From Data Fragmentation to Integration – Data Management for Engineering Cross Border Disaster Resilience: A Systematic Literature Review

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Abstract

In recent years, an increasing frequency of natural disasters has posed significant threats to human life and property. The effects of disasters are severe and spread across national, geographical, political, or cultural borders. To respond to disasters effectively, timely and reliable information of multiple actors involved is required. However, in the case of cross-border disaster management, this is impeded due to several challenges regarding the fragmentation of data and a lack of interoperability of inter-organizational data. Hence, this study aims to investigate the current state of the art of challenges and solution approaches to data integration in cross-border disaster management. Therefore, a systematic literature review is conducted. By providing a comprehensive quantitative and qualitative analysis that identifies and categorizes challenges across multiple technological, organizational, legal, and cultural dimensions, a comprehensive systematization of knowledge is given, and further research directions on data integration in disaster management are outlined.

Keywords: Cross-border collaboration; Data heterogeneity; Data interoperability; Data sharing

1 Introduction

In 2022, 387 natural disasters were reported worldwide, resulting in the loss of 30,704 lives and affecting more than 185 million other people [1]. According to the International Disaster Database (EM-DAT), the impact of disasters has caused US$ 223 billion in economic losses, a number that has quadrupled since the 1980s [1]. Among all global risks, extreme natural events such as earthquakes, floods, or tsunamis are perceived among the most likely and most potentially damaging threats overall [2]. Disasters spread across national, geographic, political, or cultural borders, confronting the affected regions with significant challenges due to multiple actors

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involved in disaster management practices. A border can be defined as a space between two distinct entities, but it can also be approached as a process of social division [3].

To cope with these disasters, gaining high levels of disaster resilience is essential for individuals, companies, societies, and systems to absorb shocks and to "bounce back" quickly to a viable state after a hazard [4]. Resilience includes transformative, adaptive, and absorptive capacities to enhance a community's ability to withstand and manage disasters and to reduce the vulnerability of systems towards crises [5]. However, to respond to disasters in an efficient and effective manner, timely and reliable information is required [6, 7]. This information includes data on local and national levels and, in case of a cross-border disaster, data from several countries and organizations. Furthermore, data standardization and interoperability must be ensured to provide a reliable foundation for decision-makers [8]. In the context of cross-border regions, efforts towards integration can come at odds with divergences that are inherent to borders. Practically, integrating and sharing information across traditional organizational boundaries requires complex interactions between technical and organizational processes, such as overcoming challenges regarding different platforms where information is stored, managing legacy systems, highly variable data quality, and multiplicity of and sometimes incompatibility of database structures, database designs, and network infrastructure [9]. Initial research shows successful approaches to developing integrative strategies addressing data interoperability in cross-border disaster management. For instance, Dao et al. [10] propose an integrated framework for information integration between diverse infrastructure systems by integrating multiple-source heterogeneous data in a common data format. Kamissoko et al. [11] discuss an improved model for resilience assessment by integrating multiple data sources and stakeholders.

However, scientific research still lacks a comprehensive overview and systematic identification of approaches addressing data fragmentation issues. Nevertheless, this knowledge is crucial, as it is a precondition and determinant to engineer resilient systems. Hence, the present paper aims to identify and summarize the current state of the literature regarding data integration in disaster management, focusing on inter-organizational data integration in cross-border disaster management practice. Therefore, the following research questions are posed:

1. *What are data integration challenges in cross-border disaster management?*
2. *Which technological approaches are applied to solving issues regarding data integration to increase cross-border disaster resilience?*

Overall, this study contributes to the understanding of cross-border disaster management by providing a comprehensive quantitative and qualitative analysis that identifies and categorizes challenges across multiple technological, organizational, legal, and cultural dimensions. This work highlights solutions proposed in scientific literature and provides valuable insights for decisionmakers to improve the effectiveness of data integration in cross-border disaster management.

The remainder of this work is structured as follows. Section 2 covers the basic foundations of disaster management, resilience, and data integration. In Section 3, the methodological procedure of the literature review is presented. Following, the results are presented in Section 4. Section 5 provides a discussion and draws conclusions.

2 Theoretical background

2.1 Disaster management and resilience

According to the International Federation of Red Cross and Red Crescent Societies (IFRC), disasters can be defined as "serious disruptions to the functioning of a community that exceeds its capacity to cope using its own resources" [12]. Disasters, as a force of natural or human-induced calamity, disrupt the functioning of societies and cause widespread destruction [12]. Thus, identifying threats, understanding vulnerabilities, and developing strategies to mitigate the impact is at the core of the management of disaster risks [13]. The disaster management process characteristically involves four phases: mitigation, preparedness, response, and recovery [14]. The response phase takes place right after the impact of a disaster, involving activities that directly address the immediate need to provide relief and reduce the impact of disasters. A disaster response requires specific predefined actions and immediate communication and coordination of the involved actors [14]. After the response phase, measures within the recovery phase are taken to return the affected's lives to a normal state. All measures taken before a disaster to prevent, prepare, and detect future hazards are included in the mitigation and preparedness phase [14]. Taking all together, the disaster management cycle is dedicated to preventing the occurrence of disasters, reducing their impacts, and thus, improving the resilience of complex technological systems, societies, or economies [15].

