integrating meteorological and indigenous knowledge-based seasonal climate forecasts for the agricultural sector. International Development Research, Ottowa, Canada

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Thirze D. G. Hermans[1] · Robert Šakić Trogrlić[2] · Marc J. C. van den Homberg[3] · Hannah Bailon[3] · Rebecca Sarku[1] · Anuszka Mosurska[1]

Robert Šakić Trogrlić
trogrlic@iiasa.ac.at

1 Sustainability Research Institute, School of Earth and Environment, University of Leeds, LS2 9JT Leeds, UK

2 Systemic Risk And Resilience (SYRR) Group, Advancing Systems Analysis (ASA) Program, International Institute for Applied System Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

3 510 An Initiative of The Netherlands Red Cross, 2593HT The Hague, The Netherlands