This process is supported by conceptualizing the broad term resilience that has its origins in diverse areas [16]. Regarding its etymology, the term 'resilience' is traced back to the Latin word 'salire', meaning to climb or to jump, and more specifically to its derivative 'resilire', which signifies the ability to rebound or recover [17, 16]. In scientific terms, the concept of resilience is rooted in two different research streams. Holling [18] originally introduced resilience as a concept to understand the robustness of an ecological system and its ability to persist within a particular state when disturbances occur. In contrast, resilience has been defined in psychology as the ability to deal with stressful life events or adversity [19]. Today, resilience is understood broadly and applied in many fields, such as engineering, sociology, economics, and organizational studies [17]. In this paper, we adopt a system approach, referring to resilience as the capacity of a system (may it be one or several organizations, a territory, or even a society) to absorb shocks [4].

2.2 From data fragmentation to integration

Data on disasters and their impact is highly heterogeneous, both structurally and semantically [20]. Particularly in the case of transboundary disasters where multiple actors and organizations are involved, different data formats, data characteristics, and different data sources exist. In this work, we refer to this problem as data fragmentation, a term that originates in database management but has been applied in different cases such as external storage, processing, or data sharing applications [21]. In the context of cross-border disaster management, data fragmentation refers to several challenges regarding diverse and heterogeneous datasets collected by various international actors jointly responding to disasters [22]. This results from differences at multiple levels, attributable to the use of differing data formats, collection mechanisms, reporting standards, or sharing practices among countries and organizations involved in disaster management [23]. The accompanying lack of standardization hampers efficient data utilization for timely decision-making in cross-border disaster management [24]. Therefore, addressing data fragmentation is crucial to overcoming interoperability issues, enhancing coordination among the respective actors, and ensuring more effective and unified disaster management efforts.

Overall, this results in the need for data integration [20]. According to Lenzerini [25] data integration refers to the problem of combining data resulting from different data sources, thus providing the user with a unified view of these data. Integrating data from multiple sources through assembling and sharing helps to produce consistent and richer information across distinct organizational entities to achieve a collective outcome [26]. It implies that data sources can be technically bridged. However, bridging data requires organizations that produce these data collaboratively to plan the respective sharing and technical operability between servers, which depends on their capacity to develop mutual trust in the long run [20].

3 Methodology

To answer the research questions, a systematic literature review was conducted, allowing the identification, evaluation, and interpretation of all available research data on the given topic to present a comprehensive, exhaustive summary of current evidence of the research field [27]. Rather than an empirical study, we addressed the research questions by thoroughly investigating the literature. Our rationale was that data fragmentation was researched from multiple stances. Findings did exist and required to be assembled in a comprehensive mode. Practically, to search for papers, a search term was defined based on the key terms of the overarching research field and extracted from the research questions. The selection of keywords for the search term was combined by relying on Boolean operators. Considering different compositions and spellings of the selected keywords, the search term as given in Table 1 was determined. As a database, the interdisciplinary database Elsevier Scopus of peer-reviewed scientific literature was selected to ensure a comprehensive coverage of all publications across multiple research fields of high-quality scientific journals and research articles. Based on paper collection and selection, we completed a quantitative and qualitative analysis of the literature on the core topic of our study.

Table 1: Details on the search term and respective inclusion criteria for the systematic literature search

Database	Scopus
Content	Title, Abstract, Keywords
Searchterm	(data OR information OR knowledge) AND (disaster) AND (integrat* OR fragment* OR interoperab* OR unif*) AND (border OR frontier OR boundar* OR "inter$organ*")
Type	Proceeding OR Journal Article
Language	English

The literature search was conducted in September 2023 and yielded 463 documents. According to the PRISMA Flow diagram and systematic procedure of literature selection according Page et al. [28], the initial set was iteratively reduced based on defined exclusion and inclusion criteria (see Figure 1). The resulting set of articles was reduced to Journal articles and Conference proceedings written in English. Thereby, books, book series, trade journals, and titles of conference proceedings were removed. Thus, a set of 330 publications was used for quantitative analysis and subjected to the screening process based on titles and abstracts. Following further refined exclusion and inclusion criteria, all studies that neither examined a disaster event nor covered a cross-border region were excluded from the literature base. Alongside this, a particular focus has been placed on studies addressing data fragmentation and integration in a cross-border setting. Hence, the set was finally reduced to a selection of 25 articles which have subsequently been used for the following qualitative content analysis. In sum, all the papers included in the sample provide information about data integration (or fragmentation) and disaster management in cross-border regions.

During the qualitative literature analysis, all information needed to answer the research questions was collected. In addition to general information on the articles, such as publication year, source, or author(s), relevant data on the specific disaster type, study region, data integration challenges, and solution approaches are categorized and analyzed.

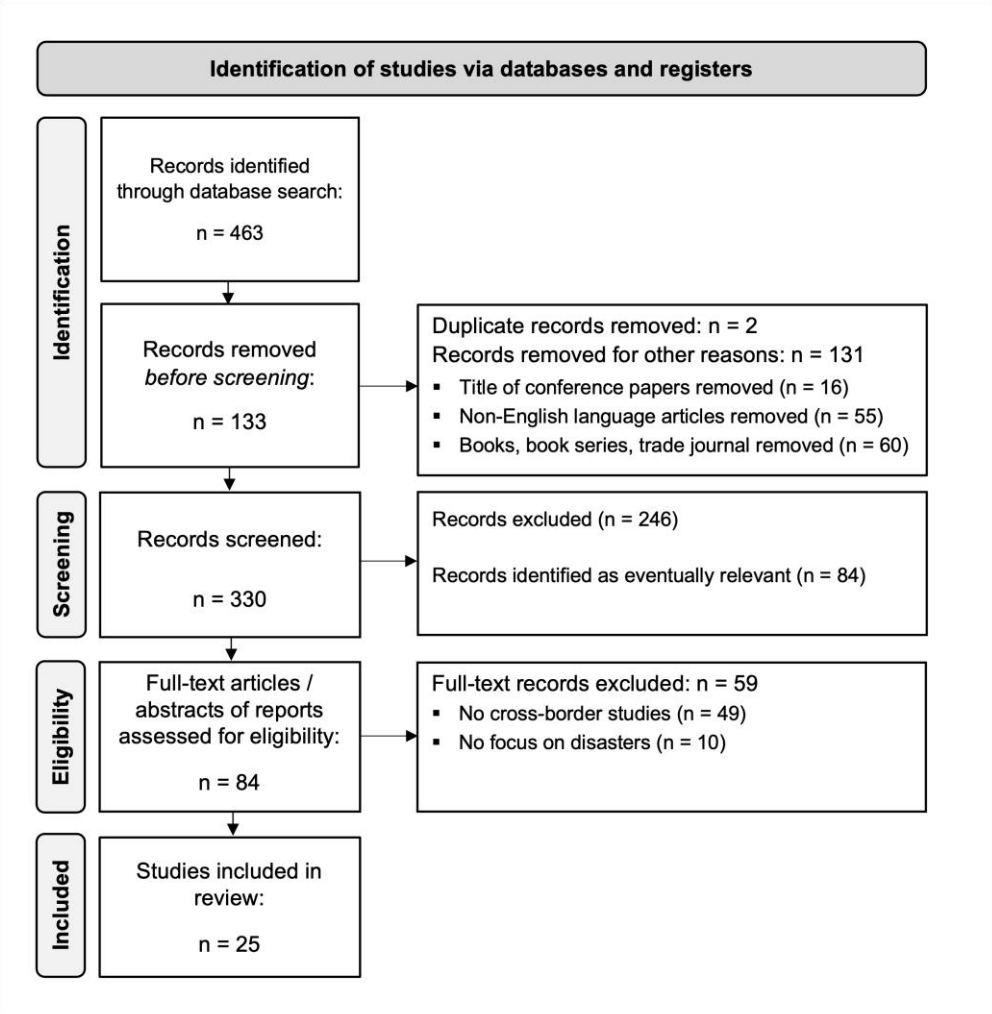

Figure 1: Systematic literature review procedure according to the PRISMA Flow Diagram

4 Multi level analysis of data fragmentation in cross-border disaster management

4.1 Quantitative analysis of reviewed articles

Considering the volume of published scientific articles over time, the frequency of publications per year has increased significantly. According to the number of publications, as presented in Figure 2, a notable number of articles was published in 2022 (32 articles). In 2018 (17 articles) and 2019 (18 articles), fewer articles were published, but overall, the distribution shows an increasing scientific relevance of the research field.

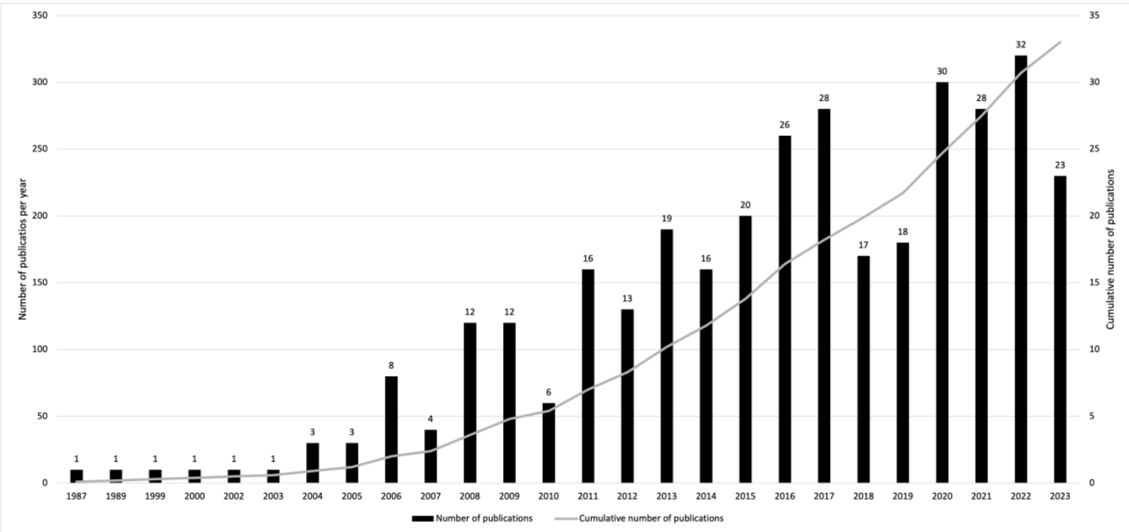

Figure 2: Number of publications per year since 2005

Using VOSviewer, an analysis of keyword co-occurrences was conducted. Figure 3 shows circles of varying sizes representing the number of co-occurrences of keywords. Keywords are clustered in five groups, marked with one color each. The circles are linked together, where the number of co-occurrences of the keywords determines the strength of each link: The more extensive the lines connecting the circles, the more significant the common occurrence of keywords.

The clustering reveals the diversity of perspectives on data integration and fragmentation for disaster management at borders. The purple cluster highlights challenges inherent to data production through sensors and geographical technologies. The yellow cluster evidences socio-technical stakes in data integration for disaster management. The green cluster reveals the importance of interoperable information systems across the border. Data integration, therefore, remains a challenge in various phases of managing cross-border disasters, highlighting the need for data integration in each phase of the disaster management cycle. The clusters also reveal that data integration is socio-technical. This advocates a comprehensive stance on its inherent challenges.

The results obtained are reflected in the set of 25 selected articles included in the following qualitative literature review. Whereas three articles address disaster prevention and preparedness, eight articles relate to disaster response. Most articles are concerned with disaster management in more general, thereby addressing all phases of disaster management, which emphasizes the topic's relevance at all stages of the disaster management cycle.

Considering the thematically relevant set of articles in further detail, 13 Conference proceedings and 12 Journal articles are included. Among the Journals, the Journal of Disaster Prevention and Mitigation, the Journal of Contingencies and Crisis Management, the Journal of Decision Systems, and the International Journal of Disaster Risk Reduction are listed. Overall, a widespread distribution within various Journals and Conference proceedings is observed, highlighting the international pertinence of the subject across multiple sectors.

When reviewing the research methods of the respective articles, it is noticeable that most articles primarily employ a qualitative research approach. Among these are several reports of research projects, established frameworks and ontologies, and results of conducted interviews. The latter method, in particular, has the potential to acquire domain-specific and context-related knowledge of disaster experts and, thus, insights into real-world challenges and solution approaches.

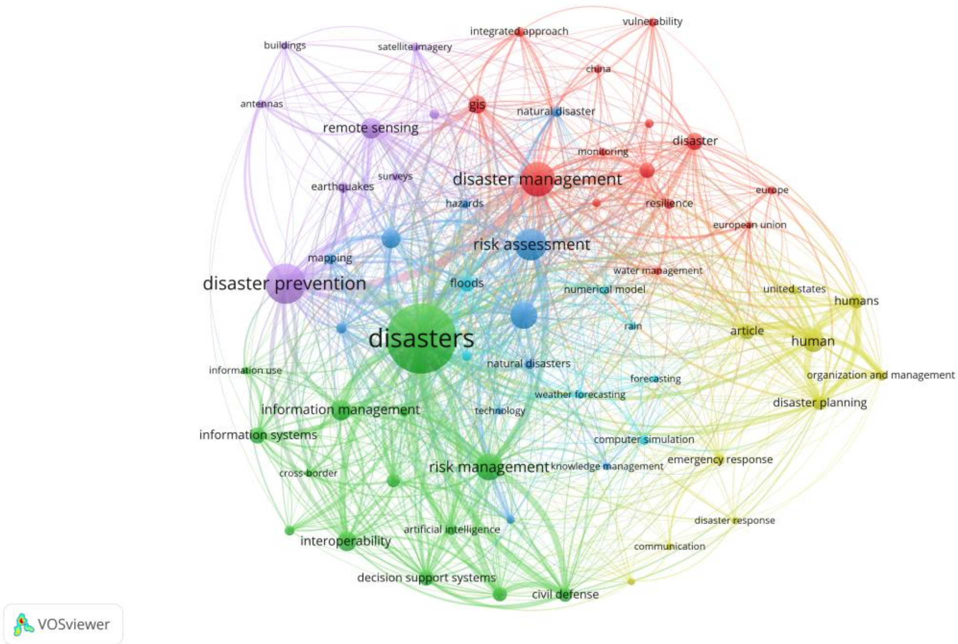

Figure 3: Mapping of keyword occurrences

4.2 Qualitative content analysis of reviewed articles

The following section includes a comprehensive qualitative analysis of difficulties and challenges in data handling in cross-border disaster management. For a comprehensive examination, a classification scheme is derived. This scheme was inspired by existing research on information integration. However, through our investigation of the literature, we identified several categories that we present in the following table. In sum, the challenges are divided into seven different categories and analyzed respectively. Based on this, solution approaches will be elaborated to achieve efficient data integration.

4.2.1 Challenges of data integration in cross-border disaster management

Table 2 shows that the management of fragmented data is accompanied by several challenges, encompassing technical and legal barriers, but also language and culture-related factors, which will briefly be discussed in the following section.

Data management challenges. In a cross-border context, data acquisition and availability pose a significant challenge. In particular, the various sides of the border can implement distinct methodologies and structures, such as varying parameters of measurement scales or resolution [36, 34]. Ertac et al. [30] study data harmonization for a flood early warning system and report differing conceptual schemes in terms of different ways to classify land cover of flood risk warning levels within the respective countries. Thus, a lack of standardization within cross-border organizations hinders data exchange between agencies [23]. Data storage can also represent a challenge, including heterogeneous, duplicate, or inconsistent recording and storage of data [37, 30, 31, 32]. Another key challenge is data interoperability, both at a syntactic [29, 30, 33, 36] and semantic level [37, 29, 38, 31, 33]. At the syntactical level, different countries and organizations use varying data formats (e.g., JPEG, PNG, PPT) [36], models, and communication protocols that represent the foundations for efficient data exchange and collaboration [29, 30, 33, 36]. At a metadata level, different metadata profiles exist due to a lack of formalization and standardization [30]. Heterogeneous data representation practically means inconsistent color codes, different graphical symbols or sets [29, 33], but also differing vocabularies and terminologies referred to as a lack of semantical data interoperability [37, 29, 38, 31, 33]. Differing vocabularies and terminologies may cause interpretation issues and diverging interpretations of words depending on the context [38]. These differences stem from difficulties in combining data from heterogeneous sources into integrated, consistent, and unambiguous information products [30].

Technical challenges. The challenges inherent to data management are accompanied by a lack of technological infrastructures and systems allowing for cross-border data sharing and storage [23, 39, 41, 24, 31, 42]. In line with a lack of standardization, various information and communication technology service and product providers exist between agencies, all with diverse requirements and characteristics [39]. These different systems can cause technical incompatibility by design [29, 42].

Informational challenges. Abdeen et al. [23] highlight informational challenges arising in multiagency collaboration. The authors report a lack of relevant information shared between partners across the border [23]. In addition, several studies report information overload as a challenge to data integration [23, 24, 31, 42, 41]. For instance, the rising amount of social media data collected, analyzed, and used in disaster response can lead to information overload, preventing disaster managers from effectively using and integrating the information [41]. Hence, the volume of information available to decision-makers may be too large, causing inefficiencies in information processing and the inability to search, find, and use the information needed [24, 31].

Communicational challenges. At an international level, cross-border resilience involves a lack of communication between organizations [23]. Månsson [43] discuss information integration in disaster risk management systems from various stakeholders. They shed light on communication issues due to a lack of incentives towards organizations to engage in communication procedures, particularly varying incentives between public and private stakeholders. Another driver of a lack of communication is diversity in language and cultural particularities, which will be discussed in the following [29].

Table 2: Overview of challenges regarding data integration

Category	Challenge	Source
Data management challenges	Lack of common methodologies and structures	[29, 30, 31, 32, 33, 34, 35]
	Data interoperability (Lack of data harmonization)	[30, 32]
	Syntactical interoperability (data formats, models and communication protocols)	[29, 30, 33, 36]
	Semantic heterogeneity (differing vocabularies, terminologies, and data representations)	[29, 31, 33, 37, 38]
	Lack of standardization	[30, 31, 32, 37]
	Heterogeneous, duplicate and inconsistent recording and storage of data	[32, 38, 39, 40]
Technical challenges	Lack of technological infrastructure	[23, 24, 31, 39, 41, 42]
	Lack of collaboration platform for data sharing	[23]
	Various information and communication technology service and product providers	[39]
Informational challenges	Incomplete information	[23, 32]
	Information overload	[23, 24, 31, 42, 41]
	Information processing delay	[24,39,43]
Communi-cational challenges	Lack of communication among agencies	[23]
	Lack of incentives to engage in communication / information exchange	[43]
Legal and regulatory challenges	Political tensions between jurisdictions	[23]
	Institutionalization and political power between actors	[23]
	Data privacy issues	[37, 42, 43]
	Legal issues (different regulation, complex legal landscape)	[29, 33, 35, 41]
Organizational challenges	Lack of formal, systematic, inter-organizational coordination procedures	[23, 41, 44, 45, 46, 47]
	Lack of understanding of available resources, contribution from each organization, roles, tasks and responsibilities	[23, 35, 42, 44]
	Diversity of organizational structures	[29, 31, 33]
	Different stakeholder objectives	[39]
Language and cultural challenges	Behavioral and risk perception issues	[23]
	Diversity in language	[29, 31, 33, 35, 37, 38]
	Lack of trust	[24, 31]
	Lack of common culture between organizations	[29, 33, 39, 41, 48]

Legal and regulatory challenges. Referring to the aforementioned data storage, Babitski et al. [37] illuminates the argument from a legal perspective, arguing that maintaining all data within a single globalized database is often not desirable due to data privacy. Moreover, the confidentiality of data and safeguarding of sensitive information is necessary since the exposure of vulnerabilities can harm organizations and undermine the people's trust in the organization [43, 42]. Furthermore, different legal regulations in different regions lead to a complex legal landscape where cross-border agencies operate in [29, 33].

Organizational challenges. The challenges of a lack of standardized data management procedures and common structures, methodologies, and policies are also reflected at the organizational level. Effective coordination between organizations is a prerequisite to achieving disaster resilience [41]. During a disaster, time dependencies between activities may occur, indicating the interdependence of activities of different organizations. For this reason, coordinating these activities is indispensable for disaster response [45, 44]. Before disasters, organizations need to co-construct joint procedures and test them in exercises. Both before and during disasters, information is a crucial ingredient for coordination between organizations. Information and data integration requires shared understanding between organizations about what and when to share, as well as the willingness to share [49]. According to Abdeen et al. [23], organizational challenges manifest in inter- and intra-organizational structures and procedures. Particularly, the lack of clarity and understanding regarding roles, tasks, and responsibilities in data sharing is commonplace within organizations [23]. Between organizations, there is an incomplete understanding of available resources and contributions from each organization, resulting in insufficient formal, systematic, and joint coordination and collaboration procedures [23, 39, 24, 31, 33].

Language and cultural challenges. Another often-discussed challenge is the language barriers that exist between different countries. Both Schütte et al. [33] and Casado et al. [29] investigate interoperability systems in the emergency management sector, focusing on Europe. With 28 member states and more than 24 official languages, a lack of a common language poses significant challenges to data handling on both IT and human levels. Cultural differences also magnify this since each organization may have its own culture, and thus, hinder the understanding of information since the concepts, structures, and reference framework may vary [33]. Klein et al. [48] highlight cultural differences across countries, which encompass beyond others uncertainty avoidance, long-term versus short-term orientation, individualism versus communitarianism, achievement versus ascription, or task-based versus relationship-based trust building. To nuance this view, the authors refer to a "cross-border identity" that exists in cross-border regions and is understood as an even more deeply rooted culture than the respective culture of the country [48]. Other behavioral factors, especially intrinsic forces such as motivation for inter-organizational collaboration, inter-personal trust, prestige, competition for resources, or cognitive constraints to proceed with the received volumes of information can hinder efficient cross-border collaboration Månsson [43] and Neville et al. [24].

4.2.2 Solution approaches

To overcome the addressed challenges in cross-border disaster management, a range of solution approaches is proposed within the reviewed articles. Building on the classification scheme of the previous section, the solution approaches are categorized accordingly and will be summarized in the following section (see Table 3).

Data management solutions. Solution approaches to managing data-related challenges in cross-border disaster management can be summarized and termed as data harmonization and data interoperability solutions [30, 24]. These solutions include approaches to standardize data [38] and approaches to ensure the interoperability of different systems, including semantic and syntactic data interoperability [23, 37, 29, 33, 32]. One avenue to achieve data standardization consists of using a common XML-based messaging standard, for instance, the Emergency Data Exchange Language (EDXL) suite of standards that facilitates emergency information sharing between government entities and other emergency organizations [38]. Ertac et al. [30] address data harmonization and interoperability in a spatial data infrastructure for a flood early warning system. In particular, the project discusses semantic data heterogeneity by solving issues related to varying spatial reference systems and consistency across the borders. Additionally, data capturing, maintenance, and visualization are covered [30]. Thereby, transforming data from heterogeneous sources into common formats is a crucial step for data harmonization to process requests [30, 29, 34, 40]. Babitski et al. [37] develop an ontology stack covering the basic disaster management concepts. The ontology includes broad categorizations of damages caused by a disaster and available resources to organizations for response. Casado et al. [29] propose a two-fold solution depicting a common modular ontology shared among all shareholders, considering different countries and cultural, semantic, and linguistic issues. In addition, the solution includes implementing a transparent service-oriented architecture (SOA), providing a mechanism so that different emergency management systems can share data and operate collectively during the management of crisis scenarios [29].

Table 3: Overview of solution approaches regarding data integration

Category	Solution	Source
Data management solutions	Development of a common, modular ontology	[29, 33, 37, 38]
	Implementation of transparent service-oriented architecture	[29]
	Development of taxonomies based on international standards	[31, 42]
	Interoperable databases and data harmonization	[24, 30, 32, 38]
Technical solutions	Development of technical platforms for collaboration and data sharing	[23, 40, 50]
	Integrated software solutions	[29, 33, 36]
Informational solutions	Promotion of a data sharing culture across entities	[23]
	Establishing information quality systems	[31]
Communicational solutions	Ontology-based messaging service	[38]
	Establishing cross-border communication channels	[33, 46, 50]
Legal and regulatory solutions	Legislative policies and procedures for multi-agency collaboration	[23, 50, 51]
Organizational solutions	Provide frequent training for staff	[23, 31, 41, 50]
	Reference process model for common understanding of coordination	[44]
	Increased networking between stakeholders at various levels	[41, 43]
Language and cultural solutions	Promoting community awareness and willingness	[23, 41]
	Including liaison officers to assist translation	[50]
	Availability of translated documents for emergency managers	[50]

Technical solutions. To enable cross-border data sharing and collaboration, a technological platform can help [23]. These technological platforms require integrated software solutions as comprehensive systems to receive and process these requests while meeting functional (e.g., specific data formats and communication protocols) and non-functional (e.g., security and policy) requirements [29]. Franke et al. [45] implements a model for coordinating activities with temporal dependencies in an extension to the Google Wave collaboration infrastructure. It builds on the Open Wave Federation Protocol to support interoperability among heterogeneous organizations. Additionally, on the user level, communication solutions to exchange and share information via web-based solutions or conferencing tools are required to facilitate communication and collaboration between stakeholders [36, 33].

Informational and communicational solutions. Establishing and ensuring information quality is essential for organizations since poor information quality can be lethal to the affected [31]. To ensure a mutual understanding among disaster managers, Elmhadhbi et al. [38] focuses on solving communication issues by proposing an ontology-based messaging service. The proposed architecture provides information tractability and consolidation for semantic translation, which enables the exchange of emergency response information among the involved stakeholders. International communication channels are established, including procedures for altering exposed neighbor regions and ensuring communication throughout an incident [50]. To overcome challenges regarding information overload, Neville et al. [31] emphasize the achievement of a balance between providing accurate information and on-demand requests for additional information needed in specific situations.

Legal and regulatory solutions. A regulatory framework for disaster-related activities is needed to foster cross-border disaster management, including long-term cross-boundary policies and strategies [51, 23, 50]. These agreements must include tasks' definitions and responsibilities, agreements on data sharing, and administrative arrangements for moving resources such as equipment and personnel over borders [50]. To ensure a common understanding by several agencies, these agreements must be bilateral and multilateral [50]. In addition, existing local or regional disaster management strategies must be merged and adapted to integrated arrangements [51, 50].

Organizational solutions. A frequently discussed challenge is coordination between organizations, including a common understanding of roles, tasks, and resources. Therefore, sustaining collaboration requires the development of partnerships among agencies in the long run [23]. This includes a shared understanding of roles in disaster management within and between organizations since common knowledge facilitates coordination among different inter-organizational stakeholders [44]. Nevertheless, disaster activities are often highly dependent, and thus, a model for coordinating activities with temporal dependencies is needed and proposed by Franke et al. [45]. Another crucial step in harmonizing coordination activities is interagency training and exercising to test practices and protocols to share information and resources [50, 23, 31, 41]. The cognitive capabilities of decision-makers are essential for responding to emergencies in rapidly changing situations. Thus, navigating in uncertain situations requires a range of skills that must be trained in advance [50].

Language and cultural solutions. For building disaster resilience, the understanding of community behavior is an essential determinant [48]. Klein et al. [48] develop a simulation framework based on a multi-agent system to study the characteristics of cross-border resilience and to support the simulation of individual, collective, and organizational behavior. The presence or absence of a border and cultural biases, communication problems, and regulatory issues are considered [48]. Furthermore, enhanced situational awareness and willingness among the community is required [23, 41]. Particularly in the case of community warning, public education and acceptance are needed for enhanced disaster preparedness and incident response for the general public [39]. Leveraging digital volunteers in disaster response and recovery presents a valuable solution approach for enhanced situational awareness, according to Kaminska [41]. Besides, inter-organizational trust is a determining factor, which must be ensured in the long run to foster collaboration Månsson [43] and Kaminska [41]. Increased trust could be reached by networking between public and private stakeholders at various levels and from training and the management of sensitive information [43, 39]. Stewart-Evans et al. [50] propose including liaison officers trained to assist cross-border communication. In the case of non-consistent languages, they serve as translators for the border regions. Nevertheless, the preparedness and response materials must be available in different languages to be accessible to multiple stakeholders [50].

5 Discussion and conclusion

5.1 Principal findings

Based on iteratively defined keywords, the Elsevier Scopus database has been selected and searched to identify relevant contributions addressing data fragmentation and data integration in cross-border disaster management. In Figure 2, the resulting number of publications per year has been presented, highlighting the subject as an increasing field of research. The conducted literature review process yielded 25 relevant publications, which were further assessed, particularly according to addressed challenges regarding the fragmentation of data and solution approaches in data integration for disaster management. Considering different phases of the disaster management cycle, most reviewed studies take a holistic perspective of disaster management, highlighting the need for developing sophisticated data integration models in each disaster management phase [52].

The main findings of the comprehensive qualitative analysis on difficulties and challenges in cross-border disaster management reveal a complex landscape with multidimensional barriers. The analysis classifies challenges into seven distinct categories, shedding light on various levels of the manifestation of data fragmentation and associated solution approaches to integrate data to achieve disaster resilience.

Various challenges concern the data generated before, during, and after disasters [52]. This includes data acquisition and storage difficulties since the extant systems are disparate and provide limited integration or hardly enable collaboration on data [53]. In particular, data interoperability issues in terms of semantic and syntactic data heterogeneity are frequently reported. The challenges inherent to collaboration on data do not only stem from data management or infrastructure management. They also depend on processes and organizational practices. This stresses the need for socio-technical approaches to data fragmentation and integration. This includes the standardization of data formats, models, and protocols, but also the harmonization of vocabularies, terminologies, processes, and representations. However, data and information sharing between multiagency stakeholders using different IT systems cannot be granted without a unified technological infrastructure [54]. This implies that issues regarding technological incompatibility from diverse information and communication technology providers with distinct requirements must be solved by integrated software solutions. A unified infrastructure can enable information exchange, but moreover, there is an additional need for willingness and incentives to engage in information exchange on the organizational level. Therefore, coordination between cross-border agencies is required. Nevertheless, adopting integrated software solutions is not enough. A lack of formal, inter-organizational coordination procedures may lead to failures such as inappropriate allocation of resources [8]. Increased networking between stakeholders at various levels and a shared understanding of coordination are needed to ensure a common understanding of available resources, contributions from each organization, tasks, and responsibilities of each partner. To nuance our view, addressing data fragmentation between cross-border entities comes with challenges. For instance, a unified data solution poses the question of international data governance, which can be undermined by legal and regulatory issues, as well as potential legacies from the border history (such as defiance or conflicts). In addition, challenges on the organizational level are in accordance to Bharosa et al. [8] and are also driven by community and individual-level related issues, including cultural and linguistic differences. However, cultural and linguistic barriers must be overcome to foster inter-organizational collaboration and to increase trust between the actors in the long run. In addition, legal perspectives emphasize the need to balance globalized data sharing with data privacy considerations.

5.2 Implications

Following the aforementioned challenges regarding data fragmentation in cross-border disaster management, several implications for research and practice arise. Overall, the results obtained from the conducted review allow researchers to accurately ground and guide further research efforts that have been previously omitted. Regarding the multidimensional challenges of data fragmentation and the need for data integration in cross-border disaster management, researchers and practitioners should focus on developing and assessing holistic frameworks that address these multiple obstacles. This includes investigating integral solutions spanning technological, organizational, legal, and cultural aspects to provide comprehensive insights. These should be applied to real-world scenarios to enhance the practical effectiveness of disaster management strategies. To strengthen the foundations for cross-border disaster management, there is a need to investigate long-term cross-boundary policies that address deep (but somewhat less visible) challenges, such as legal, cultural, and organizational ones. One avenue is the design or refinement of policies on data sharing and data privacy to ensure and facilitate a long-term collaboration between multiple agencies to increase the resilience of border regions. International concertation on data strategies (such as the data act in Europe) can trigger cross-border reflection on these policies.

5.3 Limitations and outlook

Due to the continuous increase in the occurrence of natural disasters, effective disaster management is a dynamic and continuously important research area. Therefore, the present fails to include all innovative approaches and may lack coverage of recent developments or emerging challenges in the field. In addition, cross-border dynamics are heavily influenced by the respective countries' cultural, political, and regional factors. This study acknowledges these differences but may not fully capture the nuanced variations between the wide spectrum of cross-border regions in the world. This implies that the challenges and solution approaches presented in this work may differ based on specific cultural contexts and geopolitical locations and should thus be considered in future work.

To conclude, this study provides a comprehensive quantitative and qualitative analysis of data fragmentation related to disaster management at borders. It shows that data fragmentation manifests at different levels within and between organizations. It identifies and categorizes various challenges and related solution approaches regarding data management, technical, information, communication, organizational, and cultural factors. Finally, it argues the need for integrated approaches to increase the resilience of cross-border regions.

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